The webinar will start shortly.
Please note that the webinar will be recorded.

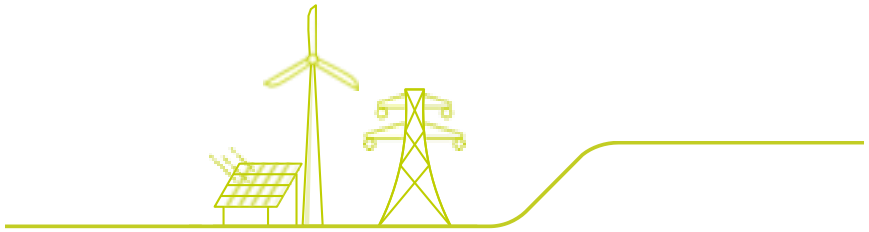
# Enduring Auction Capability

Detailed Market Design – 17/02/23

ESO

# Contents





# Project Overview

# Enduring Auction Capability

**The current design for Response services has highlighted several challenges...**

- Providers blind guess where other parties will tender – risk of oversupplying a single market when other markets are left empty
- Limited ability to split capacity and stack revenues across different services
- Limited options available to market participants (e.g., maximum of three orders per unit per delivery period, with only one child allowed for each parent order)

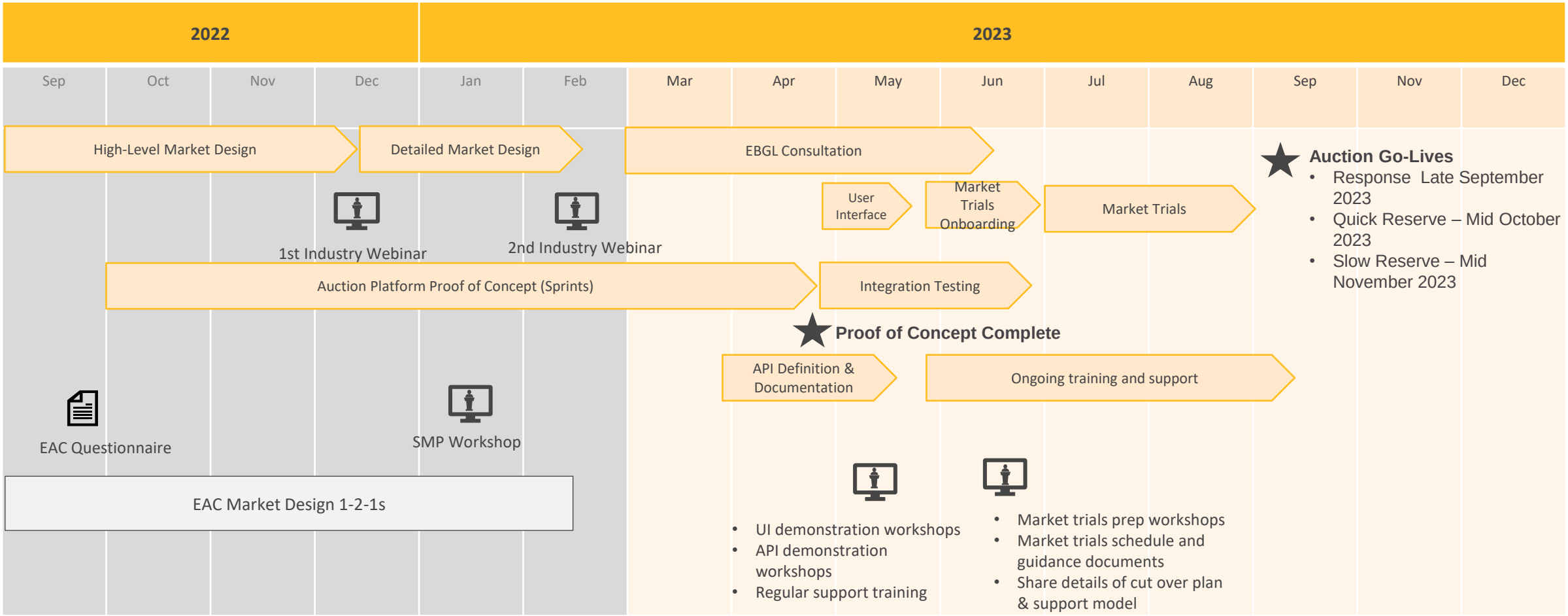
**Enduring Auction Capability**

The EAC will deliver **co-optimised procurement of day-ahead Response and Reserve services**, which would be **scalable** and **extendable** to new services and products

**Benefits of the EAC**

- Better user experience from fewer manual processes and utilisation of technology to facilitate bidding
- Closer to real-time procurement leading to increased market liquidity and participation
- Easy access across multiple markets from connected and co-optimised auctions for ancillary services
- Improved levels of flexibility and configurability to adapt to changes in service procurement

# Delivery Roadmap

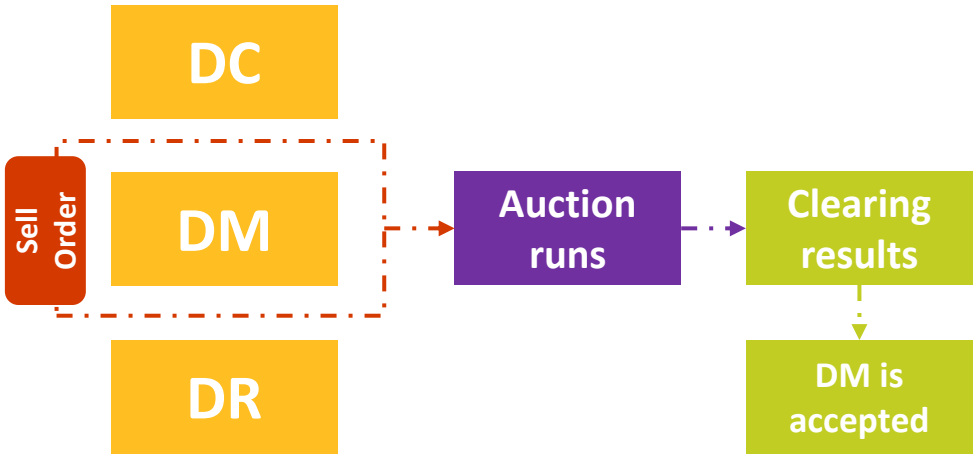


# Sell Order Design

"*Baskets*" for co-optimisation and "*substitution family*" for stacking/splitting.

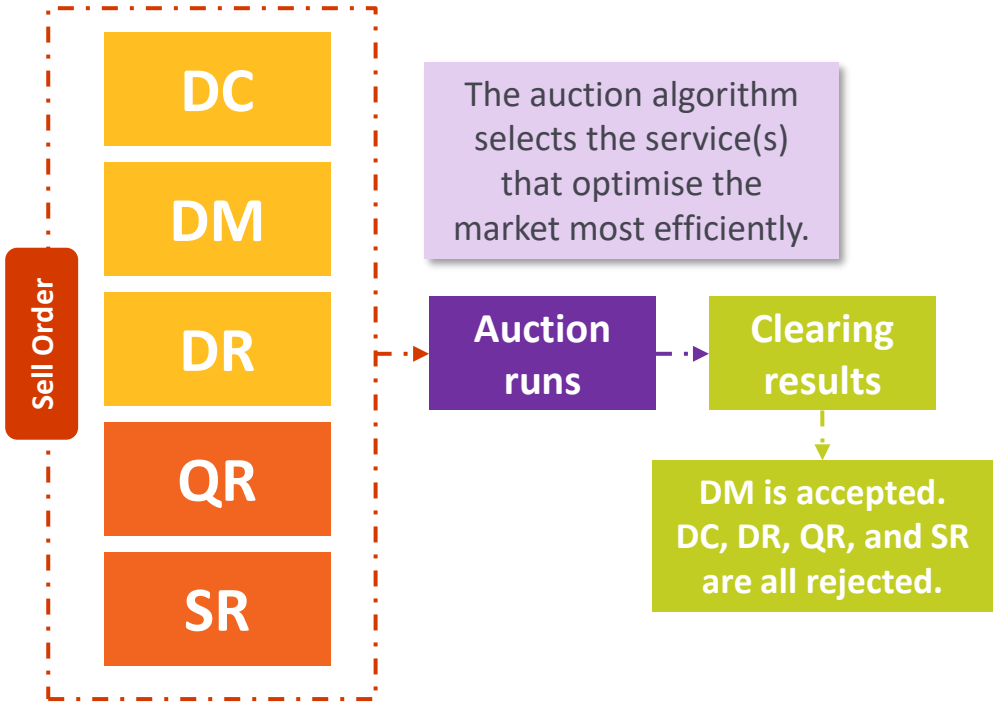
# Co-optimisation

## Current frequency response auctions




**Only one service** (i.e., either DC, DM, or DR) can be offered into the auction. Participants need to decide which service to offer ahead of the auction.

## EAC auction (with co-optimisation)




**More than one service** can be offered into the auction. Participants can offer all services they wish to provide ahead of the auction.

# Specification of a Basket

**In EAC, co-optimisation is implemented by using mutually exclusive *baskets*. Baskets can contain a mix of Response products.**

| Response (DC, DM, DR) | | | QR | SR |
|---|---|---|---|---|
| EFA 1 | EFA 1 | EFA 1 | EFA 1a | EFA 12 |
| | | | EFA 1b | |
| EFA 2 | EFA 2 | EFA 2 | EFA 2a | |
| | | | EFA 2b | |
| EFA 3 | EFA 3 | EFA 3 | EFA 3a | EFA 3a |
| | | | EFA 3b | EFA 3b |
| EFA 4 | EFA 4 | EFA 4 | EFA 4a | EFA 4a |
| | | | EFA 4b | EFA 4b |
| EFA 5 | EFA 5 | EFA 5 | EFA 5a | EFA 5a |
| | | | EFA 5b | EFA 5b |
| EFA 6 | EFA 6 | EFA 6 | EFA 6a | EFA 6a |
| | | | EFA 6b | EFA 6b |

1. Baskets are defined on **a single unit**

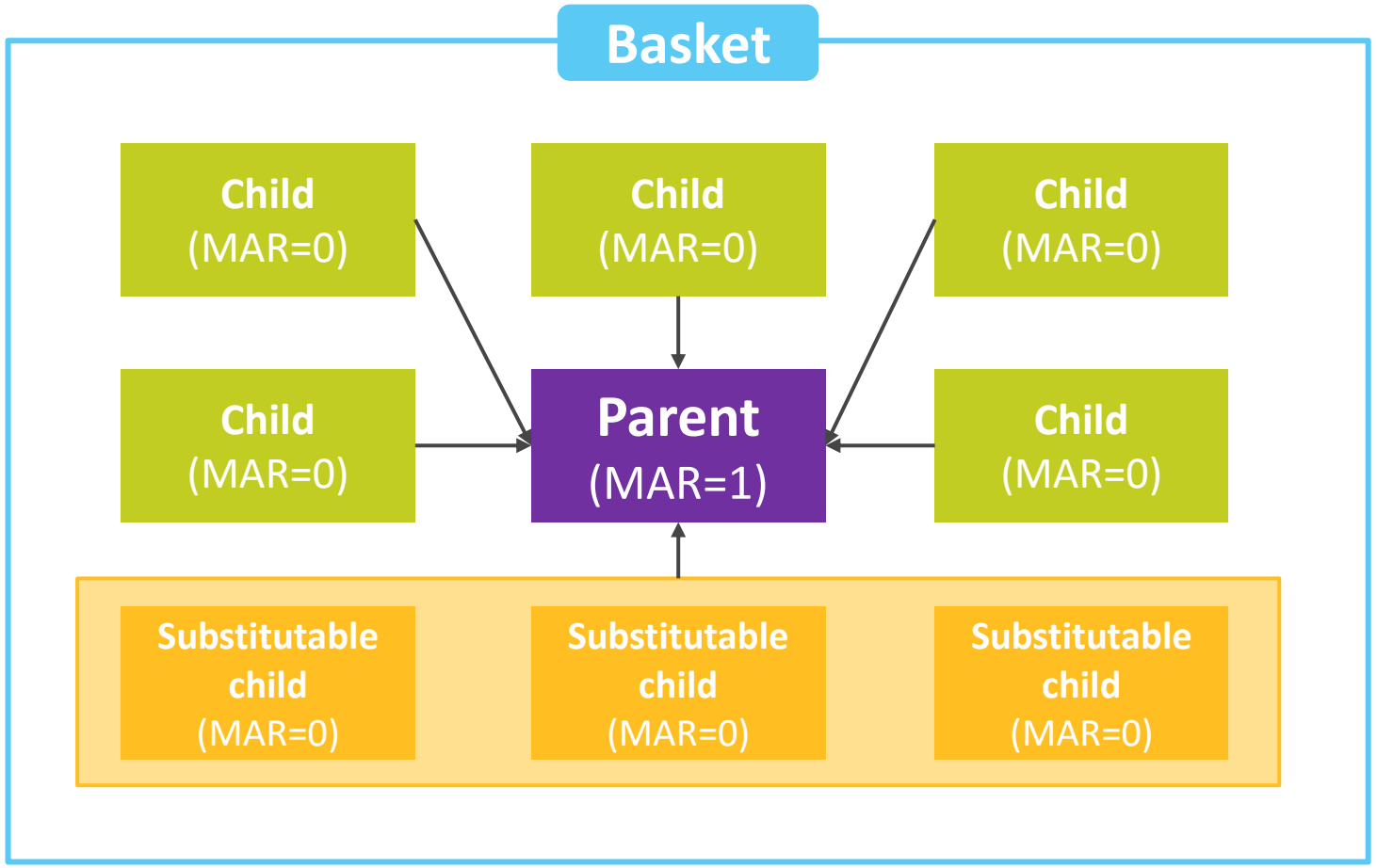
2. Baskets are defined on **a single service type**: Response, Quick Reserve, Slow Reserve.

3. Baskets are defined on **a single delivery period**

4. Each basket must contain exactly one parent order.

5. (Optional) A basket can be looped to a basket immediately preceding it.

# Specification of a Basket




- **There are three types of orders:**
  1) Parent orders
  2) Child orders
  3) Substitutable child orders.
- **Each basket must have exactly one parent order.**
  - Parent orders are non-curtailable (MAR=1).
  - The parent order can be a 0MW order.
  - The parent order can have no child, 1 child, or more than 1 children.
- **In each basket, apart from the parent order, all other orders are children of this single parent**
  - Children are fully curtailable (MAR = 0).
- **These orders could be either child orders or substitutable child orders.**
  - **Child orders:** the acceptance ratio of each child order must be less than or equal to 1. Child orders are not substitutable, and each can be accepted up to 100%
  - **Substitutable child orders:** the sum of the acceptance ratios of all substitutable child orders must be less than or equal to 1.

# Sell Order Design

| Current Frequency Response Sell Order Design | EAC Sell Order Design |
|---|---|
| ***Parent order***<br>• Non-curtailable (i.e., MAR=1)<br>• 1 parent order per service window, per product, per unit | ***Parent order***<br>• Non-curtailable (i.e., MAR=1)<br>• 1 parent order per basket (a basket is defined on a service window and a unit)<br>• A parent order can be defined on multiple products. All products in the parent order must be either accepted or rejected |
| ***Child order***<br>• Fully-curtailable (i.e., MAR=0)<br>• A child must be defined on a single product<br>• A parent order can only have at most one child per service window<br>• A child and its linked parent can be defined on the same or different service windows | ***Child order***<br>• Fully-curtailable (i.e., MAR=0)<br>• A child must be defined on a single product<br>• A parent order can have multiple children<br>• A child and its linked parent must be defined on the same service window |
| ***No splitting*** | ***Substitutable child order***<br>• Fully-curtailable (i.e., MAR=0)<br>• This order type can be used for (continuous) splitting<br>• A substitutable child and its linked parent must be defined on the same service window |
| ***No co-optimisation*** | ***Baskets***<br>• Each basket must be defined on a single unit, a single service window, a service type and a parent order. At most 25 baskets can be submitted from a unit per EFA day.<br>• This feature is designed to allow mutually exclusivity (e.g., co-optimisation) |
| ***Looped order***<br>• Looped orders have same actual acceptance ratio (AAR) | ***Parent order (for the same service window)***<br>• The parent orders of looped baskets must be either accepted or rejected<br>***Looped baskets (for consecutive service windows)***<br>• All products in a parent order must be either accepted or rejected |
| ***Multi-period order***<br>• Multi-period order has same actual acceptance ratio (AAR) | ***Looped baskets***<br>• The parent orders of looped baskets must be either accepted or rejected |

# Market Clearing Rules

- Examples of Market Clearing
- Overholding

# Market Clearing Rules

| Parent orders | Child orders | Substitutable child orders |
|---|---|---|
| ○ Parent orders must be fully accepted (or rejected).<br>○ Paradoxical rejection is allowed.<br>○ Paradoxical acceptance is not allowed. | ○ A child order may be partially accepted for any integer amount.<br>○ A child order may be accepted only if its parent is accepted.<br>○ A child order may be accepted only if it has non-negative surplus.<br>○ Paradoxical rejection is allowed.<br>○ Paradoxical acceptance is not allowed. | ○ A substitutable child order may be partially accepted for any integer amount.<br>○ A substitutable child order may be accepted only if its parent is accepted.<br>○ A substitutable child order may be accepted only if it has non-negative surplus.<br>○ The sum of the acceptance ratios (accepted volume divided by offered volume) of the orders in a substitutable order family must be less than or equal to 1.<br>○ Paradoxical rejection is allowed.<br>○ Paradoxical acceptance is not allowed. |

**Looped family**

Define a set of baskets looped together as a “looped family”.

- The parent order must be accepted from each basket in a looped family.
- A parent order may be accepted only if the total surplus of all accepted orders (parents, child, and substitutable child) in its looped family is non-negative.
- A parent order may not be accepted from a basket if a parent order is accepted from another basket which is mutually-exclusive with the first basket.

