L. CROSS-BORDER EXCHANGES

Belgium's central location in Europe means that the country's import and export capabilities are defined following the principles of flow-based capacity calculation and capacity allocation within market coupling, as introduced by the European guideline on Capacity Allocation & Congestion Management (CACM), hereafter referred to as the 'FB CACM' [ENT-6]. In the FB CACM, Belgium's net position is linked to the net position of the other countries in the same capacity calcultation region **region and to the flow-based domain which defines the possibilities for energy exchanges between those countries.** The flow-based methodology makes it possible to properly model interactions between cross-border market exchanges and the transmission grid. **It is only by replicating the functioning of the electricity market that adequacy and economic indicators can be accurately calculated.**

Since the introduction of the flow-based methodology in 2015 for CWE region and in 2022 for Core region, NTC method is no longer used to model cross-border exchanges for the day-ahead market and has been replaced by the fow-based method. Following the ACER decision on the amended CCR determination [ENT-13], Ireland has been added to the Core region and the new Central Europe CCR (CE CCR) integrating the Core and Italy North regions has been established. The application of the flow-based day-ahead capacity calculation and market coupling will thus be extended to Ireland and Italy North in the coming years. The public consultation of the DA CCM for CE CCR which has to be submitted to CE NRAs in January 2025 mentions a preliminary implementation timeline for June 2027. This study takes CE CCR as reference to model the flow-based perimeter. In the market simulations performed for Adequacy and Flexibility studies, the commercial exchanges capacities can be modeled in three different ways, as outlined hereafter:

- **For exchanges** between two **biding zones outside the CE** CCR **region,** fixed bilateral exchange capacities (also called NTC – **Net Transfer Capacities - as described in Section 1) are applied.**
- **For exchanges between the C**E CCR **region and bidding zones outside the** CE CCR **region, a** flow-based modelling (also known as 'Advanced Hybrid Coupling'- AHC) is applied from 2025 onwards. More information can be found in Section 2;
- **For exchanges** taking place **inside the C**E CCR **region**, the flow-based methodology (described in Section 3) is applied.

The Central Europe CCR is illustrated in Figure L-1.

L.1. NTC MODELLING: NON-CE BIDDING ZONES

The capacities for cross-border exchanges between non-CE BZ is modelled using Net Transfer Capacties (NTC) corresponding to fixed maximal possible commercial exchange capacities between two bidding zones.

FIGURE L-1 — CENTRAL EUROPE CCR **REGION WHERE FLOW-BASED MODELLING IS APPLIED**

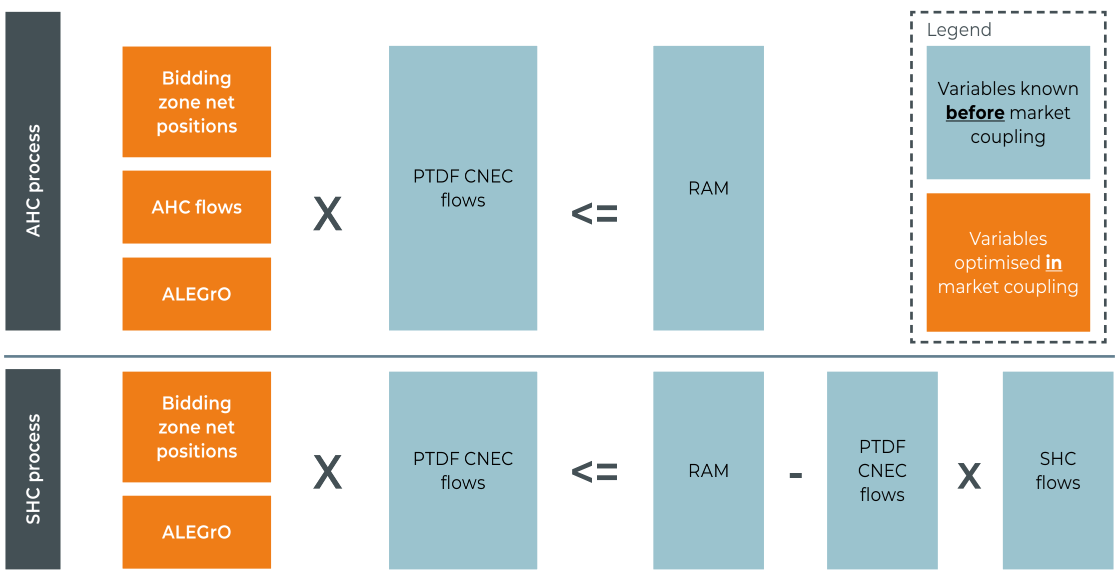
L.2. TREATMENT OF EXTERNAL FLOWS: EXCHANGES BETWEEN CE AND NON-CE BIDDING ZONES

External flows are flows in the CE grid which are induced by exchanges across bidding zone borders that do not belong to the CE region. As an example, the Nemo Link straddles such a border. External flows can be linked to the flow-based region in one of two ways:

- through **Standard Hybrid Coupling** (SHC) where the best forecast of the external flows (referred as 'SHC flows' in Figure L-2 below) is considered during the capacity calculation for the determination of the capacity margin on all Critical Network Element and Contingencies (CNECs);
- **Advanced Hybrid Coupling** (AHC) where no forecast assumption on the external flow needs to be taken during capacity calculation. The external flow is part of the flow-based optimisation variables and thus compete for the allocation of capacity on equal footing with exchanges across the bidding zone borders belonging to the CE region.

As a result, the flow-based domain calculation and allocation becomes more complex in AHC, as any external border considered adds an extra dimension to the flow-based domains. AHC introduces a major conceptual and methodological change; under SHC, the impact of the external exchanges as an external flow through each CNEC is reserved from the capacity margin of the CNEC (hence the Remaining Available Margin or RAM of the CNEC is reduced to account for this external flow). However, under AHC, those external flows are considered explicitly as a degree of freedom of the flow-based domain. The difference is illustrated in the Figure L-2, which highlights the impact of the AHC modelling.

FIGURE L-2 — HANDLING OF EXTERNAL FLOWS: AHC VS SHC



Note that SHC flows are considered commercial flows, and therefore are a part of the 70% minRAM that has to be offered to the market. In other words, the minRAM rule has to be applied on CNECs before the RAM is later further reduced to account for SHC flows, i.e. minRAM is applied in SHC on the RAM + the SHC flows component.

The implementation of AHC on borders to bidding zones outside the Core region, insofar bidding zones which are part of the SDAC (so not to the United-Kingdom nor Switzerland), excluding common borders with Italy North CCR and with SWE CCR (France-Spain border), is a formal requirement with an implementation deadline set to 30th of June 2025, subject to readiness of SDAC. With the creation of the CCR Central Europe, the Italy North borders are integrated in the flow-based perimeter and thus internal borders. The public consultation version of the CE DA CCM notifies the extension of the application of AHC also to the France-Spain border.

The reference assumption taken for the next AdeqFlex'25 study is the application of AHC on all borders to bidding zones directly connected to CE region, including borders with the United Kingdom and Switzerland. It is to be noted that this represents a perfect market model set-up, whereby United Kingdom and Switzerland are part of the single European implicit price coupling. This is a more efficient set-up compared to the existing arrangements in place. More information regarding the implications of different allocation mechanism for price coupling with the United Kingdom can be consulted in [ELI-28].

A final point to tackle are the allocation constraints. Allocations constraints are additionnal constraints in the market coupling not related to thermal limit but to other system constraints (such as steady state or dynamic voltage limits).

An overview of all allocation constraint applied by European TSOs for the single day-ahead market coupling can be consulted on AdeqFlex'23. This overview dates from 2023. In November 2023, Elia discontinued the use of the Belgian allocation constraint.

For the modelled CE flow-based perimeter, the legal framework is as follows:

- As per Core DA CCM [ACE-12], Poland is allowed to use an allocation constraint on the maximum import and export of net position in SDAC until June 2026. A new request for approval is to be submitted to the Core NRAs in case Poland wants to extend the application of its allocation constraint beyond June 2026.
- As per the public consultation version of the CE DA CCM, the Polish and Italian TSOs request the application of allocation constraints.

It remains to be seen for how long the application of these allocation constraints will be accepted by the regulatory authorities of the Core / CE regions. The reference assumption taken for Adeqflex'25 study is a perfect market model assumption that does not consider the application of allocation constraints.

L.3. FLOW-BASED METHODOLOGY

This section aims to explain in a non-exhaustive way the flow-based methodology in order for the reader to understand the key notions as well as the methodology used by Elia to create the flow-based domains used in the Adequacy and Flexibility study.

Information about the flow-based rules and methodologies are available by consulting the Capacity Calculation Regions webpage of ENTSO-E [CCR-2].

Information about the flow-based rules and methodologies are available by consulting the Capacity Calculation Regions webpage of ENTSO-E [CCR-2].

L.3.1. FLOW-BASED OPERATIONAL PROCESS

The flow-based method implemented on the day-ahead market coupling uses Power Transfer Distribution Factors (PTDFs) that make the modelling of real flows through the physical network lines possible.