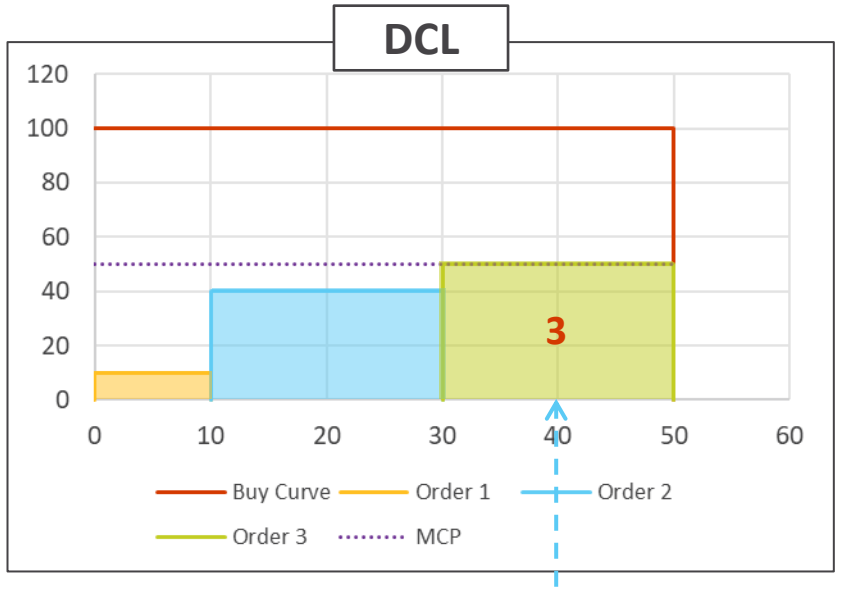
# Co-optimisation (without splitting)

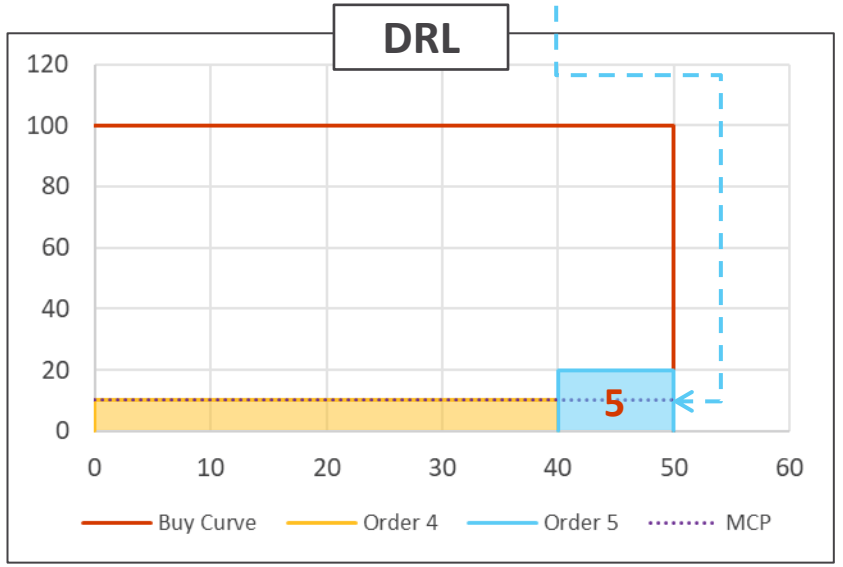
**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.1**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 10MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 20MW, £40/MW/h, parent<br>**Order 3:** Unit Z, 20MW, £50/MW/h, parent | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 4:** Unit V, 40MW, £10/MW/h, parent<br>**Order 5:** Unit Z, 10MW, £20/MW/h, parent |

Order 3 in DCL and Order 5 in DRL are two mutually exclusive parent orders and at most one can be (partially or fully) accepted.




**Clearing outcome**

- Allocating Unit Z to DCL market generates a welfare of:
  $$20MW \times (£100 - £50) = 1000$$
- Allocating Unit Z to DRL market generates a welfare of:
  $$10MW \times (£100 - £20) = 800$$

→ **The bid selection that maximises the total market welfare** is to allocate Unit Z to the DCL market and fully accept all other orders.

→ **The clearing prices** are £50/MW/h for DCL and £10/MW/h for DRL.

# Co-optimisation

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.2 (without welfare-sharing)**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 20MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 20MW, £40/MW/h, parent<br>**Order 3a:** Unit Z, 4MW, £50/MW/h, parent | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 3b:** Unit Z, 8MW, £20/MW/h, parent |

In Order 3, Unit Z wants to offer 4MW DCL and 8MW DRL as a bundle. The entire order can only be either fully accepted or fully rejected. Partial acceptance of Order 3 (e.g., accepting Order 3a alone) is not allowed.

**Clearing outcome**

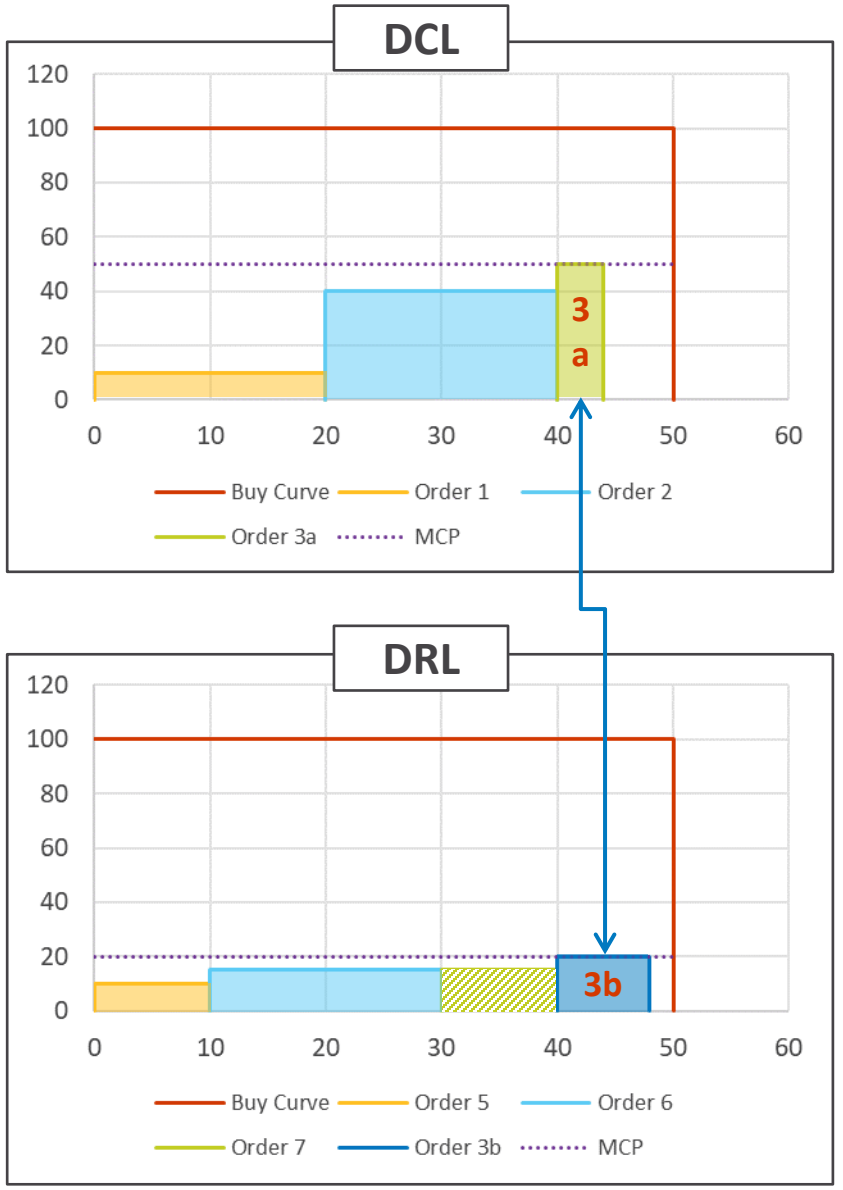
- Accepting Order 3a and 3b generates a positive welfare of:

$$4MW \times (£100 - £50) + 8MW \times (£100 - £20) = 840$$

→ **The bid selection that maximises the total market welfare** is to fully accept all orders.

→ **The clearing prices** are £50/MW/h for DCL and £20/MW/h for DRL.

→ Please note that if the volume offered in Order 3a is greater than 10MW, the entire Order 3 will be fully rejected due to the volume constraint.



# Co-optimisation

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.3 (with welfare-sharing)**

| DCL | DRL |
|---|---|
| **Buy order:** | **Buy order:** |
| **Order A:** 50MW, £100/MW/h | **Order B:** 50MW, £20/MW/h |
| **Sell order:** | **Sell order:** |
| **Order 1:** Unit X, 20MW, £10/MW/h, parent | **Order 5:** Unit V, 10MW, £10/MW/h, parent |
| **Order 2:** Unit Y, 20MW, £40/MW/h, parent | **Order 6:** Unit W, 20MW, £15/MW/h, parent |
| **Order 3a:** Unit Z, 4MW, £50/MW/h, parent | **Order 7:** Unit W, 10MW, £15/MW/h, child of 6 |
| **Order 4:** Unit T, 6MW, £80/MW/h, parent | **Order 3b:** Unit Z, 8MW, £25/MW/h, parent |

In Order 3, Unit Z wants to offer 4MW DCL and 8MW DRL as a bundle. The entire order can only be either fully accepted or fully rejected. Partial acceptance of Order 3 (e.g., accept Order 3a alone) is not allowed.

**Clearing outcome**

- Accepting Order 3a and 3b generates a positive welfare of:

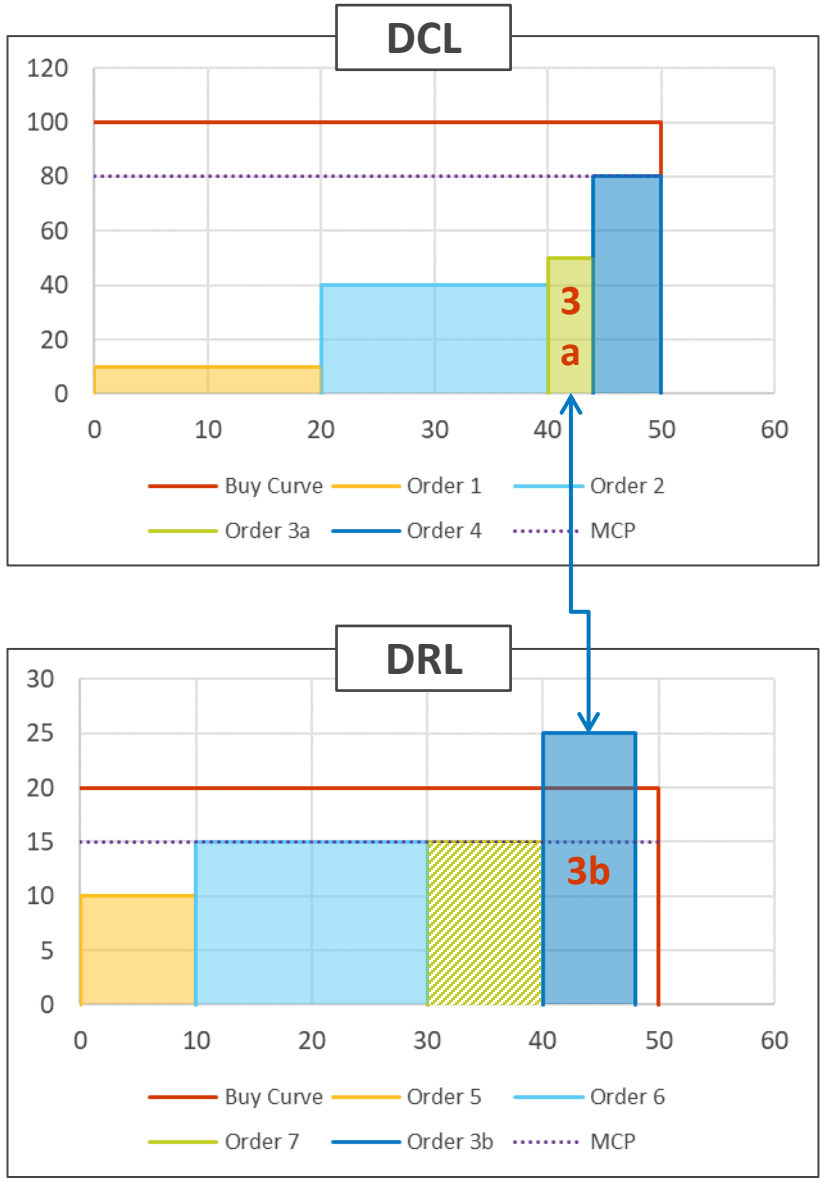
$$4MW \times (£100 - £50) + 8MW \times (£20 - £25) = 160$$

  - Order 3b can be accepted if the entire order has non-negative welfare.

→ **The bid selection that maximises the total market welfare** is to fully accept all orders.

→ **The clearing price** is £80/MW/h for DCL and for DRL the price must be…

- → no greater than £20/MW/h so it's no greater than the buyer's willingness to pay.
- → no less than £15/MW/h so Order 6 and 7 are not paradoxically accepted.
- → The price must be greater than or equal to $\frac{(4MW \times £50 + 8MW \times £25) - (4MW \times £80)}{8MW} = £10$
- → DRL clears at £15/MW/h.



# Co-optimisation (with continuous splitting)

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.4**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 10MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 10MW, £40/MW/h, parent<br>**Order 3:** Unit Z, 20MW, £50/MW/h, parent<br>**Order 4:** Unit Z, 20MW, £50/MW/h, substitutable child of Order 3 | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 8:** Unit Z, 10MW, £20/MW/h, substitutable child of Order 3 |

Order 4 in DCL and Order 8 in DRL are two substitutable child orders, both linked to the single parent Order 3 in DCL.

**Clearing outcome**

- Allocating 100% Order 4 to DCL market generates a welfare of:

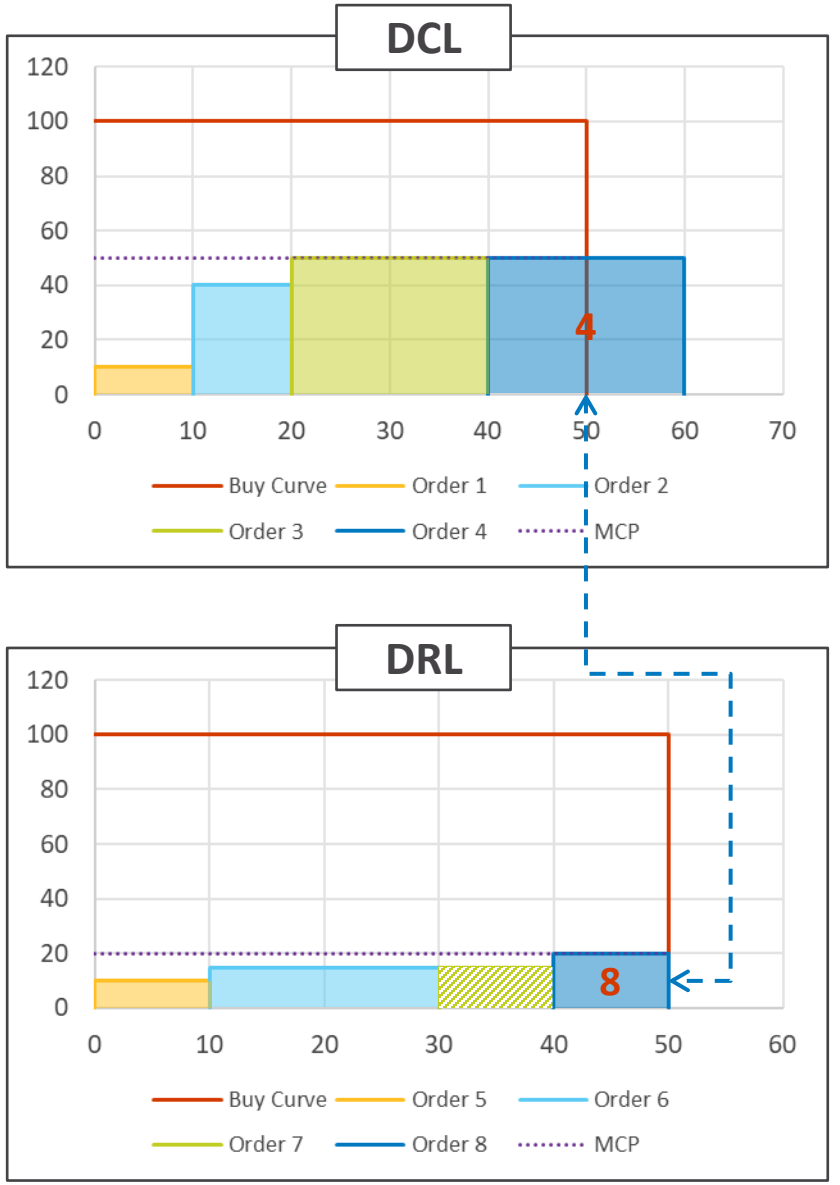
$$20MW \times (£100 - £50) = 1000$$

  - However, this solution is infeasible because at most 10MW (i.e., 50%) of Order 4 can be accepted in the DCL market (total requirement for DCL is 50MW).
  - Allocating 50% Order 4 to DCL market and 50% of Order 8 to the DRL market generates a welfare of:

$$10MW \times (£100 - £50) + 5MW \times (£100 - £20) = 900$$

- Allocating 100% Order 8 to DRL market generates a welfare of:

$$10MW \times (£100 - £20) = 800$$




**Note:** Increase the accepted volume of DRL market by 1MW, the market welfare of DRL increases by 80 but the market welfare of DCL reduces by 100.

# Co-optimisation (with continuous splitting)

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.4**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 10MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 10MW, £40/MW/h, parent<br>**Order 3:** Unit Z, 20MW, £50/MW/h, parent<br>**Order 4:** Unit Z, 20MW, £50/MW/h, substitutable child of Order 3 | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 8:** Unit Z, 10MW, £20/MW/h, substitutable child of Order 3 |

Order 4 in DCL and Order 8 in DRL are two substitutable child orders, both linked to the single parent Order 3 in DCL.

**Clearing outcome**

- Allocating 100% Order 4 to DCL market generates a welfare of:

$$20MW \times (£100 - £50) = 1000$$

  - However, this solution is infeasible because at most 10MW (i.e., 50%) of Order 4 can be accepted in the DCL market (total requirement for DCL is 50MW).
  - Allocating 50% Order 4 to DCL market and 50% of Order 8 to the DRL market generates a welfare of:

$$10MW \times (£100 - £50) + 5MW \times (£100 - £20) = 900$$

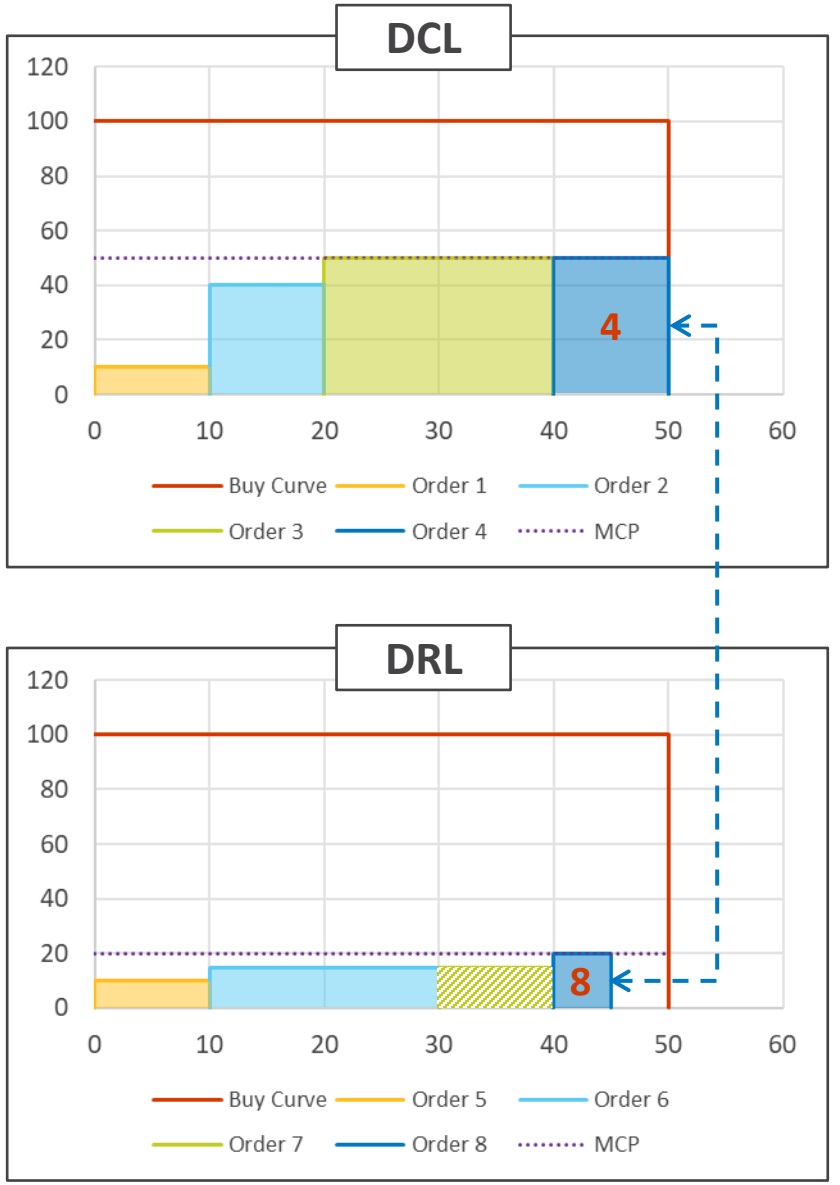
- Allocating 100% Order 8 to DRL market generates a welfare of:

$$10MW \times (£100 - £20) = 800$$

→ **The bid selection that maximises the total market welfare** is to accept 50% of Order 4, 50% of Order 8, and fully accept all other orders.

→ **Clearing prices** are £50/MW/h for DCL and £20/MW/h for DRL.

**Note:** Increase the accepted volume of DRL market by 1MW, the market welfare of DRL increases by 80 but the market welfare of DCL reduces by 100.



# Overholding

**One or more buy orders may be paradoxically accepted as a result of market clearing.**

**Example**

**Buy order:**
**Order A:** 200MW, £200/MW/h
**Order B:** 100MW, £100/MW/h
**Order C:** 50MW, £0/MW/h
**Sell order:**
**Order 1:** Unit X, 350MW, £10/MW/h, parent

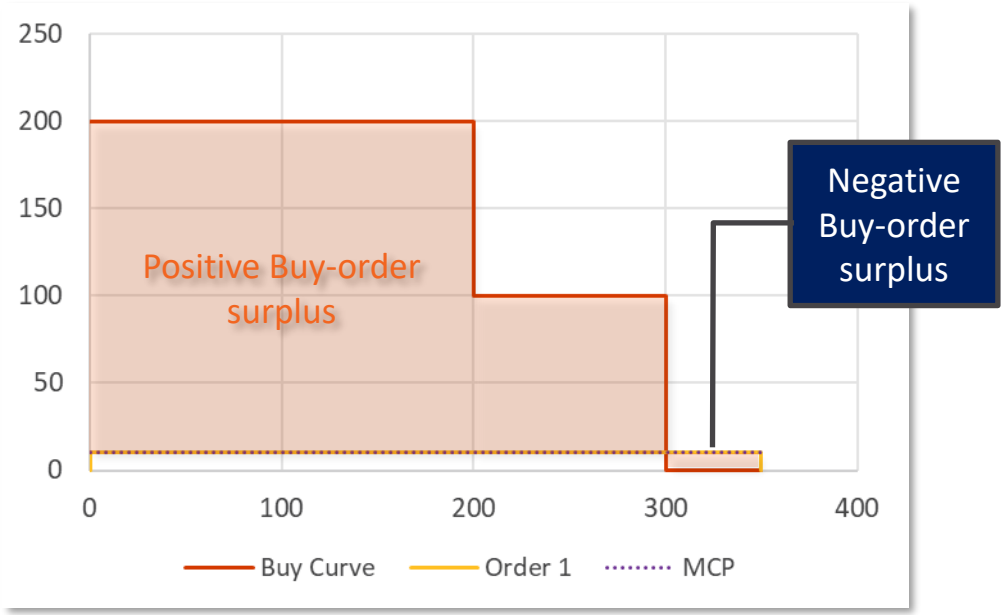
**Clearing Outcome**

- Accepting Order 1 has a positive welfare of:

$$200MW \times 200 + 100MW \times 100 - 350MW \times 10 = 46500$$

→ **The bid selection that maximises the total market welfare** is to fully accept Order 1.

→ **The clearing price** is £10/MW/h



# Splitting (Revenue Stacking)

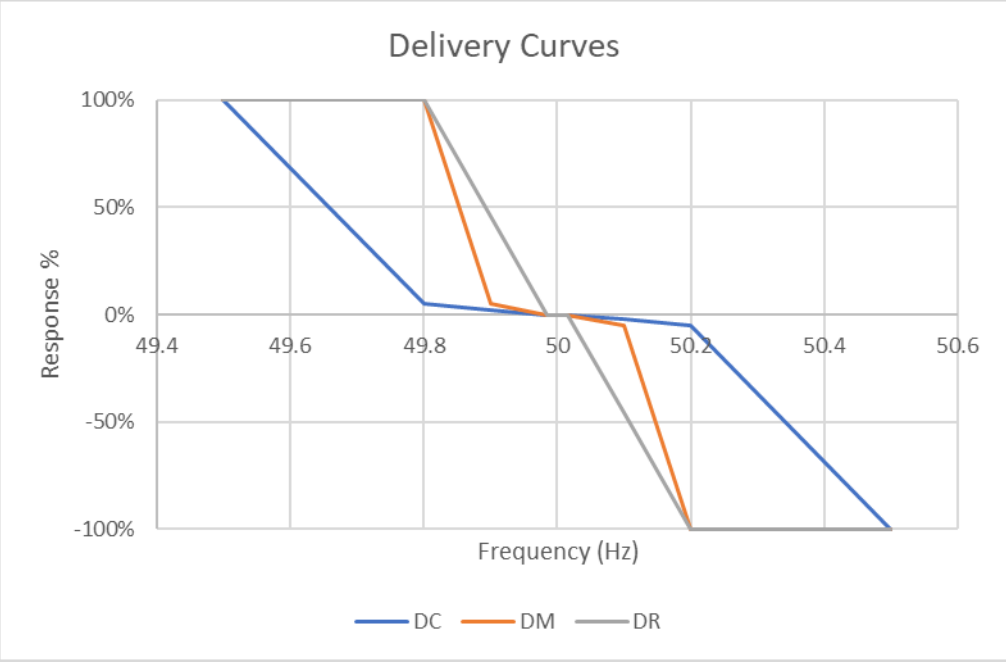
# Splitting

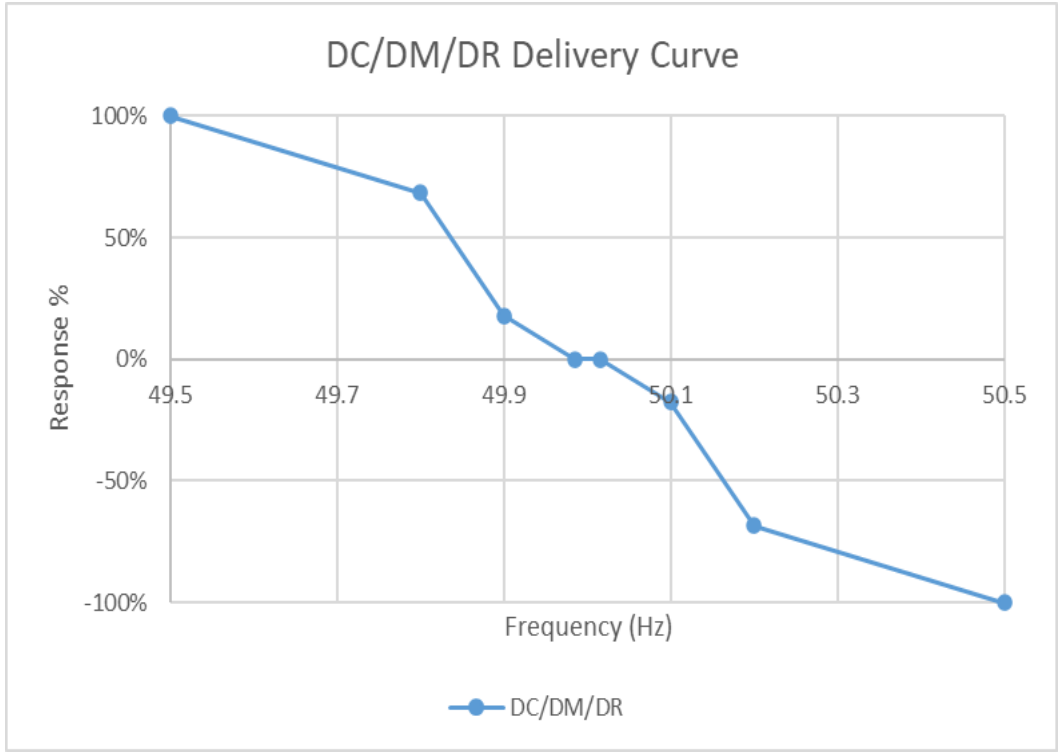
| | | Dynamic Containment | | Dynamic Moderation | | Dynamic Regulation | | Slow Reserve | | Quick Reserve | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DCL | DCH | DML | DMH | DRL | DRH | PSR | NSR | PQR | NQR |
| DC | DCL | | | | | | | | | | |
| | DCH | | | | | | | | | | |
| DM | DML | | | | | | | | | | |
| | DMH | | | | | | | | | | |
| DR | DRL | | | | | | | | | | |
| | DRH | | | | | | | | | | |
| Slow Reserve | PSR | | | | | | | | | | |
| | NSR | | | | | | | | | | |
| Quick Reserve | PQR | | | | | | | | | | |
| | NQR | | | | | | | | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | N/A | Yes | No | | | | | | |

# Splitting

With the introduction of the new faster-acting frequency response services, ESO is seeking to optimise the utilisation of assets within the fast FRS market by introducing Revenue Stacking.



# Splitting

A delivery curve derived from contracted service will be calculated based on total volume contracted and individual volumes per service.

| f | DC | DM | DR |
|---|---|---|---|
| 49.5 | 100.00% | 100.00% | 100.00% |
| 49.8 | 5.00% | 100.00% | 100.00% |
| 49.9 | 2.30% | 5.00% | 45.95% |
| 49.985 | 0.00% | 0.00% | 0.00% |
| 50.015 | 0.00% | 0.00% | 0.00% |
| 50.1 | -2.30% | -5.00% | -45.95% |
| 50.2 | -5.00% | -100.00% | -100.00% |
| 50.5 | -100.00% | -100.00% | -100.00% |


| f | Stacked |
|---|---|
| 49.5 | 100.00% |
| 49.8 | 68.33% |
| 49.9 | 17.75% |
| 49.985 | 0.00% |
| 50.015 | 0.00% |
| 50.1 | -17.75% |
| 50.2 | -68.33% |
| 50.5 | -100.00% |

# Splitting

A delivery curve derived from contracted service will be calculated based on total volume contracted and individual volumes per service.

| f | DC | DM | DR |
|---|---|---|---|
| 49.5 | 100.00% | 100.00% | 100.00% |
| 49.8 | 5.00% | 100.00% | 100.00% |
| 49.9 | 2.30% | 5.00% | 45.95% |
| 49.985 | 0.00% | 0.00% | 0.00% |
| 50.015 | 0.00% | 0.00% | 0.00% |
| 50.1 | -2.30% | -5.00% | -45.95% |
| 50.2 | -5.00% | -100.00% | -100.00% |
| 50.5 | -100.00% | -100.00% | -100.00% |

(DC*k1+DM*k2+DR*k3)

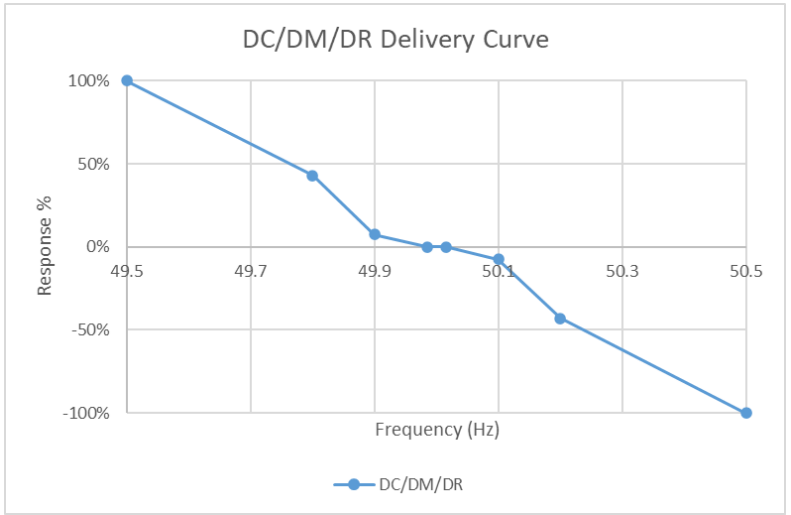
| f | Stacked |
|---|---|
| 49.5 | 100.00% |
| 49.8 | 43.00% |
| 49.9 | 7.47% |
| 49.985 | 0.00% |
| 50.015 | 0.00% |
| 50.1 | -7.47% |
| 50.2 | -43.00% |
| 50.5 | -100.00% |

**DC = 30 MW -> $k1 = \frac{30}{50}$**

**DM = 15 MW -> $k2 = \frac{15}{50}$**

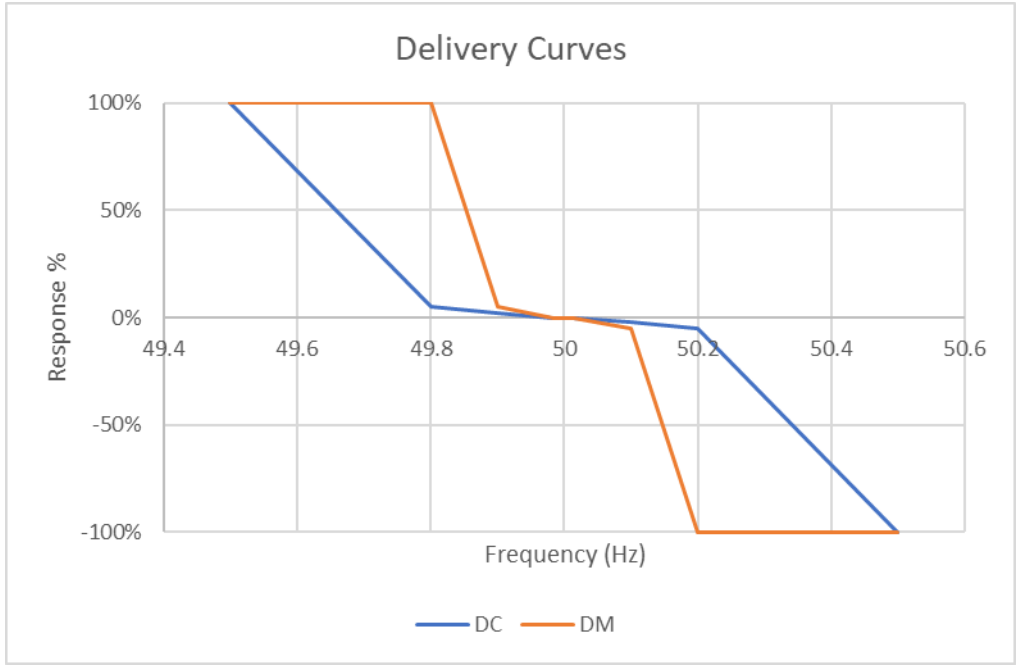
**DR = 5 MW -> $k3 = \frac{5}{50}$**

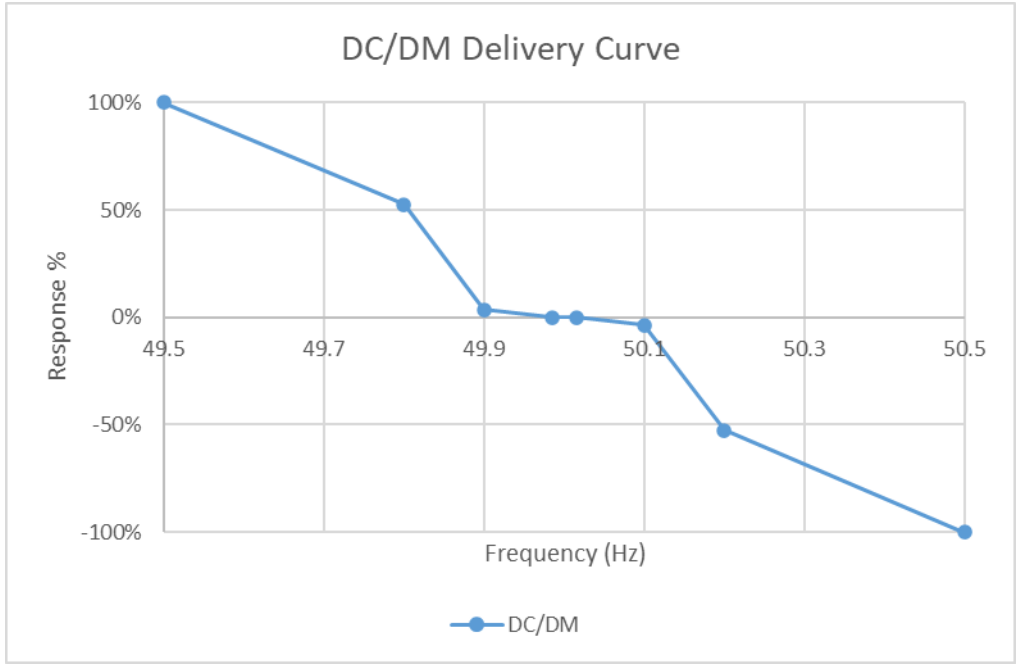
**Total Volume= 50MW**



# Fast Services (DC/DM)

When stacking fast services, delivery curves can be stacked without change to the parameters of the service, i.e. the ramp and lag times are unchanged, and each service keeps its design accordingly.

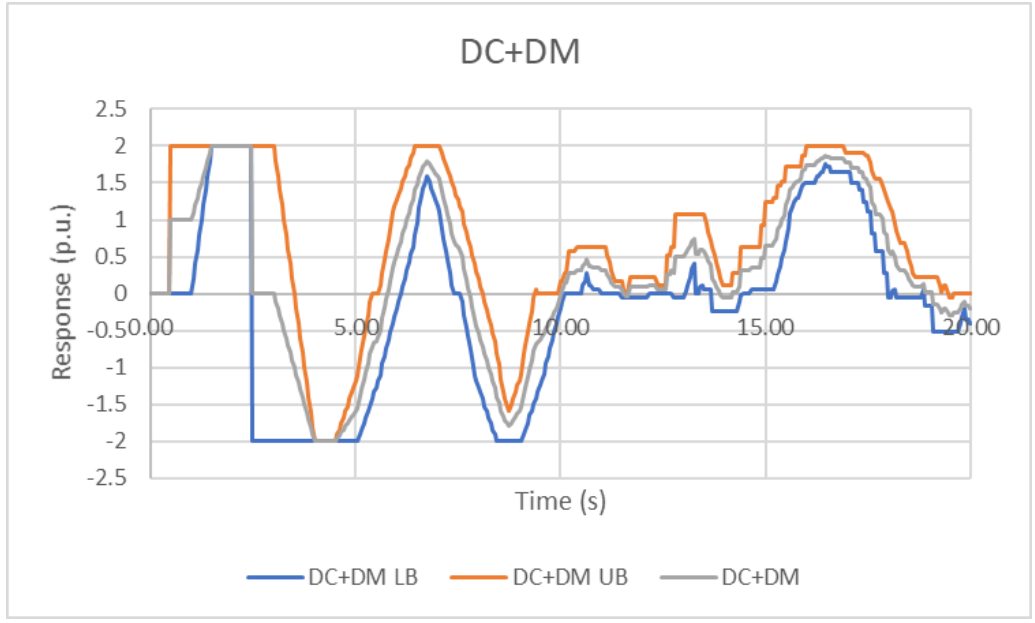


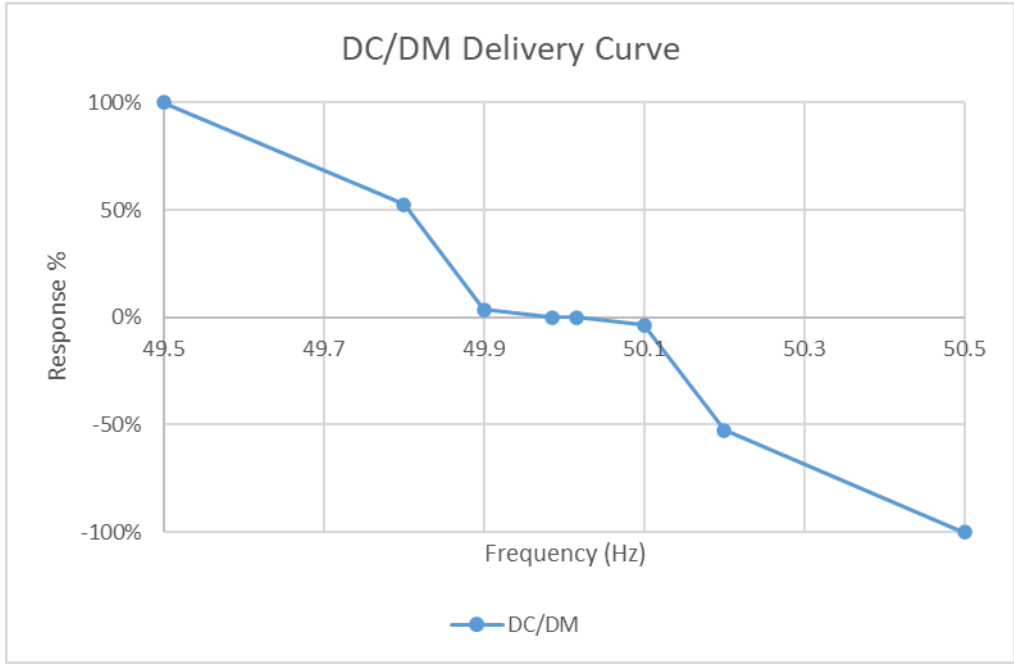




| | DC | DM | Stacked Service | Units |
|---|---|---|---|---|
| Max time to full delivery | 1 | 1 | 1 | s |
| Lag upper bound (max initiation time) | 0.5 | 0.5 | 0.5 | s |
| Ramp time upper bound | 0.5 | 0.5 | 0.5 | s |
| Ramp rate | 2 | 2 | 2 | 1/s |

# Splitting (DC/DM)

When stacking fast services, delivery curves can be stacked without change to the parameters of the service, i.e. the ramp and lag times are unchanged, and each service keeps its design accordingly.