For each hour of the year, the impact of energy exchanges on each Critical Network Element (also called critical 'branch' in the past) taking into account the N-1 criterion is calculated (see later in this section the explanation on the N-1 criterion). The combination of Critical Network Elements and Contingencies (CNECs) forms the basis of the flow-based calculation.

A reliability margin on each CNEC is considered and, where appropriate, 'remedial actions' are also taken into account. These actions can be taken preventively, or after an outage has occurred, to partly relieve the loading of the concerned critical network element. Those actions make it possible to maximise exchanges thanks to changes in the topology of the grid or by the use of phase shifting transformers.

This procedure finally leads to constraints which form a domain of safe possible energy exchanges between the 'flow-based' countries within the relevant Capacity Calculation Region (CCR) under consideration (this is called the flow-based domain).

Different assumptions are made for the calculation of this domain, such as the expected renewable generation, consumption, energy exchanges outside the CCR area, location of generation, outage of units and lines, etc.

For every hour there might be a different flow-based domain because:

- the topology of the grid can change;
- outages or maintenance of grid elements can be present;

The operational calculation of the flow-based domain for a given day is started two days before real-time operation and is used to define the limits of energy exchange between countries for the day-ahead market.

The N-1 security criterion for the grid

Interconnection capacity takes into account the margins that transmission system operators (TSOs) must maintain in order to follow the European rules ensuring the security of supply. A line or grid element can be lost at any time. The remaining lines must be able to cope with the changes in electricity flow due to any such outage. In technical terms, this is called the N-1 rule: for a given number N of lines that are transmitting a given amount of energy, there cannot be an overloaded line in case of the outage of one of the lines. This is important to avoid that a chain reaction arises and, by extension, the network stability of the entire European network can be endangered. The flow-based domain calculation process therefore accounts for the N-1 principle.

Note however, that European rules stipulate that this criterion must be fulfilled at each moment, including in the event of maintenance or repair works. In such cases, it is possible that interconnection capacity available for exchanges will have to be reduced. Wherever possible, maintenance and repair works are avoided during the most critical periods, e.g. around the peak consumption times of the year, but cannot be ruled out, especially after winter weather conditions.

L.3.2. FLOW-BASED ADAPTATION IN THE SIMULATION

Bidding zones act as 'copper plates' from a market perspective. Within a bidding zone the market price is the same for all market participants (the 'copper plate assumption' entails unlimited transmission capacities within the zone). A higher resolution is required in order to simulate the internal flows and consequently assess the loop flows. A finer grid resolution is provided by 'small zones', subsets of the bidding zones which also serve as copper plates. An initial simulation involving these small zones is required in order to take account of the loop flows caused by internal exchanges (between small zones).

Finally, due to the extra complexity arising from the large number of constraints induced by the modelling of flow-based in this adequacy study, the complexity of the problem must be reduced to a level that is computationally feasible. This whole process will be detailed further in the sections below.

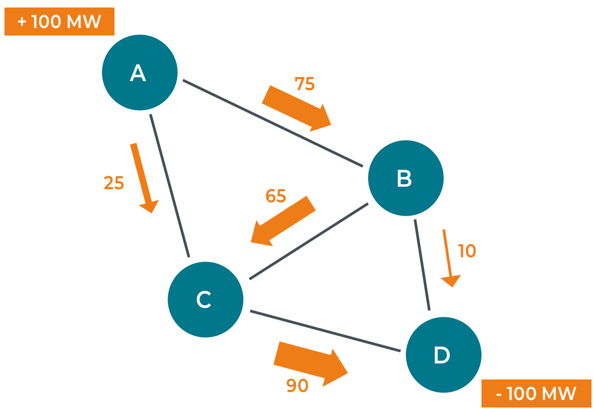
L.3.3. CALCULATION OF PTDF

The first step is the calculation of the so-called "Power Transfer Distribution Factors" (PTDF) within a given flow-based geographical area (network parameters and topology are defined).

The PTDF factors estimate (the change of) the flow that can be expected in the different Critical Network Elements as a function of a position change of a bidding zone and/or of a controllable device (HVDC, PST..).

Let's assume the simplified grid example below in Figure L-3:

FIGURE L-3 — REPRESENTATION OF A NODAL SYSTEM AND DISTRIBUTION FLOWS



For example, if an exchange from Node A to Node D of 100 MW occurs, the PTDF factors could be:

- 75% of the injection in Node A goes to Node B and 25% of the injection in Node A goes to Node C;
- 65% of the injection from Node A goes from Node B to Node C and 10% of the injection from Node A goes from Node B to Node D;
- Finally the portion of the total injection in Node A passing through Node C is 25% + 65% = 90%, going to Node D.