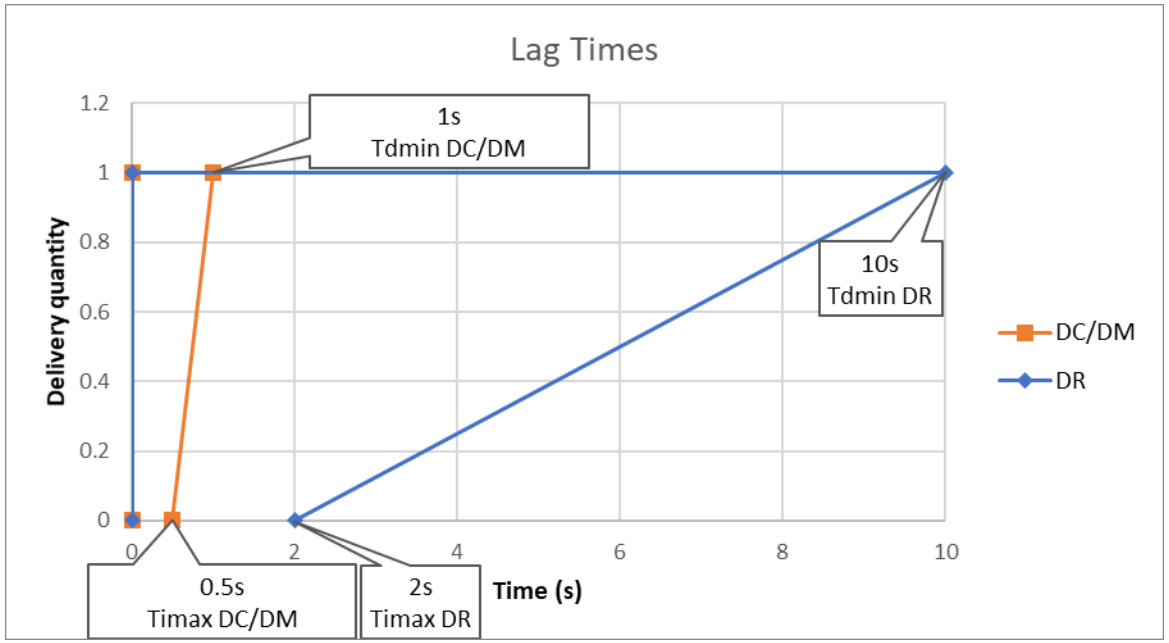




| | DC | DM | Stacked Service | Units |
|---|---|---|---|---|
| Max time to full delivery | 1 | 1 | 1 | s |
| Lag upper bound (max initiation time) | 0.5 | 0.5 | 0.5 | s |
| Ramp time upper bound | 0.5 | 0.5 | 0.5 | s |
| Ramp rate | 2 | 2 | 2 | 1/s |

# Splitting (DR/DC/DM)

When stacking a slow service with fast services, the service parameters of the fastest service will define the speed of the stacked service.

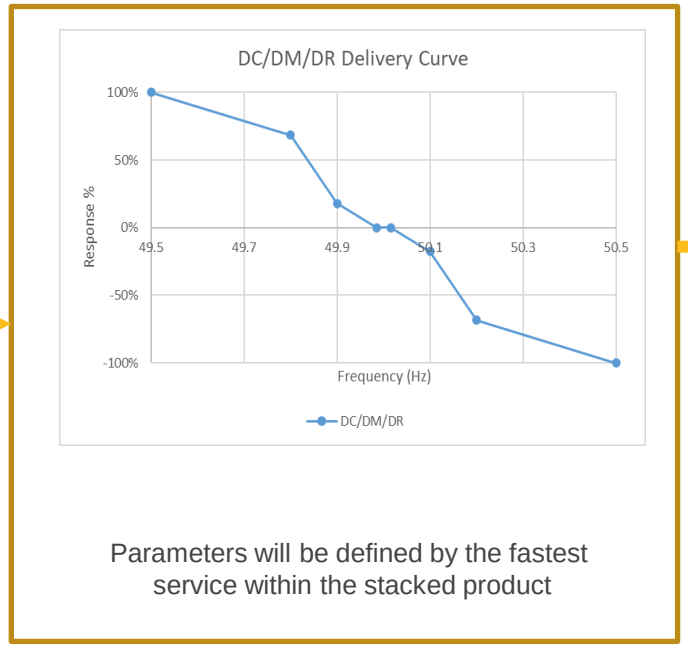
| | Stacked Service Parameters | Units |
|---|---|---|
| Max time to full delivery ($T_{dMAX}$) | $\min(T_{dMAX\_service1}, T_{dMAX\_service2})$ | s |
| Lag upper bound ($T_{iMAX}$) | $\min(T_{iMAX\_service1}, T_{iMAX\_service2})$ | s |
| Ramp time upper bound ($tr_{max}$) | $\min(tr_{\max\_service1}, tr_{\max\_service2})$ | s |
| Ramp rate ($rr_{min}$ ) | $\max(rr_{\min\_service1}, rr_{\min\_service2})$ | 1/s |



# Splitting (DR/DC/DM)

*K* factor will be calculated with respect to the stacked service, and a single *K* factor will apply across all services.

Services contracted




Standard Performance Monitoring

K factor for stacked product

DC Score

DM Score

DR Score

# Negative Pricing

# Negative Availability Price

## Current Observation

- Current target market design for frequency response has no payment for utilisation. When providing HF response (i.e., DCH, DMH, DRH), a unit will take power from the grid but not be settled for that energy.
- If power prices are high, this can be a valuable benefit of providing HF response. Providers may bid all the way down to £0/MW/h to capture the “free energy”. This has been observed a few times in the DRH markets.

## Potential Problem

- When everyone bids £0/MW/h, how does the algorithm accept the executed offers? How does performance monitoring work?

## Proposed Solution

- The new market design will allow for negative offer prices and negative clearing prices (this means participants pay the ESO to deliver an Ancillary Service).

# Penalty Calculation for Negative Clearing Prices

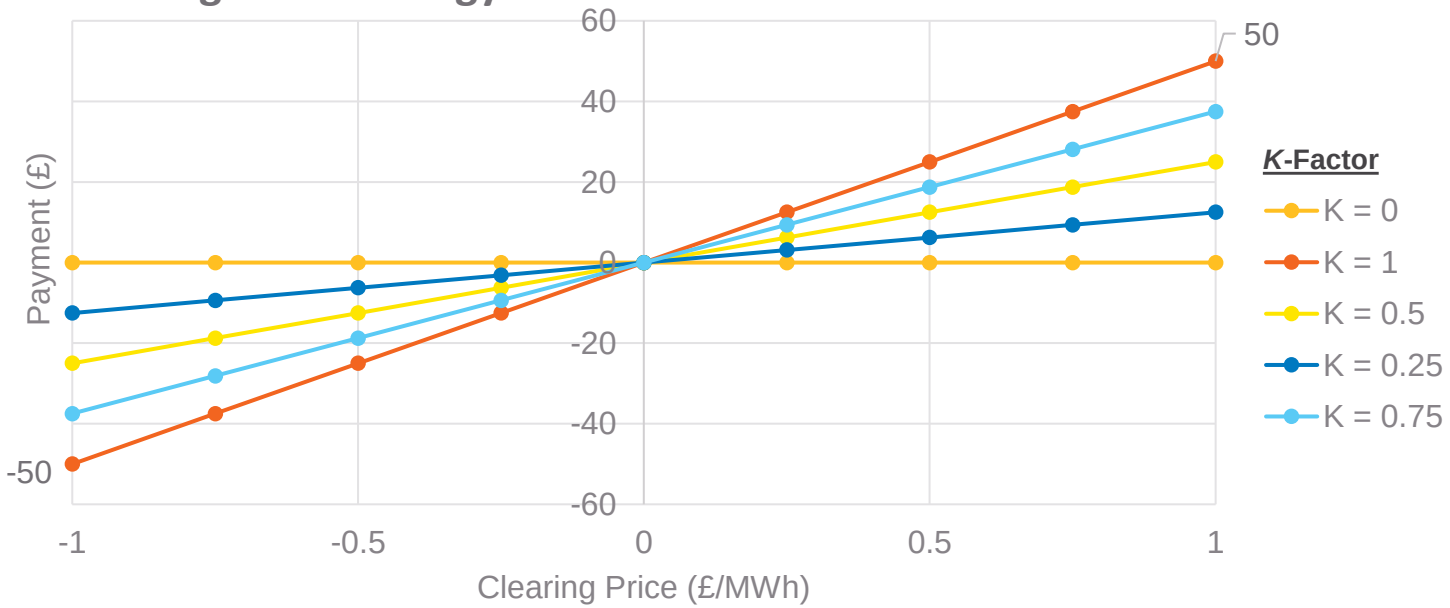
Current **penalty factor** methodology doesn't cater for scenarios in which the auction clearing price is **negative**. Indeed, for a given cleared volume and a negative clearing price, with the current methodology, a provider with poor performance (higher penalty) would have to pay the ESO less than a provider with good performance (lower penalty).

## Reminder

- When clearing price is **positive** (payment from ESO to provider), provider is penalised with less payment from ESO.
- When clearing price is **negative** (payment from provider to ESO), provider is penalised with more payment to ESO.

## Example (the volume contracted is 100 MW and the duration is 0.5 h)

### Existing Methodology




Net payment to provider

| Clearing Price (£/MW/h) | *K* = 1 | *K* = 0.5 | *K* = 0 |
|---|---|---|---|
| **-1** | -50 | -25 | 0 |
| **0** | 0 | 0 | 0 |
| **1** | 50 | 25 | 0 |

Poor performance not penalised

# Penalty Calculation for Negative Clearing Prices

Current **penalty factor** methodology doesn't cater for scenarios in which the auction clearing price is **negative**. Indeed, for a given cleared volume and a negative clearing price, with the current methodology, a provider with poor performance (higher penalty) would have to pay the ESO less than a provider with good performance (lower penalty).

## Reminder

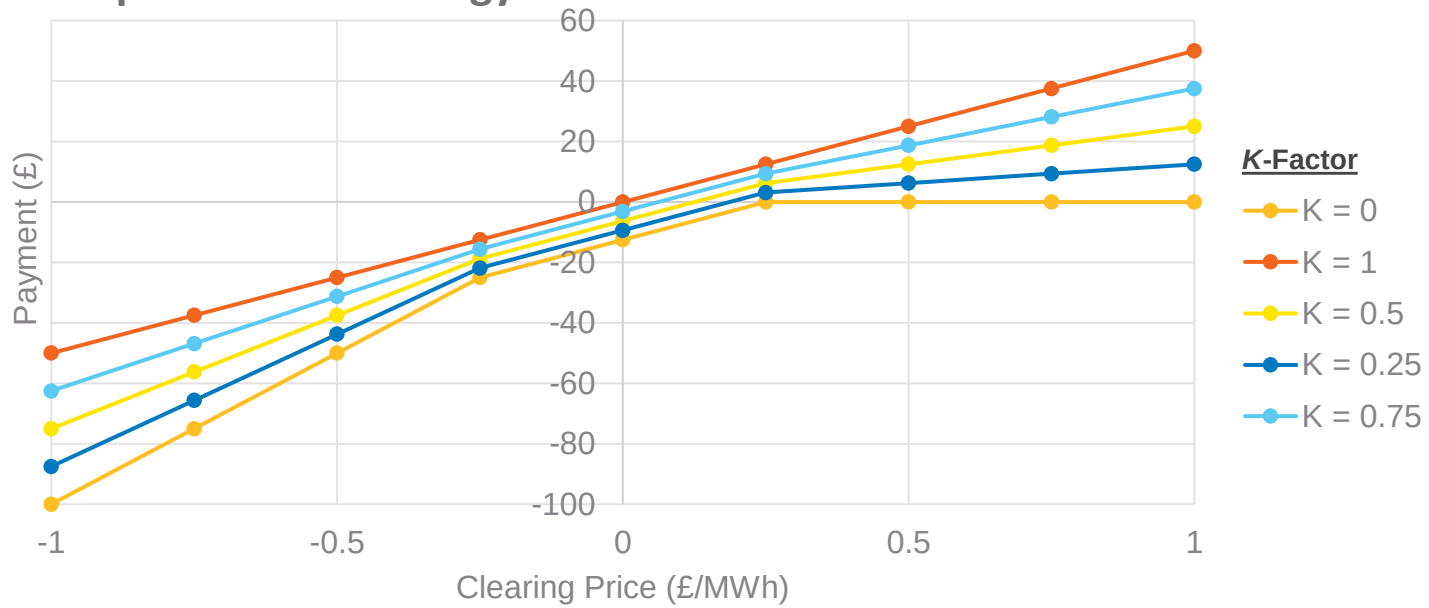
- When clearing price is **positive** (payment from ESO to provider), provider is penalised with less payment from ESO.
- When clearing price is **negative** (payment from provider to ESO), provider is penalised with more payment to ESO.

Net payment to provider

| Clearing Price (£/MW/h) | *K* = 1 | *K* = 0.5 | *K* = 0 |
|---|---|---|---|
| **-1** | -50 | -75 | -100 |
| **0** | 0 | -6.25 | -12.5 |
| **1** | 50 | 25 | 0 |

## Example (the volume contracted is 100 MW and the duration is 0.5 h)

**Proposed Methodology**




- ✓ Poor performance penalised
- ✓ Even at zero clearing price

# Penalty Calculation for Negative Clearing Prices

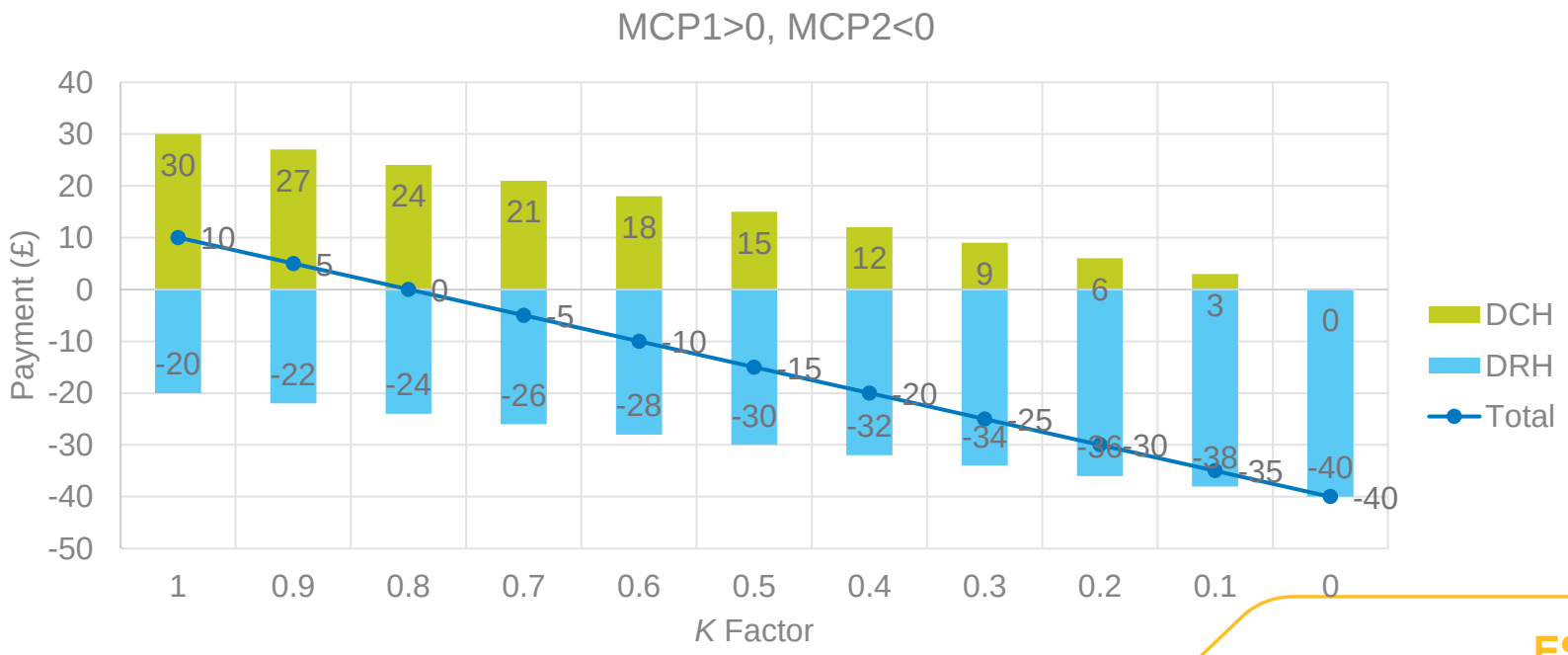
**Special Case: Splitting**

- In this case, the penalties are calculated for each service independently (different volumes and prices) but with the same performance (*K*-factor).
- The amount the participant will get paid for each service will be the same as if they were delivering a single service with that same *K*-factor.
- This minimises the risk that a participant may game the penalty when splitting by underperforming on the least valuable service delivering perfectly on the more profitable service

For example:

| Service | Cleared Volume (MW) | Clearing Price (£/MW/h) |
|---|---|---|
| DCH | 60 | 1 |
| DRH | 40 | -1 |

Asset's capacity = 100 MW



# Q&A

# Q&A

Please submit your questions using the Teams Q&A function.

# Appendix

# Appendix 1. Sell Order Design

# Mutually Exclusivity

| Unit X | Response | | |
|---|---|---|---|
| | DC | DM | DR |
| EFA 1 | A | B | C |
| EFA 2 | A | B | C |
| EFA 3 | A | B | C |
| EFA 4 | A | B | C |
| EFA 5 | A | B | C |
| EFA 6 | A | B | C |

**Mutually exclusive orders**

**Examples:**

For a single unit X and a single EFA, I want to offer either one of the three options:

**Order A:** 20 MW DCL, £2

**Order B:** 15 MW DML, £5

**Order C:** 10 MW DRL, £20

Order A, B, C are mutually exclusive to each other.

→ However, participants may want to offer mixed services as a bundle. These bundles are mutually exclusive to each other.

→ **To facilitate this, we introduce a new sell order design called "(mutually exclusive) baskets".**

# Mutually Exclusivity

**In EAC, co-optimisation is implemented by using mutually exclusive *baskets*. Baskets can contain a mix of Response products.**

| Unit X | Response | | |
|---|---|---|---|
| | DC | DM | DR |
| EFA 1 | A | B | C |
| EFA 2 | A | B | C |
| EFA 3 | A | B | C |
| EFA 4 | A | B | C |
| EFA 5 | A | B | C |
| EFA 6 | A | B | C |

**Mutually exclusive baskets**

**Examples:**

For a single unit X and a single EFA, I want to offer:

**Basket A:**

Order A1: 20 MW DCL, £2

Order A2: 20 MW DCH, £1

**Basket B:**

Order B1: 15 MW DML, £5

Order B2: 15 MW DMH, £3

**Basket C:**

Order C1: 10 MW DCL, £2

Order C2: 10 MW DCH, £1

Order C3: 5 MW DRL, £20

Order C4: 5 MW DRH, £0

Baskets A, B, C are mutually exclusive to each other.

# Specification of a Basket

| Data Field | Comment |
|---|---|
| **Basket ID** | |
| **Unit ID** | Baskets are defined on a single unit. |
| **Service Type** | Response/ Quick Reserve/ Slow Reserve |
| **Delivery Period** | Baskets are defined on a single delivery period, appropriate to the Service Type. |
| **Parent Order** | A basket must have a parent order, which is non-curtailable (i.e., MAR=1). The volume of the parent order can be 0MW for all products. |
| **Loop Basket ID** | ID of a basket immediately preceding this basket. May be left blank. |

**Notes:**

A. Service Type: the service type of a basket determines what products can be put in the basket and the possible delivery periods (e.g., 4-hour, 2-hour, 8-hour).

B. Looped baskets: baskets of which respective parent orders are looped linked

C. Multi-period blocks are enabled by looping adjacent baskets together.

D. Response and reserve services can be looped into multi-period blocks (i.e. delivered sequentially – not stacked).

# Basket Overview

| | |
|---|---|
| **Basic Principles** | • A basket contains orders belonging to a single unit, service type, and delivery period.<br>• A basket must be fully deliverable (full acceptance of the parent and all child orders plus 100% acceptance of the substitution family must be feasible for the unit). This is the responsibility of the participant. |
| **Key Validations** | • A basket contains exactly one parent order (which may have 0 volume) and may contain 1 or more child orders and 1 or more substitutable child orders.<br>• A basket may be looped only to a basket immediately preceding it ("start delivery time" of basket must equal "end delivery time" of looped basket). |
| **Mutual Exclusivity** (see note below) | • A basket is mutually exclusive with all other concurrent baskets (i.e., defined on the same delivery period or a portion of the delivery period) |
| **Limitations (TBD)** | • Maximum of M baskets per unit in a single auction.<br>• Maximum of N child orders in a single basket.<br>• Maximum of L substitutable child orders in a single basket.<br>• Maximum of K baskets per unit per EFA day. |

**Note:** The participant does not indicate which baskets are mutually exclusive. The EAC platform determines this from the service type and delivery periods of each basket.

# Specification of a Parent Order

| Data Field | Comment |
|---|---|
| **Order ID** | |
| **Order Type** | **Parent** |
| **Basket ID** | Orders belong to only one basket |
| **Volume** | A volume for each product. May be 0 for some or all products. |
| **Price** | A single price in £/MW/h |

**Notes:**

A. Parent orders have a MAR of 1. They must be completely accepted or rejected.

B. The unit, delivery period, and service type of the order depends on the basket to which it belongs.

C. The products included in each parent order depend on the service on which its basket is defined.

D. A parent order can be defined on multiple products.

E. A basket must have exactly 1 parent order (which may have 0 volume for all products).

**Parent Order for Frequency Response**

| Order ID | Order Type | Basket ID | DCL | DCH | DML | DMH | DRL | DRH | Price |
|---|---|---|---|---|---|---|---|---|---|
| P1 | Parent | B1 | 18 | 16 | 0 | 0 | 4 | 4 | 12.25 |

**Parent Order for Quick Reserve**

| Order ID | Order Type | Basket ID | PQR | NQR | Price |
|---|---|---|---|---|---|
| P2 | Parent | B2 | 0 | 30 | 8.30 |

**Parent Order for Slow Reserve**

| Order ID | Order Type | Basket ID | PSR | NSR | Price |
|---|---|---|---|---|---|
| P3 | Parent | B3 | 80 | 150 | 19.35 |

# Specification of a Child Order

| Data Field | Comment |
|---|---|
| **Order ID** | |
| **Order Type** | **Child** |
| **Basket ID** | Orders belong to only one basket |
| **Volume** | A volume for a single product. Exactly one product must have a non-zero volume. Other products must have 0 volumes. |
| **Price** | A single price in £/MW/h |

**Notes:**

A. Child orders have a MAR of 0. They are fully curtailable.
   a) A child order is linked to a parent, which is the parent order in the same basket (and which may have 0 volume).
   b) All child orders in a basket must be defined on the same parent order

B. The unit, delivery period, and service type of the order depends on the basket to which it belongs

C. The products included in each child order depend on the service on which the basket of its parent is defined.

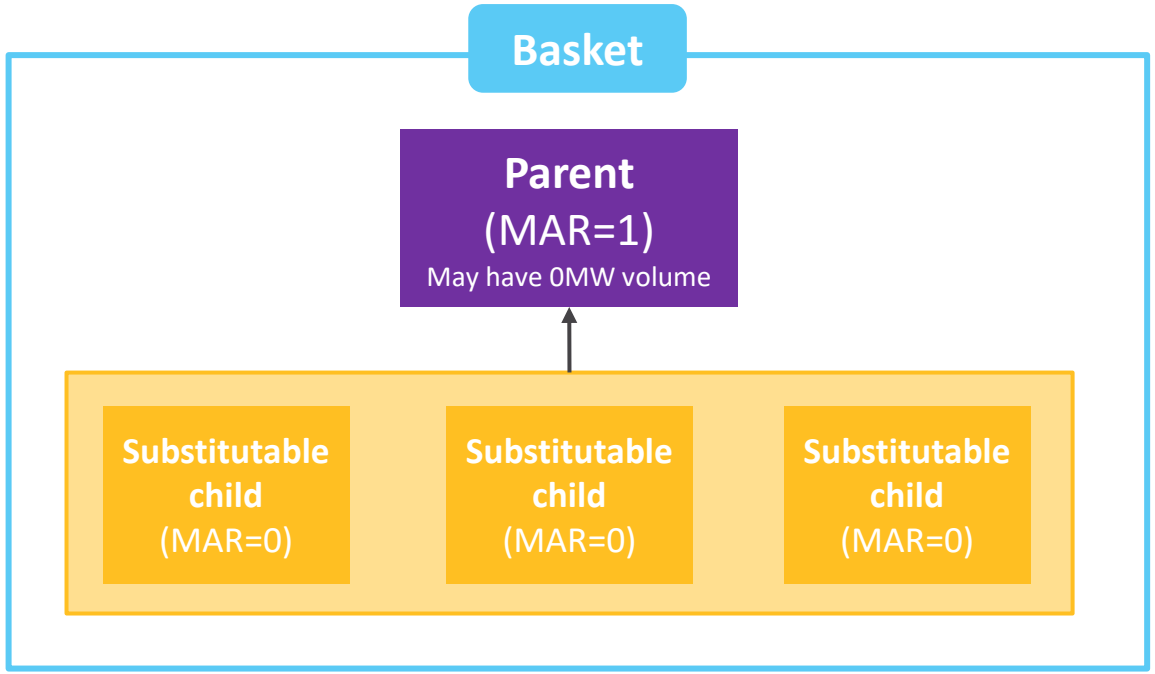
D. A child can only be defined on 1 product.

E. More than 1 child order is allowed in a single basket.

**Example of a basket with child orders for response**

| Order ID | Order Type | Basket ID | DCL | DCH | DML | DMH | DRL | DRH | Price |
|---|---|---|---|---|---|---|---|---|---|
| P1 | Parent | B1 | 10 | | | | | | 0.01 |
| C1 | Child | B1 | 5 | | | | | | 5 |
| C2 | Child | B1 | | | | 4 | | | 7 |

# Substitution Family – the implementation of (continuous) splitting/stacking




**A basket must be fully deliverable (full acceptance of the parent and all child orders plus 100% acceptance of the substitution family must be feasible for the unit). This is the responsibility of the participant.**

**Substitution family**

**Examples:**

My technology is capable of delivering DCL, DML, and DRL simultaneously. I wish to split (in a very flexible way). Here are my capacity for each service:

At most 20MW of DCL
At most 16MW of DML
At most 10MW of DRL

In a single basket B, I can offer three substitutable child orders. These three orders form a single substitution family:

**Order A:** 20 MW DCL, £2
**Order B:** 16 MW DML, £5
**Order C:** 10 MW DRL, £20

→ The sum of the acceptance ratios of a substitution family must be less than or equal to 1. I.e.,

$$x_A + x_B + x_C \leq 1$$

where $x_{order\ i}$ is the acceptance ratio of order $i$.

→ Potential clearing results:

1) 20MW DCL, $(x_A, x_B, x_C) = (1,0,0)$
2) 10MW DCL, $(x_A, x_B, x_C) = (0.5,0,0)$
3) 10MW DCL + 5MW DRL, $(x_A, x_B, x_C) = (0.5,0,0.5)$
4) 5MW DCL + 4MW DML + 5MW DRL , $(x_A, x_B, x_C) = (0.25,0.25,0.5)$

# Specification of a Substitutable Child Order

| Data Field | Comment |
|---|---|
| **Order ID** | |
| **Order Type** | **Substitutable child** |
| **Basket ID** | Orders belong to only one basket |
| **Volume** | A volume for each product. May be 0 for some (but not all) products. |
| **Price** | A single price in £/MW/h |

**Notes:**

A. Substitutable orders have a MAR of 0. They are fully-curtailable.
   a. A substitutable order is linked to a parent, which is the parent order in the same basket (and which may have 0 volume).
   b. All substitutable orders in a basket must be defined on the same parent order
   c. All substitutable orders in a basket form a single substitution family
   d. The sum of the acceptance ratios of a substitution family must be less than or equal to 1.

B. The unit, delivery period, and service type of a substitutable order depend on the basket to which its parent belongs

C. The products included in each substitutable order depend on the service on which the basket of its parent is defined.

D. A substitutable order can be defined on multiple products.

E. More than 1 substitutable order is allowed in a single basket.

**Example of a basket with a substitution family**

| Order ID | Order Type | Basket ID | DCL | DCH | DML | DMH | DRL | DRH | Price |
|---|---|---|---|---|---|---|---|---|---|
| P1 | Parent | B1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S1 | Substitutable Child | B1 | 0 | 0 | 0 | 0 | 5 | 5 | 12.25 |
| S2 | Substitutable Child | B1 | 0 | 0 | 0 | 0 | 0 | 10 | 4.65 |
| S3 | Substitutable Child | B1 | 16 | 0 | 0 | 0 | 0 | 0 | 9.75 |

# Mutually Exclusive Baskets

**A basket is mutually exclusive with all other concurrent baskets (i.e., defined on the same delivery period or a portion of the delivery period). The participant does not indicate which baskets are mutually exclusive. The EAC platform determines this from the service type and delivery periods of each basket.**

## Scenario 1

| | | |
|---|---|---|
| EFA 1<br>B1 | EFA 1<br>B2 | EFA 1<br>B3 |

- B1, B2, and B3 are mutually exclusive to each other.

## Scenario 2

| | | |
|---|---|---|
| EFA 5<br>B4 | EFA 5a<br>B5 | EFA 5a<br>B6 |
| | | |
| EFA 6<br>B7 | EFA 6a<br>B8 | EFA 6a<br>B9 |
| | | |

- B4, B5, and B6 are mutually exclusive to each other.
- B7, B8, and B9 are mutually exclusive to each other.

→ You can have B4+B8, etc.

## Scenario 3

| | | |
|---|---|---|
| EFA 5<br>B10 | EFA 5a<br>B11 | EFA 5a<br>B12 |
| | EFA 5b<br>B13 | EFA 5b<br>B14 |
| | EFA 6a<br>B15 | EFA 6a<br>B16 |
| | EFA 6b<br>B17 | EFA 6b<br>B18 |

- B10, B11, and B12 are mutually exclusive to each other.
- B10, B13, and B14 are mutually exclusive to each other.
- B15 and B16 are mutually exclusive to each other.
- B17 and B18 are mutually exclusive to each other.

→ You can have B11+B14, B12+B13, B10+B15+B17, etc.

## Scenario 4

| | | | |
|---|---|---|---|
| EFA 1<br>B19 | EFA 1<br>B20 | EFA 1a<br>B21 | EFA 12<br>B23 |
| | | EFA 1b<br>B22 | |
| | | EFA 2a<br>B24 | |
| | | EFA 2b<br>B25 | |

- B19, B20, B21, and B23 are mutually exclusive to each other.
- B19, B20, B22, and B23 are mutually exclusive to each other.
- B24 and B23 are mutually exclusive to each other.
- B25 and B23 are mutually exclusive to each other.

→ You can have B21+B22, B24+B25, B19+B24, etc.

# Appendix 2. Market Clearing Rules

# Market Clearing Rules

| Parent orders | Child orders | Substitutable child orders |
|---|---|---|
| ○ Parent orders must be fully accepted (or rejected).<br>○ Paradoxical rejection is allowed.<br>○ Paradoxical acceptance is not allowed. | ○ A child order may be partially accepted for any integer amount.<br>○ A child order may be accepted only if its parent is accepted.<br>○ A child order may be accepted only if it has non-negative surplus.<br>○ Paradoxical rejection is allowed.<br>○ Paradoxical acceptance is not allowed. | ○ A substitutable child order may be partially accepted for any integer amount.<br>○ A substitutable child order may be accepted only if its parent is accepted.<br>○ A substitutable child order may be accepted only if it has non-negative surplus.<br>○ The sum of the acceptance ratios (accepted volume divided by offered volume) of the orders in a substitutable order family must be less than or equal to 1.<br>○ Paradoxical rejection is allowed.<br>○ Paradoxical acceptance is not allowed. |

**Looped family**

Define a set of baskets looped together as a “looped family”.

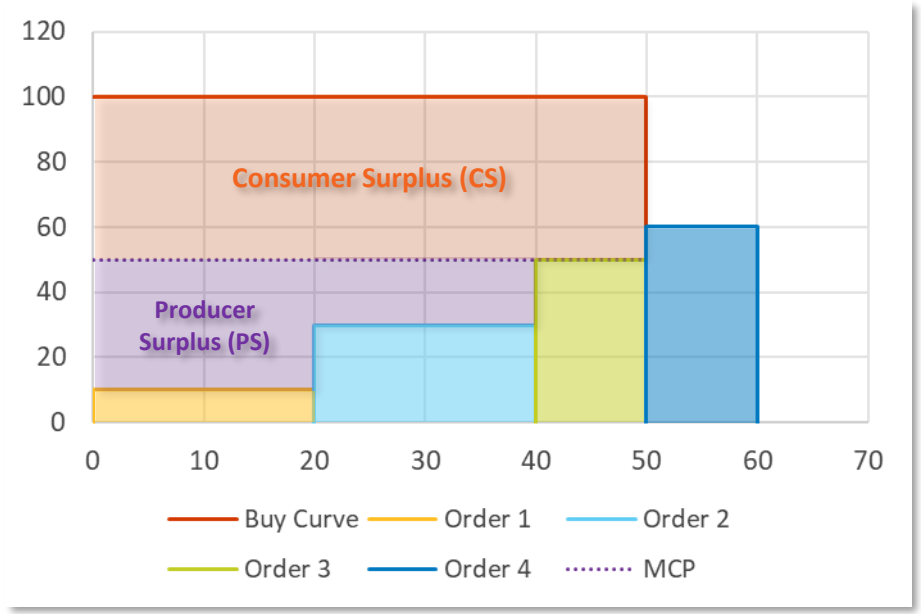
- The parent order must be accepted from each basket in a looped family.
- A parent order may be accepted only if the total welfare of all accepted orders (parents, child, and substitutable child) in its looped family is non-negative.
- A parent order may not be accepted from a basket if a parent order is accepted from another basket which is mutually-exclusive with the first basket.

# To find a feasible solution…

$$\boldsymbol{Total\ Market\ Welfare}$$
$$= \boldsymbol{Consumer\ Suprlus + Producer\ Surplus}$$
$$= (\boldsymbol{ESO\ Buy\ Order\ Price\ - Sell\ Order\ Price}) \times \boldsymbol{Executed\ Volume}$$

$$Consumer\ Surplus$$
$$= ESO's\ Willing\ to\ Pay - Total\ Auction\ Procurement\ Cost$$
$$= (ESO\ Buy\ Order\ Price\ -\ Market\ Clearing\ Price) \times Executed\ Volume$$

$$Producer\ Surplus$$
$$= Supplier\ Revenue - Cost$$
$$= (Market\ Clearing\ Price\ - Sell\ Order\ Price) \times Executed\ Volume$$




**The solution should:**

- ✓ **find the <u>bid selection</u> that maximises total market welfare (subject to pricing constraints)**
- ✓ **find the <u>clearing prices</u> such that:**
  - ≥ sellers willingness to receive
  - ≤ the buyer's willingness to pay
  - minimise total cost

# Market Clearing Examples

# Paradoxical Acceptance

**All sell orders cannot be paradoxically accepted.** I.e., the market clearing price must be greater than or equal to the price of any accepted order.

**Example 1**

**Buy order (elastic):**

**Order A:** 30MW, £100/MW/h

**Order B:** 20MW, £50/MW/h

**Order C:** 10MW, £10/MW/h

**Order D:** 5MW, £2/MW/h

**Sell order:**

**Order 1:** Unit X, 20MW, £50/MW/h, parent

# Paradoxical Rejection

**All sell orders may be paradoxically rejected.** I.e., an order may be rejected even if its price is less than the market clearing price.