The PTDFs thus indicate how the energy flows are (unevenly) distributed over the different paths between the different nodes of the network when the X MW injection/extraction occurs at two points of the network. The distribution given by the PTDFs is determined both by the topology of the grid and the technical characteristics (impedances) of the grid.

It should be noted that PTDF's are calculated for the flows over the grid elements in N state as well as when grid contingencies occur (N – 1 state).

The PTDFs are represented as a matrix which is computed based on a reference grid model for the targeted time horizon. A PTDF matrix consists of lines/rows representing the different CNEC's that are taken into account, and columns representing the variables in the flow-based domain. Each CNEC refers to the combination of a Critical Network Element and a Contingency. The variables can represent the net positions of the market nodes under consideration, the HVDC flows, PST positions, etc.. depending on the degrees of freedom of the market coupling algorithm, e.g. whether Standard Hybrid Coupling (SHC) or Advanced Hybrid Coupling (AHC) is considered. Aside from a PTDF matrix, the flow-based framework also requires the capacity of each Critical Network Element. These capacities correspond to the steady-state seasonal ratings of the network elements.

L.3.4. CALCULATION OF ZONAL PTDF FROM NODAL PTDF: APPLYING GSK

Bidding zones are zones where all generation and consumption within a given zone have the same wholesale price, hence one 'zonal' PTDF should be defined for the entire zone. Therefore, a mapping is needed between the market 'zonal' level and the grid 'nodal' level, in order to define those 'zonal' PTDFs. In the example below an illustration between the nodal and zonal representation is provided.

A 'zonal PTDF' is needed in order to calculate the effect that a commercial exchange between two market zones, will have on any grid element. The calculation of 'zonal PTDFs' from 'nodal PTDFs' is based on the so-called 'generation shift keys' (GSKs). With this GSK, the nodal PTDF can be converted into a 'zonal PTDF' by assuming that the bidding zone net position is spread among its nodes according to the GSK. Therefore a 'zonal PTDF' is the sum of all 'nodal PTDFs' weighted by their nodal GSK. Below an illustration (Figure L-4) of this relation between 'zonal PTDFs', 'nodal PTDFs' and GSKs is provided.

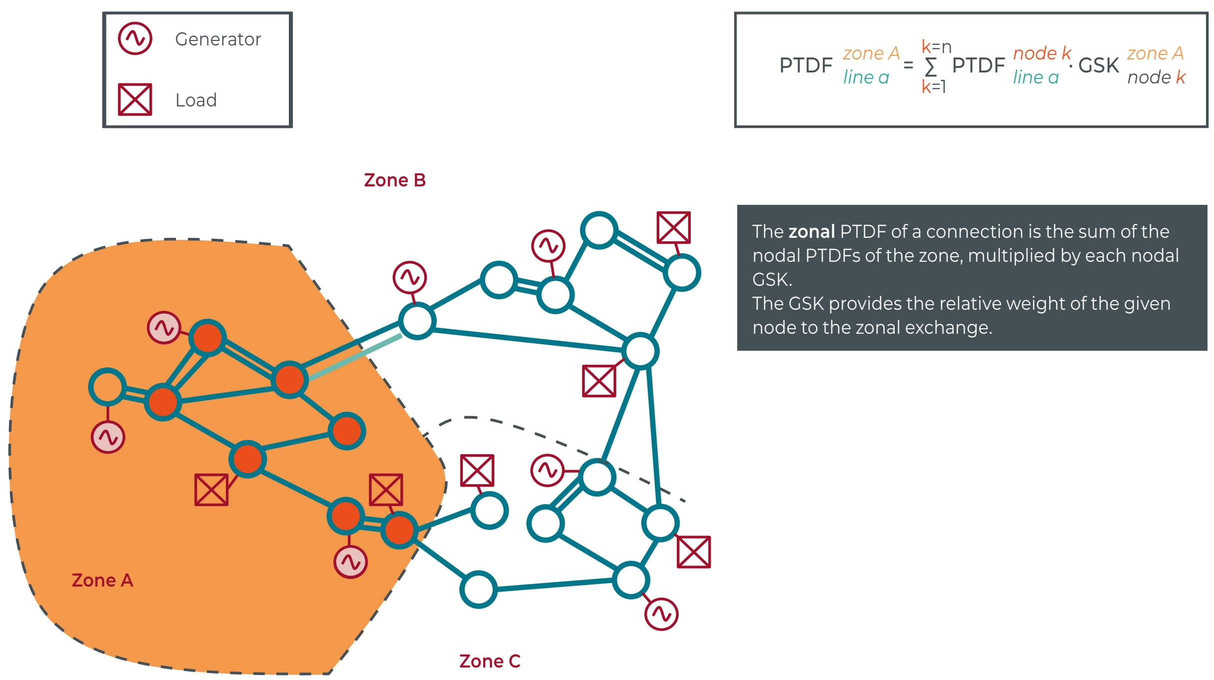
Within each zone, the GSK can be defined as:

$$GSK_{Zone,Node} = \frac{P^{Nominal}_{Z,N}}{\sum_{N\epsilon Z} P^{Nominal}_{Z,N}}$$

where $\sum_{N\epsilon Z} P^{Nominal}_{Z,N} = NGC^{Z}$ is equal to the dispatchable installed net generating capacity (NGC) within the corresponding zone Z and $P^{Nominal}_{Z,N}$ is equal to the installed capacity connected to the node N within zone Z. Nuclear, DSR, transmission-connected storage and renewable capacities are therefore excluded from the GSK calculation in this study..

These 'pro-rata distribution keys' are an important assumption for the calculation of the zonal PTDFs since, they fix the geographical distribution of generation units per type T at each node N with respect the total installed capacity per type for the given network topology. GSKs therefore define the weight of each of the nodal PTDFs in the definition of zonal PTDFs.

FIGURE L-4 — CALCULATION OF ZONAL PTDFS APPLYING GSKS



L.3.5. CALCULATING THE INITIAL LOADING OF EACH CNEC

The notion of the initial loading of each CNEC is related to the so-called 'Reference Flow' (Fref) in the operational Flow-based framework. The 'Reference Flow' (Fref) is the physical flow computed from the common 2-Day Ahead Congestion Forecast (D2CF) base case and reflects the loading of the Critical Network Elements given the exchange programs of the chosen reference day, thus given the 'likely market direction' according to D2CF.

The 2-Day Ahead Congestion Forecast (D2CF) which is provided by each of the participating TSOs in the capacity calculation process for their grid, provides the best estimate of the state of the CCR electric system for day D. This D2CF forecast provides an estimation of:

- the Net Exchange program between the zones;
- the exchanges expected through DC cables;
- planned grid outages, including tie-lines and the topology of the grid as foreseen for D+2;
- forecasted load and its pattern;
- forecasted renewable energy generation, e.g. wind and solar generation;
- outages of generating units, based on the latest generator availability info.

As it will be presented below, the flow-based methodology followed here replicates this principle when calculating the initial loading of each CNEC.

For each CNEC, a procedure is followed to calculate the Remaining Available Margin (RAM) (see Figure L-5), which is the physical capacity on the CNEC that can be used by the market coupling algorithm to accommodate cross-border exchanges, and which is defined as follows:

$$RAM = F_{max} - (FRM + F_i)$$

$$\text{with } F_i = F_{Ref} - \sum_j PTDF_j \cdot NP_j$$

- F_{ref} = Reference flow over the network element in the base grid model where cross-border exchanges are still present;
- NP_j = Net position (Balance) of Bidding Zone 'j' inside the CCR (e.g. Core) in the Reference situation;
- $PTDF_j$ = Zonal PTDF of bidding zone 'j' for the considered CNEC branch 'i';
- F_i = Flow over the network element 'i' when cross-border exchanges within the CCR (e.g. Core) are cancelled;
- FRM = Flow Reliability Margin, used by TSOs to account for the uncertainty due to forecast errors.
- F_{max} = The maximal allowable physical flow over the concerned CNEC branch 'i' in order to comply with operational and thermal – structural limits.

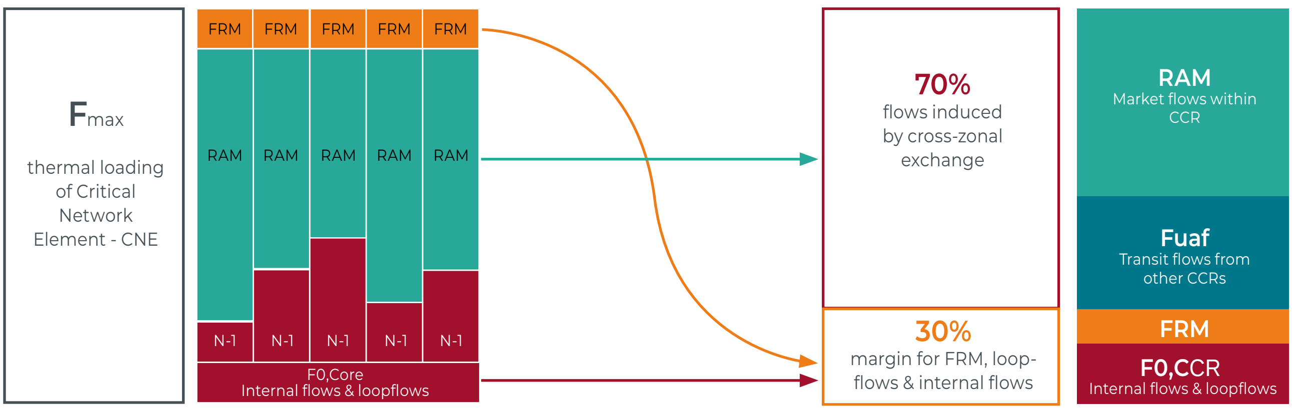
An important factor determining the final RAM is therefore the 'initial flow' Fi, reflecting the flow over the network element when all bidding zones within the CCR (e.g. Core) are at zero balance. This flow therefore includes:

- the flows resulting from internal exchanges in the Bidding Zone where the CNEC is located (mostly relevant for CNEC's within a Bidding Zone, but much less important for cross-border (XB) CNECs;
- the flows resulting from internal exchanges in other Bidding Zones than the one where the CNEC is located (loop flows);
- the flows resulting from exchanges over non-CE bidding zone borders, the so-called unscheduled allocated flows (Fuaf).

European legislation requires a minimum capacity for each CNEC margin (minRAM) to be made available to the market for the totality of cross-zonal exchanges. For this reason, every time a CNEC's margin (RAM) after preloading is less than the required minimum margin to be given to the market (e.g. 70% Fmax), the minimum margin is enforced (see Figure L-5).

Note that no FRM and LTA inclusion are considered in the calculation of the flow-based domains used in this study (see further below).

FIGURE L-5 — DEFINITION OF REMAINING AVAILABLE MARGIN (RAM)



L.3.6. VALIDATION PROCESS

Finally, Core TSOs shall validate and have the right to correct cross-zonal capacity for reasons of operational security during the validation process individually and in a coordinated way [ACE-9]. This validation process is in two steps:

- If the allocated capacity (RAM_{bv}, RAM before validation) is considered by the TSO as being able to violate the operational security limits, TSO must verify if this violation can be avoided by the application of remedial actions (RA). These remedial actions (non-costly or costly) will have been communicated beforehand between TSOs and their use must be coordinated by the Coordinated Capacity Calculator (CCC) with the neighbouring CCCs in the event of an impact on the neighbouring Capacity Calculation Regions. Thus, for CNECs where the RAs are not sufficient to prevent this operational security violation, the Core TSOs in coordination with the CCC can reduce the RAM_{bv} to the maximum value that prevents this violation. This reduction in RAM_{bv} is referred to as a 'coordinated validation adjustment' (CVA) and the adjusted RAM is called 'RAM after coordinated validation';
- After coordinated validation, each Core TSO shall validate and have the right to decrease the RAM for reasons of operational security during the individual validation [ACE-9], Article 20, paragraph 5. This individual adjustment is called 'individual validation adjustment' (IVA). It should be a positive value and only decrease the RAM of a CNEC to ensure operational security considering the previous coordinated validation process.

Therefore, for each CNEC where validation needs to be applied, its final RAM after both validation process (RAM_{av}) can be expressed as:

$$RAM_{av} = RAM_{bv} - CVA - IVA$$

This two-step validation process is not included in the flow-based domain creation process used in this study. Therefore, the created domains constitute an optimistic approach to the RAM given to the market and therefore justifies the sensitivities performed in the study which allow for reductions of this RAM, i.e. the application of different levels of validation.

L.3.7. CALCULATING THE FLOW-BASED CAPACITY DOMAIN

2-dimensional flow-based domain projection

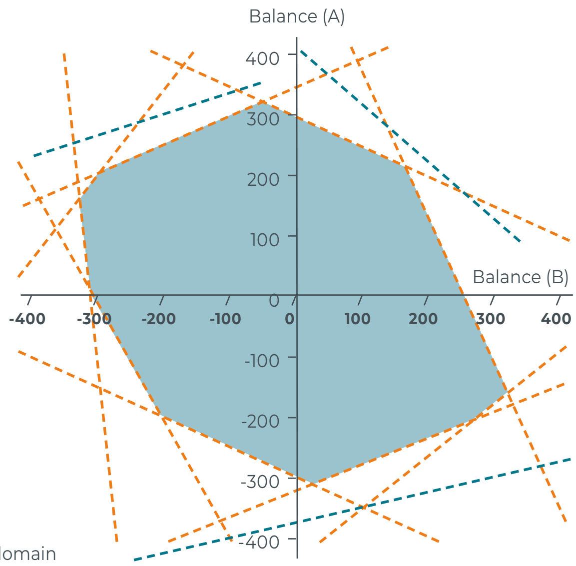
Figure L-6 shows how the flow-based domain can be determined by combining the calculated remaining available margins (RAMs) and the zonal PTDFs for each relevant Critical Network Element and Contingency (CNEC) pair. The first constraint is determined for line 1, in a situation without contingencies. It can be drawn from the table that the CNEC has a RAM of 150 MW, a zonal PTDF for zone A of -30%, for zone B of 25% and for zone C of 10%. The same exercise is now performed for all other lines and contingency pairs, ultimately resulting in a collection of constraints (RAM, $PTDF_A$, $PTDF_B$, $PTDF_C$).