**Example 2**

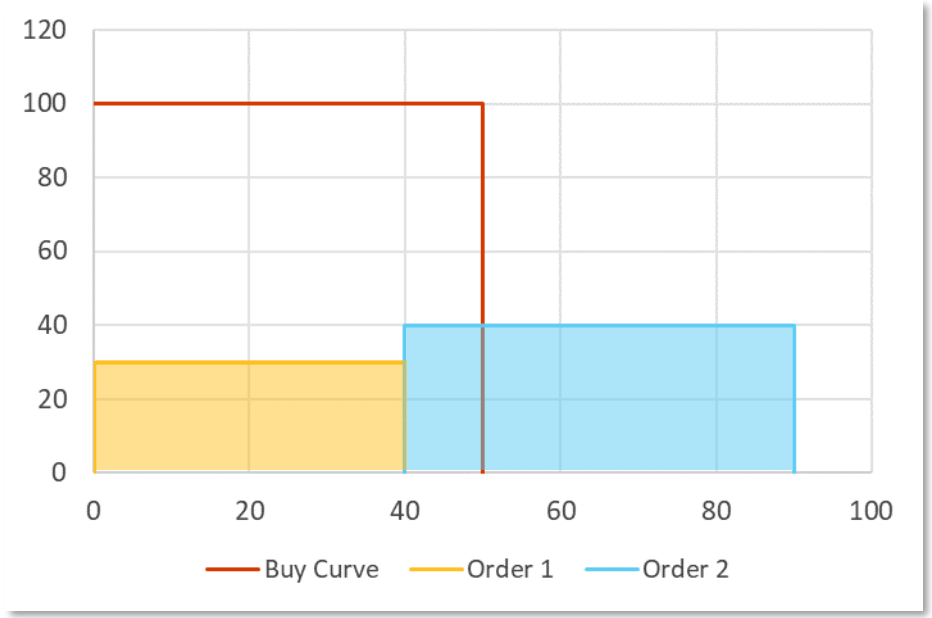
**Buy order:**

**Order A:** 50MW, £100/MW/h

**Sell order:**

**Order 1:** Unit X, 40MW, £30/MW/h, parent

**Order 2:** Unit Y, 50MW, £40/MW/h, parent



# Welfare Sharing between Parent and Child

**There is no welfare sharing across orders that have no parent-child links or loop links.**

**Example 3.1**

**Buy order:**

**Order A:** 50MW, £100/MW/h

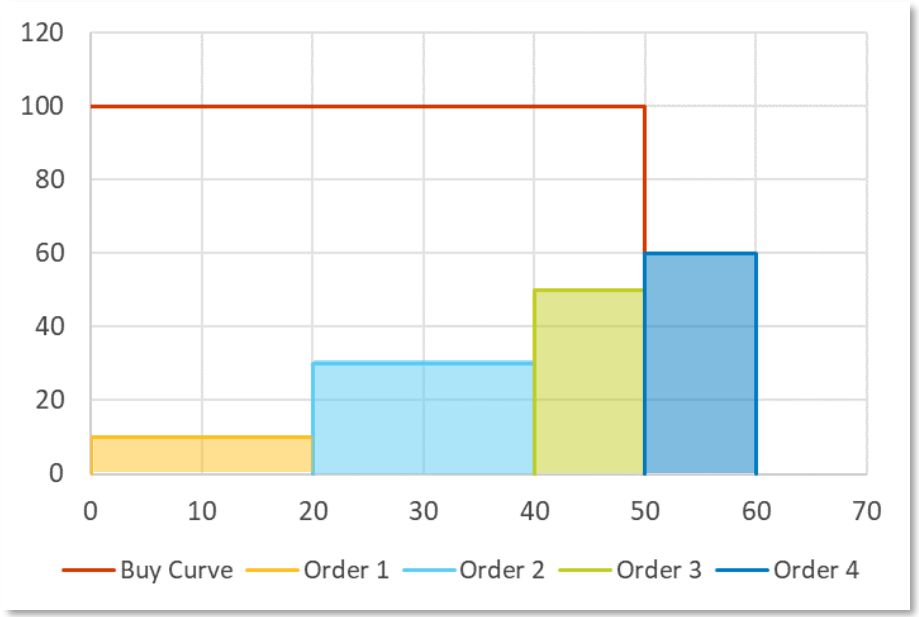
**Sell order:**

**Order 1:** Unit X, 20MW, £10/MW/h, parent

**Order 2:** Unit Y, 20MW, £30/MW/h, parent

**Order 3:** Unit Z, 10MW, £50/MW/h, parent

**Order 4:** Unit W, 10MW, £60/MW/h, parent



# Welfare Sharing between Parent and Child

**Child (and substitutable child) can contribute welfare to its parent. Parent cannot contribute welfare to any of its child.**

**Example 3.2**

**Buy order:**

**Order A:** 50MW, £100/MW/h

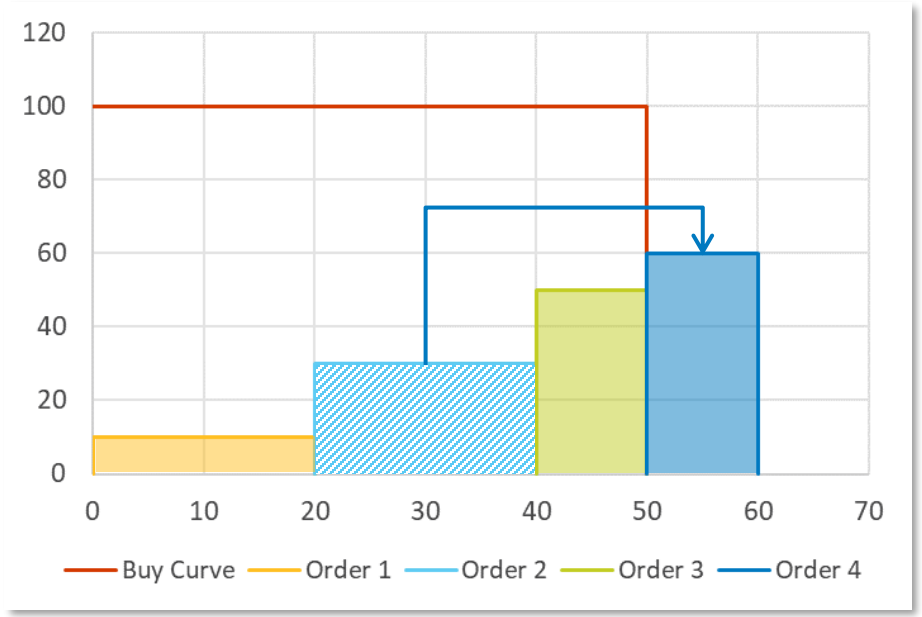
**Sell order:**

**Order 1:** Unit X, 20MW, £10/MW/h, parent

**Order 2:** Unit Y, 20MW, £30/MW/h, child of Order 4

**Order 3:** Unit Z, 10MW, £50/MW/h, parent

**Order 4:** Unit Y, 10MW, £60/MW/h, parent



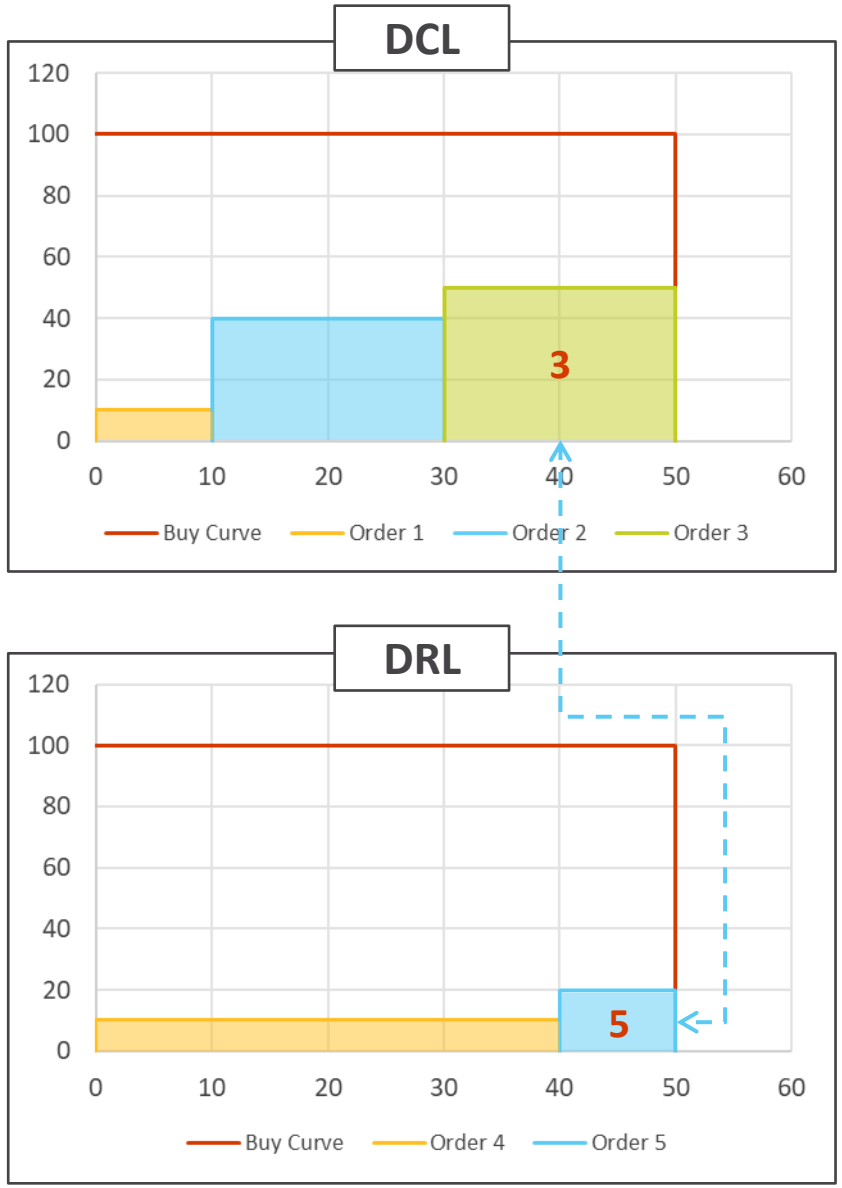
# Co-optimisation (without splitting)

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.1**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 10MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 20MW, £40/MW/h, parent<br>**Order 3:** Unit Z, 20MW, £50/MW/h, parent | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 4:** Unit V, 40MW, £10/MW/h, parent<br>**Order 5:** Unit Z, 10MW, £20/MW/h, parent |

Order 3 in DCL and Order 5 in DRL are two mutually exclusive parent orders and at most one can be (partially or fully) accepted.



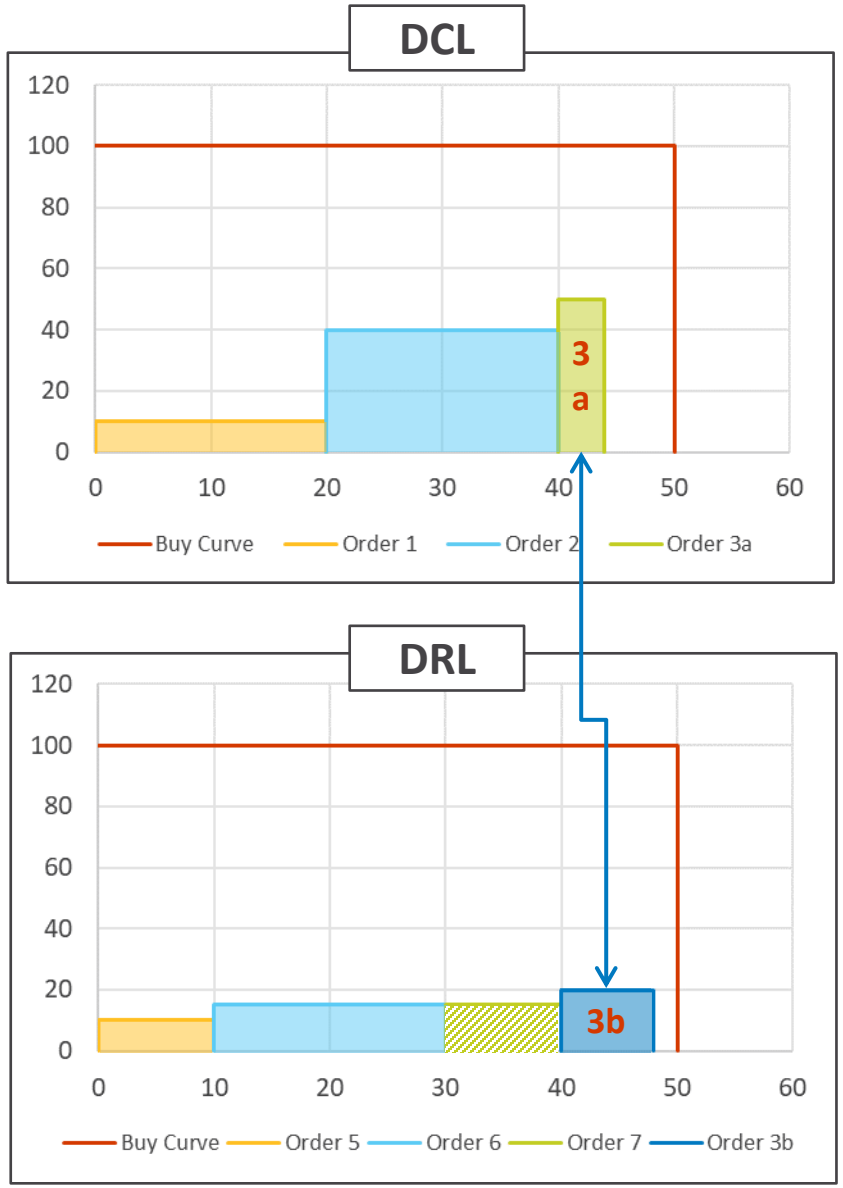
# Co-optimisation

**Bids will be allocated to the market(s) that generates the highest welfare.**

### Example 4.2 (without welfare-sharing)

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 20MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 20MW, £40/MW/h, parent<br>**Order 3a:** Unit Z, 4MW, £50/MW/h, parent | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 3b:** Unit Z, 8MW, £20/MW/h, parent |

In Order 3, Unit Z wants to offer 4MW DCL and 8MW DRL as a bundle. The entire order can only be either fully accepted or fully rejected. Partial acceptance of Order 3 (e.g., accepting Order 3a alone) is not allowed.



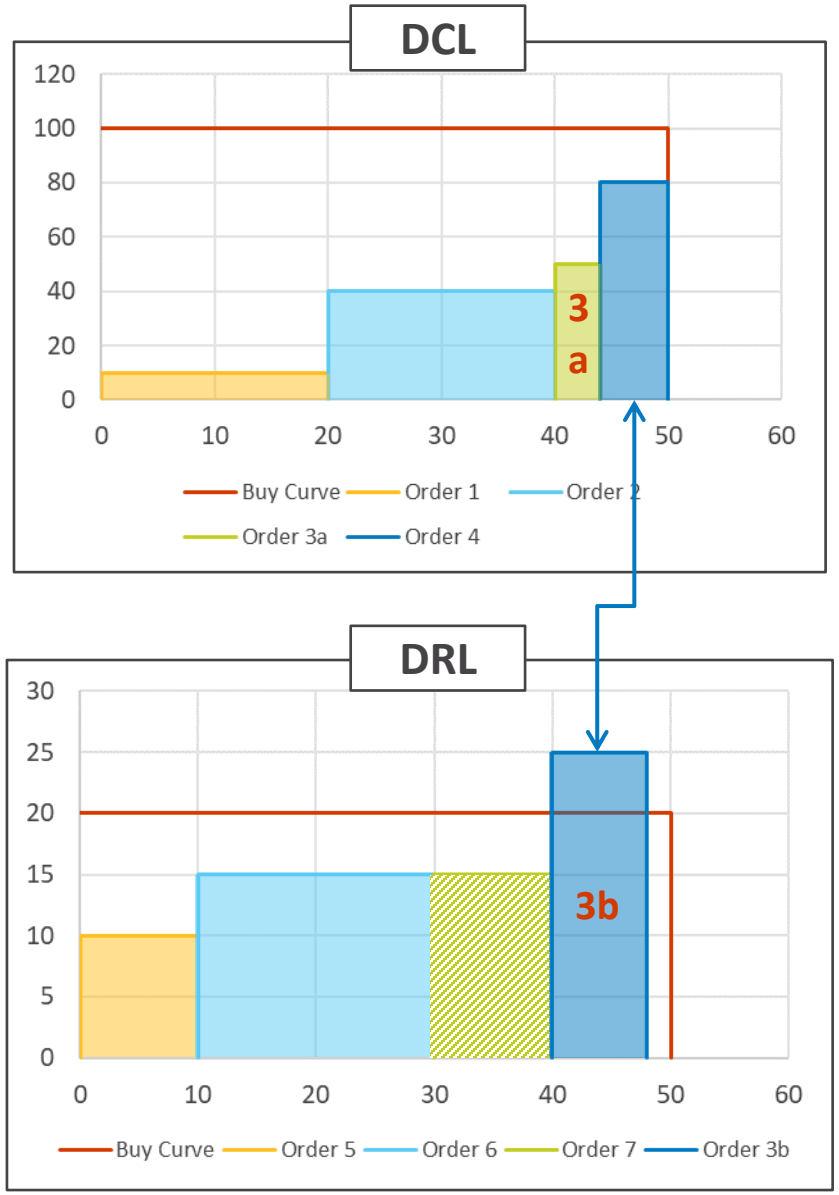
# Co-optimisation

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.3 (with welfare-sharing)**

| DCL | DRL |
|---|---|
| **Buy order:** | **Buy order:** |
| **Order A:** 50MW, £100/MW/h | **Order B:** 50MW, £20/MW/h |
| **Sell order:** | **Sell order:** |
| **Order 1:** Unit X, 20MW, £10/MW/h, parent | **Order 5:** Unit V, 10MW, £10/MW/h, parent |
| **Order 2:** Unit Y, 20MW, £40/MW/h, parent | **Order 6:** Unit W, 20MW, £15/MW/h, parent |
| **Order 3a:** Unit Z, 4MW, £50/MW/h, parent | **Order 7:** Unit W, 10MW, £15/MW/h, child of 6 |
| **Order 4:** Unit T, 6MW, £80/MW/h, parent | **Order 3b:** Unit Z, 8MW, £25/MW/h, parent |

In Order 3, Unit Z wants to offer 4MW DCL and 8MW DRL as a bundle. The entire order can only be either fully accepted or fully rejected. Partial acceptance of Order 3 (e.g., accept Order 3a alone) is not allowed.



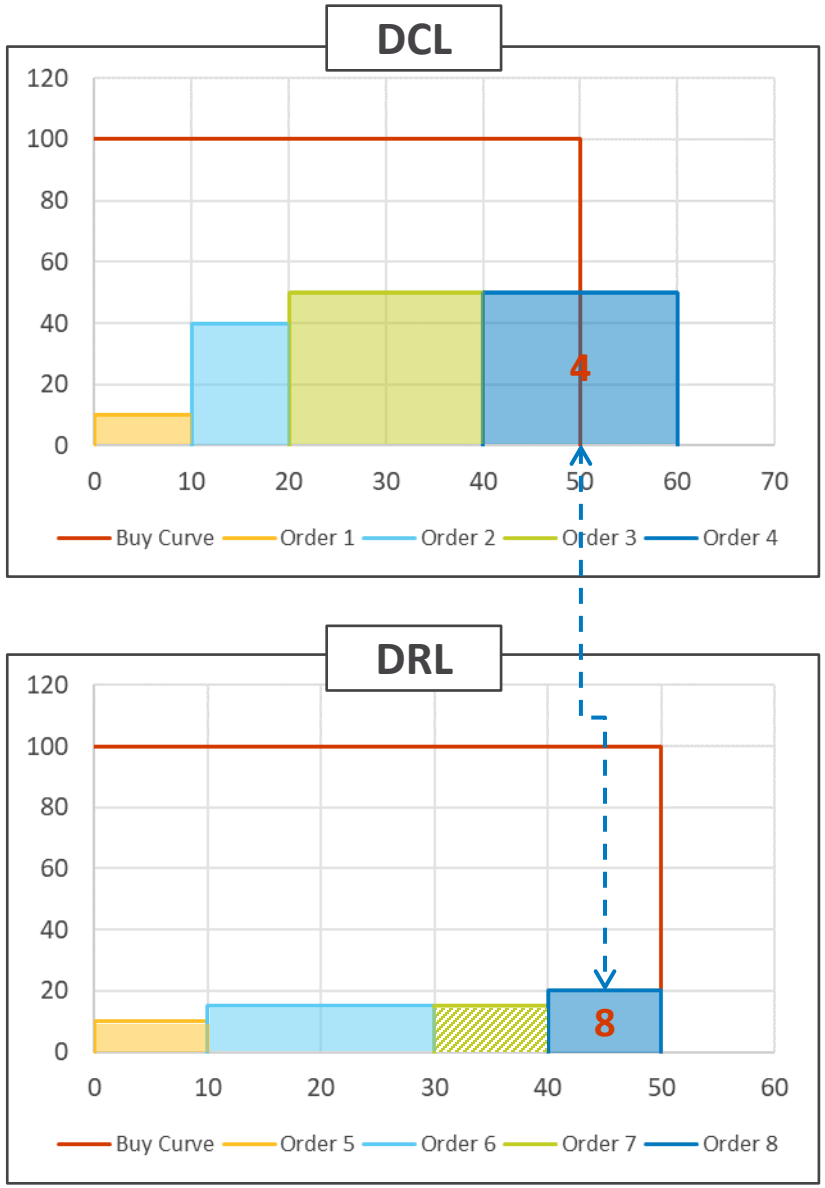
# Co-optimisation (with continuous splitting)

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.4**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 10MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 10MW, £40/MW/h, parent<br>**Order 3:** Unit Z, 20MW, £50/MW/h, parent<br>**Order 4:** Unit Z, 20MW, £50/MW/h, substitutable child of Order 3 | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 8:** Unit Z, 10MW, £20/MW/h, substitutable child of Order 3 |

Order 4 in DCL and Order 8 in DRL are two substitutable child orders, both linked to the single parent Order 3 in DCL.



# Solutions to Market Clearing Examples

# Paradoxical Acceptance

**All sell orders cannot be paradoxically accepted.** I.e., the market clearing price must be greater than or equal to the price of any accepted order.

**Example 1**

**Buy order (elastic):**

**Order A:** 30MW, £100/MW/h

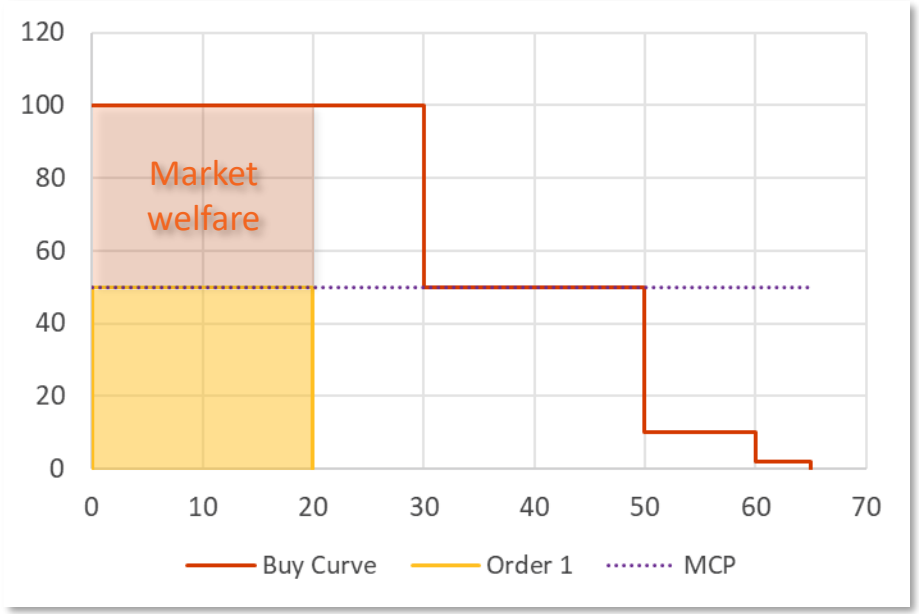
**Order B:** 20MW, £50/MW/h

**Order C:** 10MW, £10/MW/h

**Order D:** 5MW, £2/MW/h

**Sell order:**

**Order 1:** Unit X, 20MW, £50/MW/h, parent




**Clearing Outcome**

- Accepting Order 1 has a positive welfare of:

$$20MW \times (£100 - £50) = 1000$$

→ **The bid selection that maximises the total market welfare** is to fully accept Order 1.

→ **The clearing price…**

- → must not be less than £50/MW/h, otherwise Order 1 is paradoxically accepted (i.e. accepted below its willing to receive)
- → must not be greater than £100/MW/h as it needs to be below the buy curve
- → the clearing price is £50/MW/h

# Paradoxical Rejection

**All sell orders may be paradoxically rejected.** I.e., an order may be rejected even if its price is less than the market clearing price.

**Example 2**

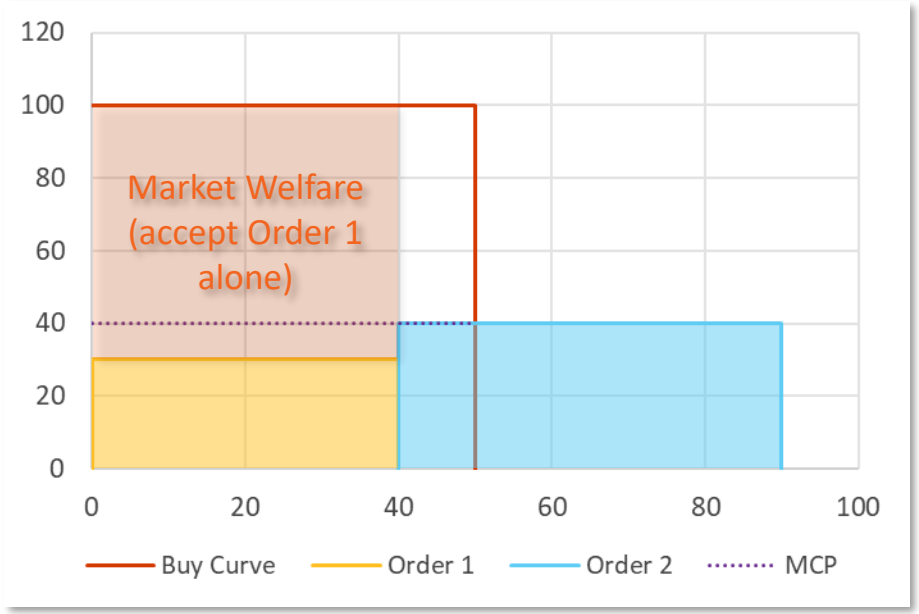
**Buy order:**

**Order A:** 50MW, £100/MW/h

**Sell order:**

**Order 1:** Unit X, 40MW, £30/MW/h, parent

**Order 2:** Unit Y, 50MW, £40/MW/h, parent




**Clearing Outcome**

- Accepting Order 1 alone has a positive welfare of:
  $$40MW \times (£100 - £30) = 2800$$
- Accepting Order 2 alone has a positive welfare of:
  $$50MW \times (£100 - £40) = 3000$$
- The welfare of accepting nothing is 0.
- Order 1 and 2 cannot be accepted simultaneously due to the volume constraint.

→ **The bid selection that maximises the total market welfare** is to fully reject Order 1 and fully accept Order 2.

→ **The clearing price** is £40/MW/h. Order 1 is paradoxically rejected because its price is lower than the clearing price.

# Paradoxical Rejection

**All sell orders may be paradoxically rejected.** I.e., an order may be rejected even if its price is less than the market clearing price.

**Example 2**

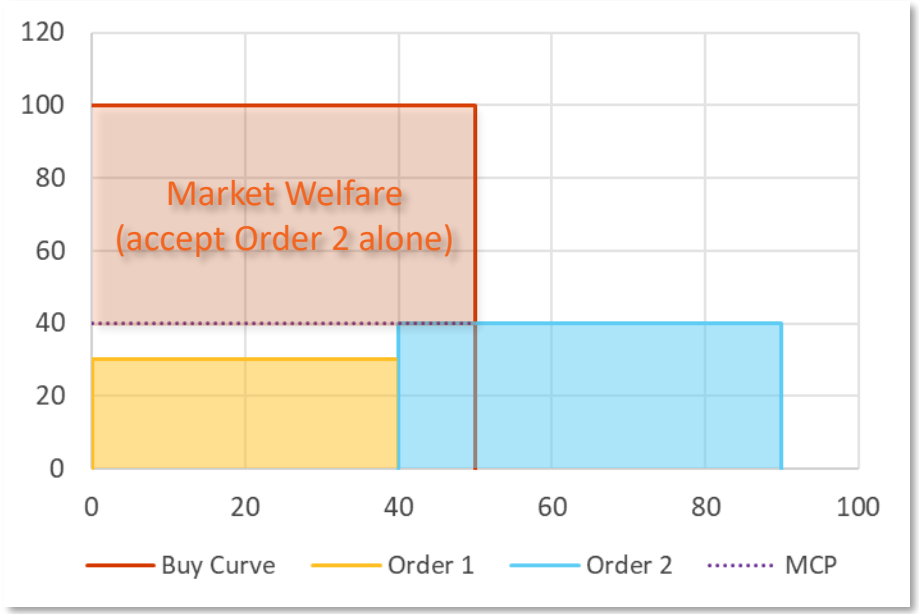
**Buy order:**

**Order A:** 50MW, £100/MW/h

**Sell order:**

**Order 1:** Unit X, 40MW, £30/MW/h, parent

**Order 2:** Unit Y, 50MW, £40/MW/h, parent




**Clearing Outcome**

- Accepting Order 1 alone has a positive welfare of:
  $$40MW \times (£100 - £30) = 2800$$
- Accepting Order 2 alone has a positive welfare of:
  $$50MW \times (£100 - £40) = 3000$$
- The welfare of accepting nothing is 0.
- Order 1 and 2 cannot be accepted simultaneously due to the volume constraint.

→ **The bid selection that maximises the total market welfare** is to fully reject Order 1 and fully accept Order 2.

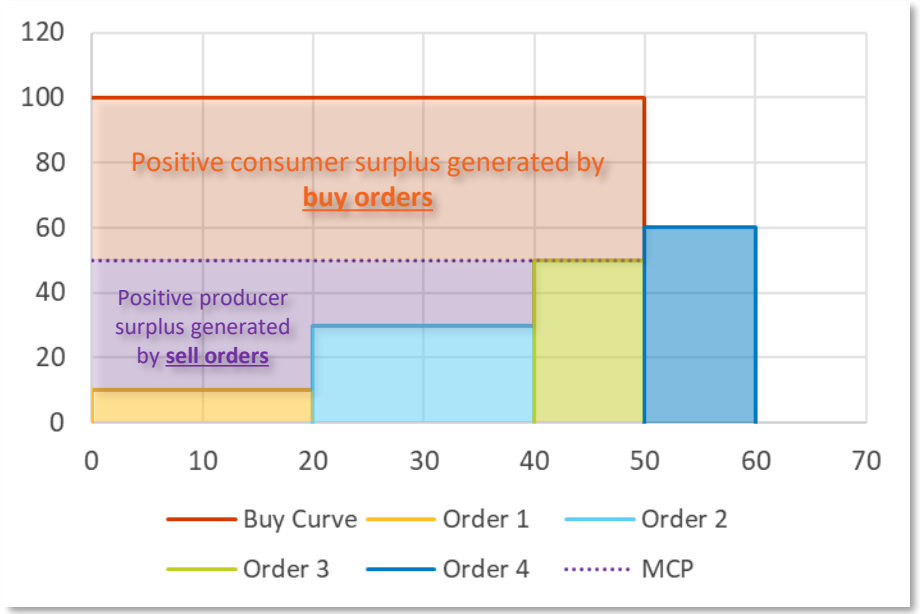
→ **The clearing price** is £40/MW/h. Order 1 is paradoxically rejected because its price is lower than the clearing price.

# Welfare Sharing between Parent and Child

**There is no welfare sharing across orders that have no parent-child links or loop links.**

**Example 3.1**

**Buy order:**
**Order A:** 50MW, £100/MW/h
**Sell order:**
**Order 1:** Unit X, 20MW, £10/MW/h, parent
**Order 2:** Unit Y, 20MW, £30/MW/h, parent
**Order 3:** Unit Z, 10MW, £50/MW/h, parent
**Order 4:** Unit W, 10MW, £60/MW/h, parent




**Clearing Outcome**

- Accepting any order generates positive welfare as all order prices are below the buy curve.

→ **The bid selection that maximises the total market welfare** is to fully accept Order 1, 2, and 3, and fully reject Order 4. Order 4 is rejected due to the volume constraint.

→ **The clearing price** is £50/MW/h. No order is paradoxically rejected.

# Welfare Sharing between Parent and Child

**Child (and substitutable child) can contribute welfare to its parent. Parent cannot contribute welfare to any of its child.**

**Example 3.2**

**Buy order:**

**Order A:** 50MW, £100/MW/h

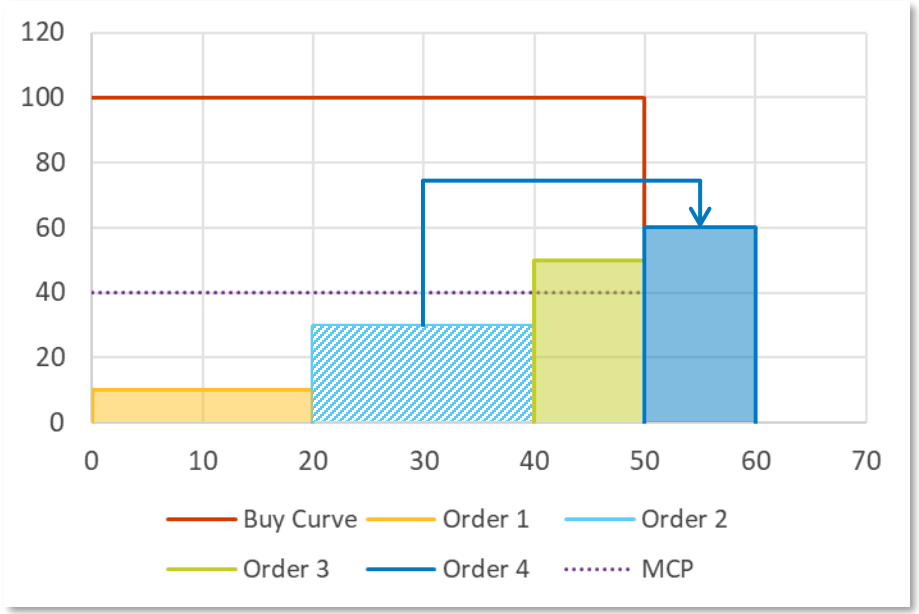
**Sell order:**

**Order 1:** Unit X, 20MW, £10/MW/h, parent

**Order 2:** Unit Y, 20MW, £30/MW/h, child of Order 4

**Order 3:** Unit Z, 10MW, £50/MW/h, parent

**Order 4:** Unit Y, 10MW, £60/MW/h, parent




**Clearing Outcome**

- Accept Order 1&3&4, and 50% of Order 2 has a positive welfare of:
  $20MW \times £90 + 10MW \times £50 + 10MW \times £40 + 10MW \times £70 = 3400$
- Accept Order 1&2&4, and reject Order 3 has a positive welfare of:
  $20MW \times £90 + 10MW \times £40 + 20MW \times £70 = 3600$

→ **The bid selection that maximises the total market welfare** is to fully accept Order 1, 2, and 4, and fully reject Order 3.

→ **The clearing price** has to be..

- → at least £10 so Order 1 is not paradoxically accepted
- → at least $\frac{20MW \times £30 + 10MW \times £60}{20MW + 10MW} = £40$ so the linked parent-child order pair is not paradoxically accepted
- → at most £100 so it is below the buy curve
- → the clearing price is £40/MW/h. No order is paradoxically rejected.

# Co-optimisation (without splitting)

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.1**

| DCL | DRL |
|---|---|
| **Buy order:** | **Buy order:** |
| **Order A:** 50MW, £100/MW/h | **Order B:** 50MW, £100/MW/h |
| **Sell order:** | **Sell order:** |
| **Order 1:** Unit X, 10MW, £10/MW/h, parent | **Order 4:** Unit V, 40MW, £10/MW/h, parent |
| **Order 2:** Unit Y, 20MW, £40/MW/h, parent | **Order 5:** Unit Z, 10MW, £20/MW/h, parent |
| **Order 3:** Unit Z, 20MW, £50/MW/h, parent | |

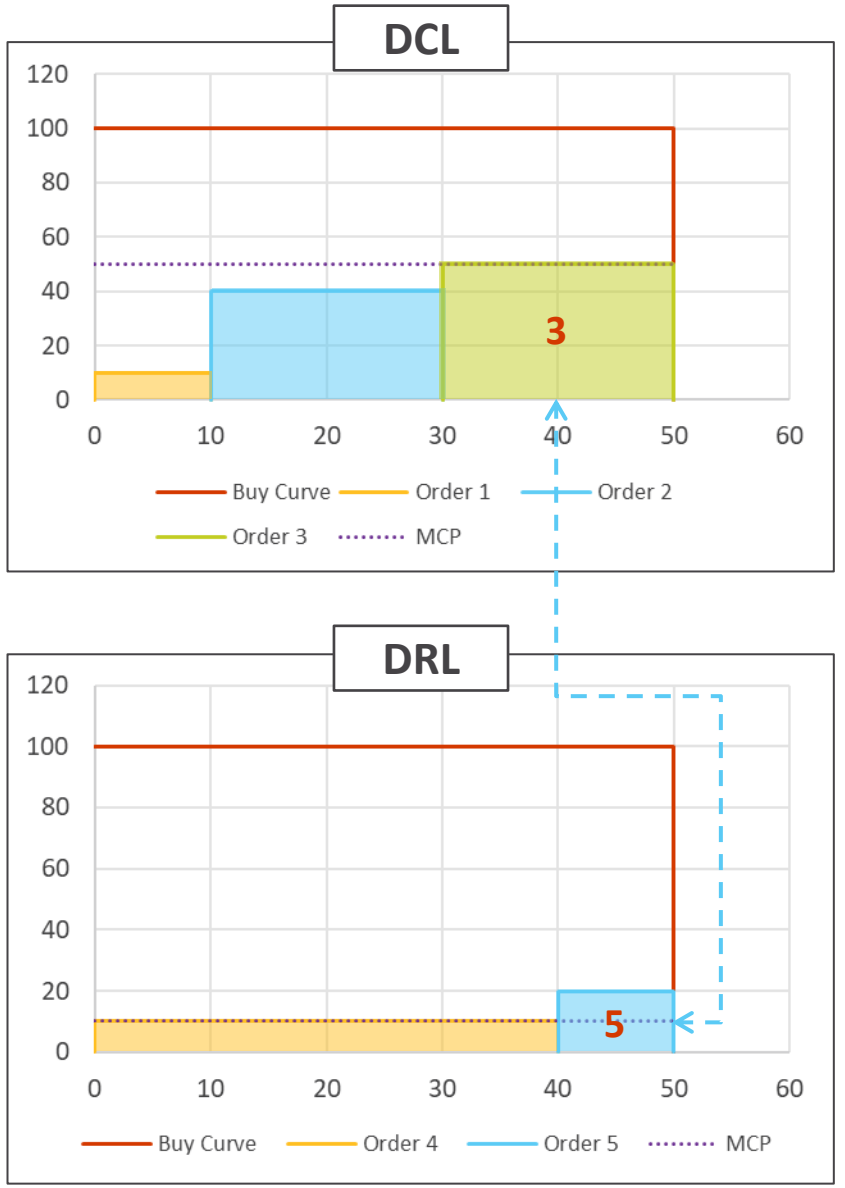
Order 3 in DCL and Order 5 in DRL are two mutually exclusive parent orders and at most one can be (partially or fully) accepted.