These constraints can be understood as geometrical planes in the dimensions defined by the balances of the difference zones: Balance(A), Balance(B), Balance(C)... For the purpose of illustration, the constraints can be plotted between two balances as the projection of these planes, so they reduce to lines. Figure L-6 depicts such projection for Balance (A) vs Balance (B), where the constraints are represented by the grey dotted lines. Generally, the convention is used where positive balances represent net exports and negative balances represent net imports.

As a final step, the total set of constraints can be reduced by removing all non-relevant constraints. Constraints are considered non-relevant when other constraints are always reached earlier. This procedure is also called 'pre-solving' the domain and leads to the final combination of relevant constraints forming the secure domain, colored in blue in Figure L-6. Under perfect foresight conditions, every combination of secure exchanges between all different zones is part of this domain.

FIGURE L-6 — INITIAL FB CAPACITY DOMAIN CALCULATION AND VISUALISATION

Critical network elements	Incident	Remaining Available Margin (MW)	Influence of the exchange on each line (PTDF)		
			A	B	C
Line 1	No incident	150	-30%	25%	10%
	Incident 1	120	-17%	35%	-18%
	Incident 2	100	15%	30%	12%
Line 2	No incident	150	60%	25%	25%
	Incident 3	50	4%	-15%	4%
Line 3	No incident	-	-	-	-
	Incident 4	-	-	-	-



--- Constraints --- Active/ Limiting constraint FB domain

Understanding 2-dimensional flow-based domain representations on multi-dimensional domains

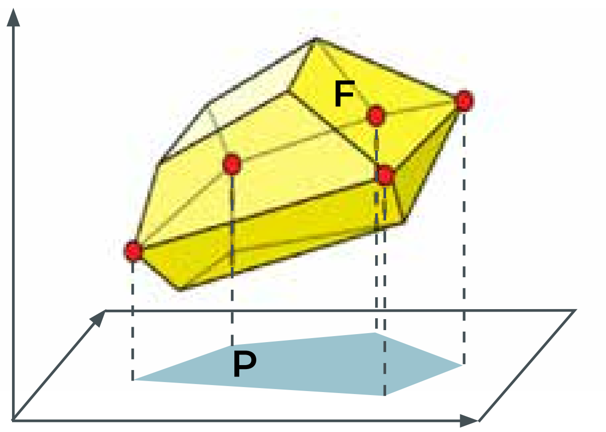
The example of the previous subsections has been done for two dimensions, e.g. the Balance or Net-Position corresponding to two countries considered within the region where the study is carried out.

For the current study, the flow-based domains considered are polytopes having up to **50** dimensions. For a better understanding of the domains, a two-dimensional representation is used. This representation is to be seen as a projection of the higher-dimensional domain onto a two-dimensional plane.

To obtain this, first the domain polytope which is described by its planes is converted into its vertices. Then these vertices are projected onto the desired plane. A convex hull of these points, which can be seen as the smallest convex polytope which contains all points (or more graphically: the polygon you get when you 'shrink wrap' around all points) is then calculated. All points which are not on the convex hull are omitted. Figure L-7 shows a theoretical example of such a projection [SCA-1]. Note that not all vertices are part of the convex hull.

The resulting 2-dimensional representation of the flow-based domain should be interpreted as follows: '*for any point within the 2-dimensional domain, for which the net positions of 2 countries can be read from the axes, a combination of net positions for the dimensions that are not depicted exists so that this point can be attained*'.

FIGURE L-7 — PROJECTIONS OF A MULTI-DIMENSIONAL FLOW-BASED DOMAIN (2D PROJECTION)



Usually, the Belgian adequacy situation was closely related to French security of supply. For that reason it was relevant to show a projection of the flow-based domain onto the Belgium-France plane. In the future, the correlation between countries will evolve. As requested by some stakeholders, other projections are also shown in this study. By convention, export is depicted as positive, whereas import is negative. A positive net position thus means a net export position towards the relevant CCR (e.g. Core/Central Europe region).