## Clearing outcome

- Allocating Unit Z to DCL market generates a welfare of:
$$20MW \times (£100 - £50) = 1000$$
- Allocating Unit Z to DRL market generates a welfare of:
$$10MW \times (£100 - £20) = 800$$

→ **The bid selection that maximises the total market welfare** is to allocate Unit Z to the DCL market and fully accept all other orders.

→ **The clearing prices** are £50/MW/h for DCL and £10/MW/h for DRL.



# Co-optimisation

**Bids will be allocated to the market(s) that generates the highest welfare.**

### Example 4.2 (without welfare-sharing)

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 20MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 20MW, £40/MW/h, parent<br>**Order 3a:** Unit Z, 4MW, £50/MW/h, parent | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 3b:** Unit Z, 8MW, £20/MW/h, parent |

In Order 3, Unit Z wants to offer 4MW DCL and 8MW DRL as a bundle. The entire order can only be either fully accepted or fully rejected. Partial acceptance of Order 3 (e.g., accepting Order 3a alone) is not allowed.

**Clearing outcome**

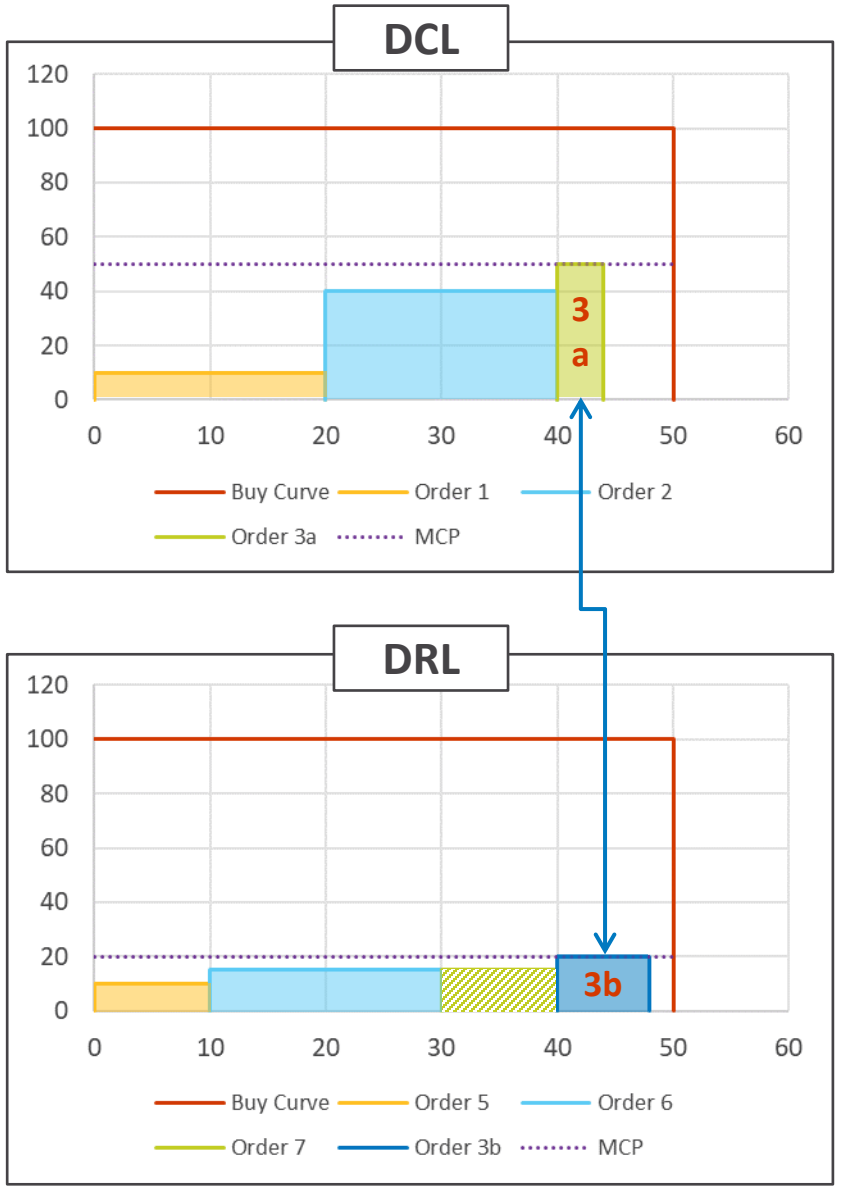
- Accepting Order 3a and 3b generates a positive welfare of:

$$4MW \times (£100 - £50) + 8MW \times (£100 - £20) = 840$$

→ **The bid selection that maximises the total market welfare** is to fully accept all orders.

→ **The clearing prices** are £50/MW/h for DCL and £20/MW/h for DRL.

→ Please note that if the volume offered in Order 3a is greater than 10MW, the entire Order 3 will be fully rejected due to the volume constraint.



# Co-optimisation

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.3 (with welfare-sharing)**

| DCL | DRL |
|---|---|
| **Buy order:** | **Buy order:** |
| **Order A:** 50MW, £100/MW/h | **Order B:** 50MW, £20/MW/h |
| **Sell order:** | **Sell order:** |
| **Order 1:** Unit X, 20MW, £10/MW/h, parent | **Order 5:** Unit V, 10MW, £10/MW/h, parent |
| **Order 2:** Unit Y, 20MW, £40/MW/h, parent | **Order 6:** Unit W, 20MW, £15/MW/h, parent |
| **Order 3a:** Unit Z, 4MW, £50/MW/h, parent | **Order 7:** Unit W, 10MW, £15/MW/h, child of 6 |
| **Order 4:** Unit T, 6MW, £80/MW/h, parent | **Order 3b:** Unit Z, 8MW, £25/MW/h, parent |

In Order 3, Unit Z wants to offer 4MW DCL and 8MW DRL as a bundle. The entire order can only be either fully accepted or fully rejected. Partial acceptance of Order 3 (e.g., accept Order 3a alone) is not allowed.

**Clearing outcome**

- Accepting Order 3a and 3b generates a positive welfare of:

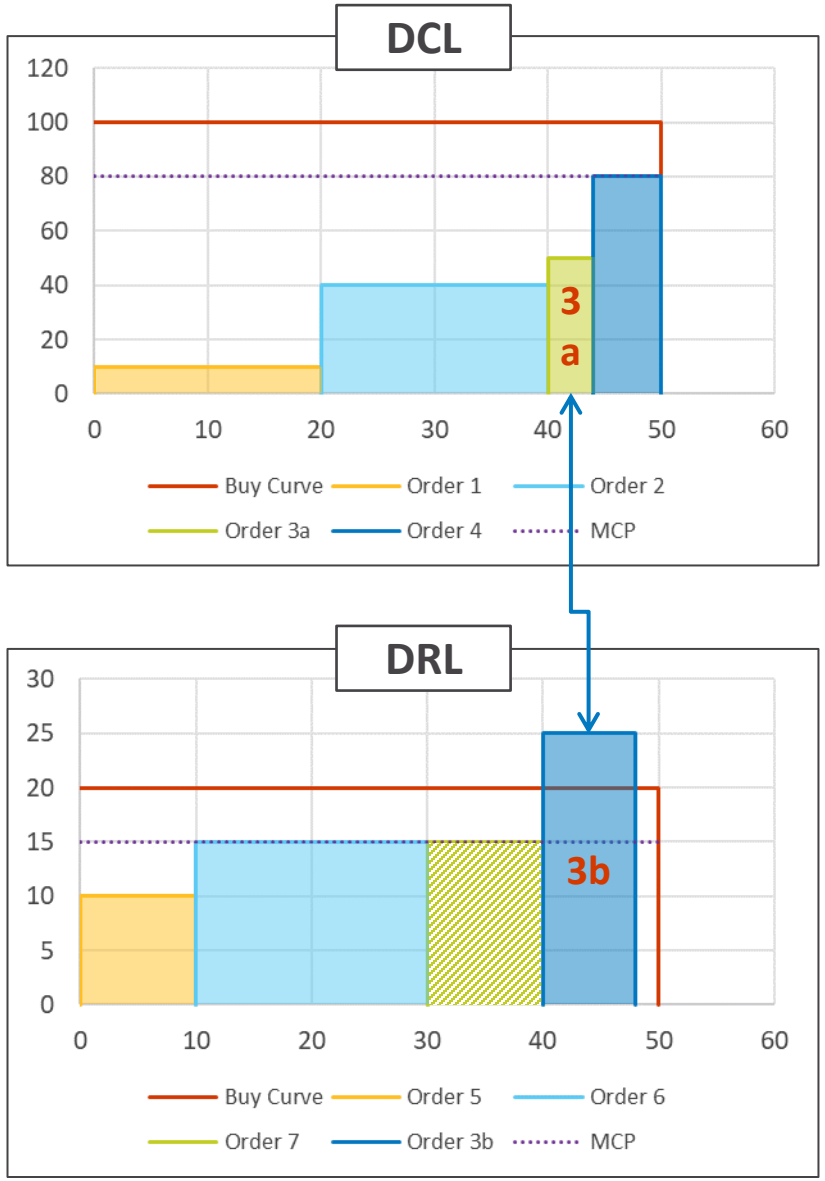
$$4MW \times (£100 - £50) + 8MW \times (£20 - £25) = 160$$

  - Order 3b can be accepted if the entire order has non-negative welfare.

→ **The bid selection that maximises the total market welfare** is to fully accept all orders.

→ **The clearing price** is £80/MW/h for DCL and for DRL the price must be…

- → no greater than £20/MW/h so it's no greater than the buyer's willingness to pay.
- → no less than £15/MW/h so Order 6 and 7 are not paradoxically accepted.
- → The price must be greater than or equal to $\frac{(4MW \times £50 + 8MW \times £25) - (4MW \times £80)}{8MW} = £10$
- → DRL clears at £15/MW/h.



# Co-optimisation (with continuous splitting)

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.4**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 10MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 10MW, £40/MW/h, parent<br>**Order 3:** Unit Z, 20MW, £50/MW/h, parent<br>**Order 4:** Unit Z, 20MW, £50/MW/h, substitutable child of Order 3 | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 8:** Unit Z, 10MW, £20/MW/h, substitutable child of Order 3 |

Order 4 in DCL and Order 8 in DRL are two substitutable child orders, both linked to the single parent Order 3 in DCL.

**Clearing outcome**

- Allocating 100% Order 4 to DCL market generates a welfare of:

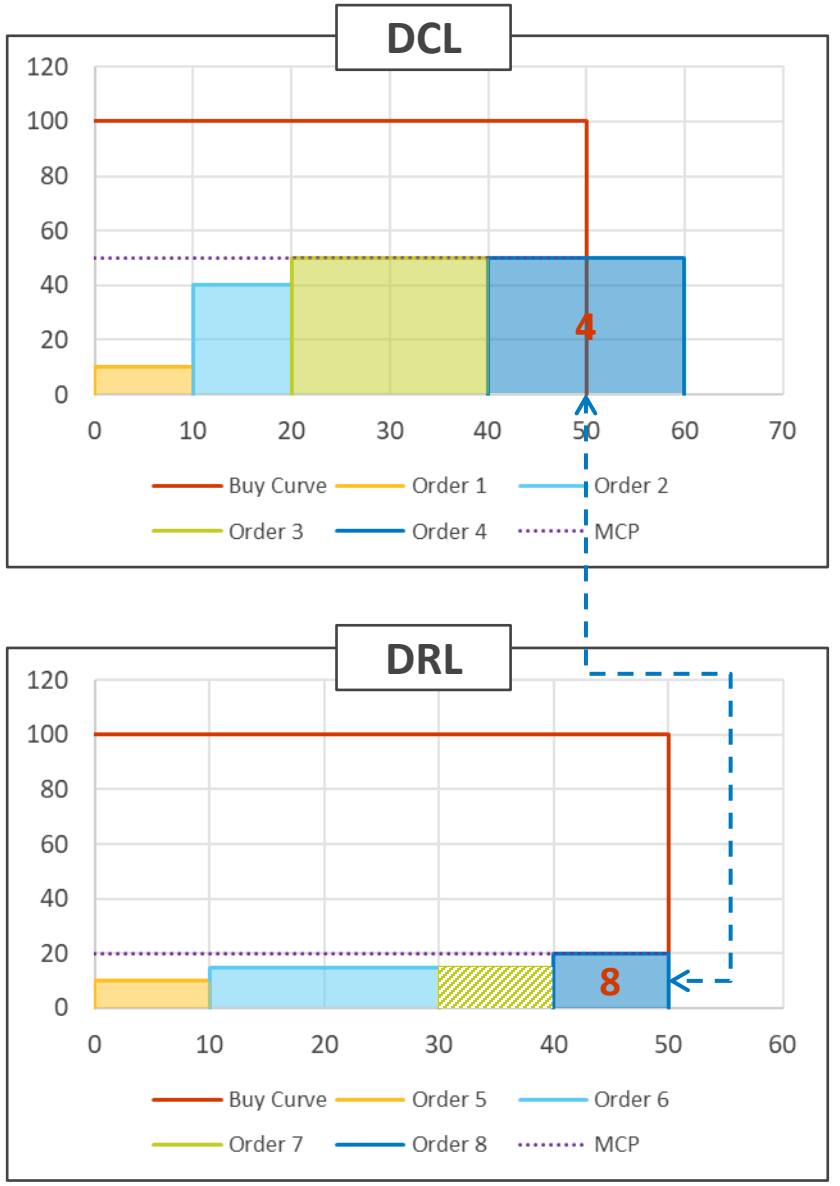
$$20MW \times (£100 - £50) = 1000$$

  - However, this solution is infeasible because at most 10MW (i.e., 50%) of Order 4 can be accepted in the DCL market (total requirement for DCL is 50MW).
  - Allocating 50% Order 4 to DCL market and 50% of Order 8 to the DRL market generates a welfare of:

$$10MW \times (£100 - £50) + 5MW \times (£100 - £20) = 900$$

- Allocating 100% Order 8 to DRL market generates a welfare of:

$$10MW \times (£100 - £20) = 800$$




**Note:** Increase the accepted volume of DRL market by 1MW, the market welfare of DRL increases by 80 but the market welfare of DCL reduces by 100.

# Co-optimisation (with continuous splitting)

**Bids will be allocated to the market(s) that generates the highest welfare.**

**Example 4.4**

| DCL | DRL |
|---|---|
| **Buy order:**<br>**Order A:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 1:** Unit X, 10MW, £10/MW/h, parent<br>**Order 2:** Unit Y, 10MW, £40/MW/h, parent<br>**Order 3:** Unit Z, 20MW, £50/MW/h, parent<br>**Order 4:** Unit Z, 20MW, £50/MW/h, substitutable child of Order 3 | **Buy order:**<br>**Order B:** 50MW, £100/MW/h<br>**Sell order:**<br>**Order 5:** Unit V, 10MW, £10/MW/h, parent<br>**Order 6:** Unit W, 20MW, £15/MW/h, parent<br>**Order 7:** Unit W, 10MW, £15/MW/h, child of 6<br>**Order 8:** Unit Z, 10MW, £20/MW/h, substitutable child of Order 3 |

Order 4 in DCL and Order 8 in DRL are two substitutable child orders, both linked to the single parent Order 3 in DCL.

**Clearing outcome**

- Allocating 100% Order 4 to DCL market generates a welfare of:

$$20MW \times (£100 - £50) = 1000$$

  - However, this solution is infeasible because at most 10MW (i.e., 50%) of Order 4 can be accepted in the DCL market (total requirement for DCL is 50MW).
  - Allocating 50% Order 4 to DCL market and 50% of Order 8 to the DRL market generates a welfare of:

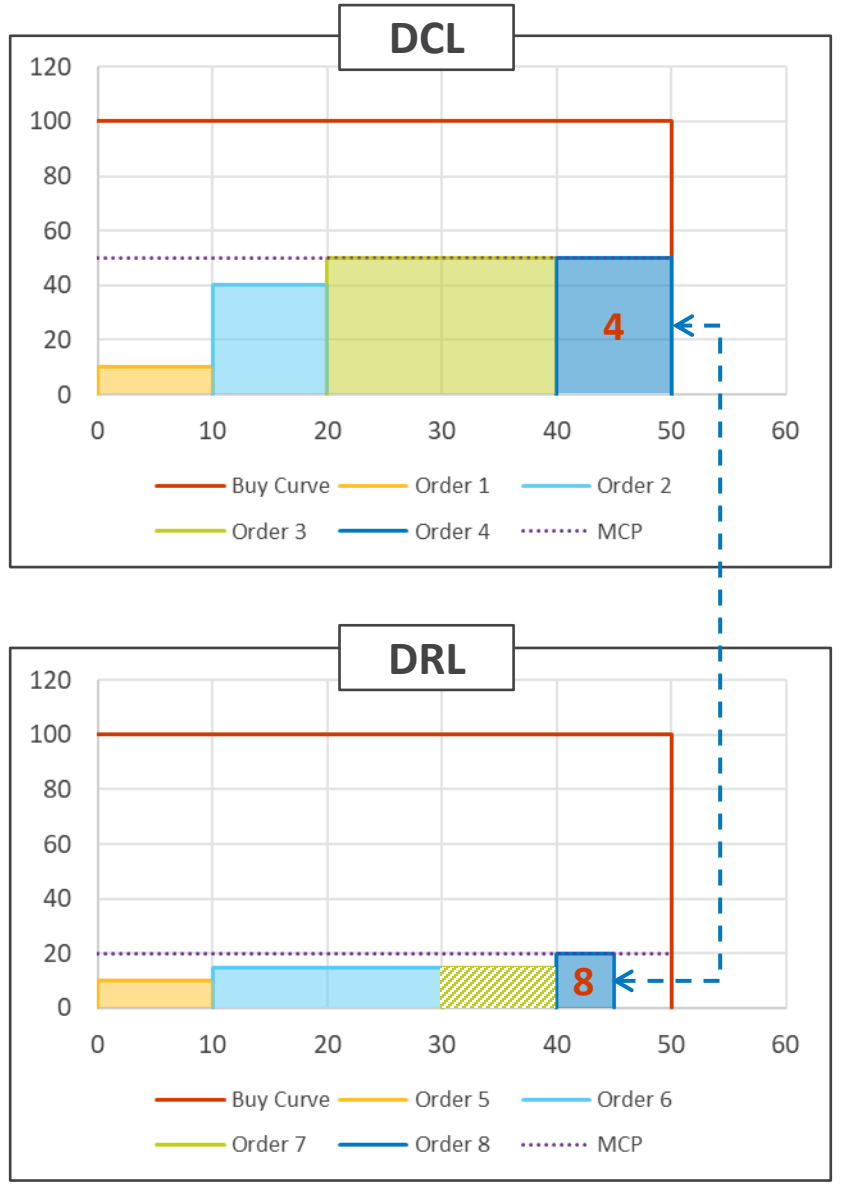
$$10MW \times (£100 - £50) + 5MW \times (£100 - £20) = 900$$

- Allocating 100% Order 8 to DRL market generates a welfare of:

$$10MW \times (£100 - £20) = 800$$

→ **The bid selection that maximises the total market welfare** is to accept 50% of Order 4, 50% of Order 8, and fully accept all other orders.

→ **Clearing prices** are £50/MW/h for DCL and £20/MW/h for DRL.




**Note:** Increase the accepted volume of DRL market by 1MW, the market welfare of DRL increases by 80 but the market welfare of DCL reduces by 100.