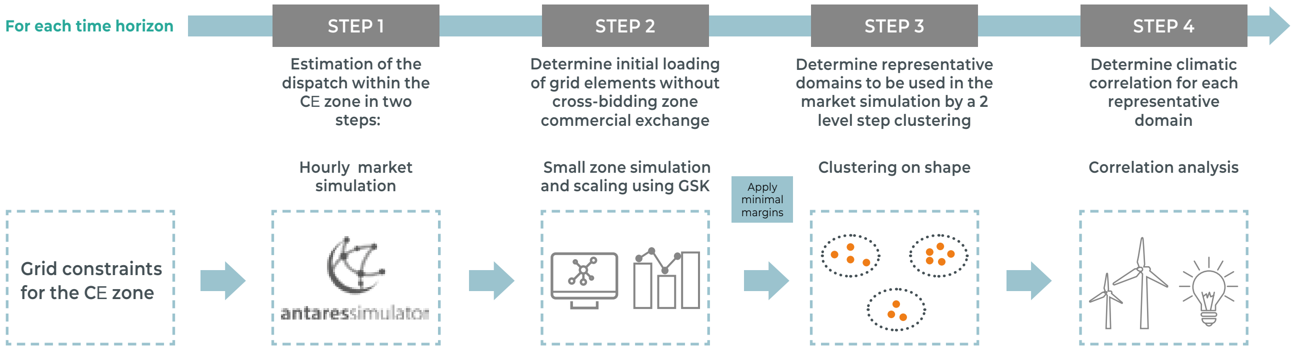
In SHC, all flow-based domain representations only depict CE balances, as opposed to bidding zone balances. Hence, the import possibilities of CE countries from outside CE are not shown. In the Antares model for the previous study AdeqFlex'23 [ELI-0] in case of SHC simulations, e.g. France could import from other countries within the limits of the NTC constraints on the concerned borders.

L.4. FLOW-BASED DOMAIN CREATION PROCESS

The flow-based framework developed by Elia for this study aims to mimic the currently applied operational framework as well as integrate the predicted flow-based evolutions. This process is illustrated in Figure L-8 and further explained in the following paragraphs.

When creating flow-based domains, the following assumption was made: no grid maintenance is planned throughout Europe in the winter periods. In other words, while the impact of single contingencies was taken into account through the CNEC definition process, it was assumed that prior to a contingency, the European transmission grid is always fully available and operational. For winter months (when focusing on the representation of scarcity events), this optimistic assumption was retained; for summer months, however, assuming that there wouldn't be any grid maintenance was deemed unrealistic. As a proxy for this reduced availability of the transmission grids, the domains generated for the summer months usually assume a specific percentage of fixed RAM applied to the available transmission grid. This approach does not impact the adequacy requirements calculated, as the stress situations occur during winter periods for Belgium.

FIGURE L-8 — PROCESS FOR THE DEVELOPMENT OF THE FLOW-BASED DOMAINS



L.4.1. STEP 1: ESTIMATION OF THE DISPATCH

The first simulation, called 'flow estimation', aims to determine the set points of the different controllable devices, i.e. HVDCs and PSTs. This first run is crucial for grid feasibility.

The second run, or 'base case simulation' mimics the capacity allocation and congestion management (CACM) capacity calculation (CC) process and allows for a good estimation of the pre-loading on CNECs. Once fully set up, the flow-based framework performs an initial simulation to determine the initial loading of each CNEC. In general, around 1/2 of the PST tap ranges in Belgium and about 1/3 for other countries were used to optimise initial flows compared to their predefined set points to maximise the socioeconomic benefits of the system. The flows from this simulation determine the 'Reference Flows'.

L.4.2. STEP 2: INITIAL LOADING OF GRID ELEMENTS

In a next step, combining geographical information on the location of load and generation within CE with the hourly market dispatch from Step 1, the loadings of grid elements associated with the hourly commercial exchanges resulting from the market simulation in Step 1 can be determined for each hour. For determining the market domain, initial loadings of grid elements in the absence of commercial exchanges are required. Using the bidding-zone GSK, the net position of each of the bidding zones is scaled to zero. Commercial exchanges between bidding zones are thus cancelled, and the remaining flow on grid elements equalled the initial loadings (loop flows and potentially some internal flows). The process used to scale the net positions of all bidding zones to zero is the same as the one used in flow-based operations today.

Such initial loadings could potentially pre-use a significant portion of the physical capacity of grid elements, and thereby restrict market operations. Since 1 January 2020, the 'Clean Energy for all Europeans Package' has been effective. It introduced specific requirements related to the availability of transmission capacity for market exchanges. To model the application of those rules for future time horizons, virtual minimal margins were applied to each CNEC for determining the final hourly flow-based domains.

L.4.3. STEP 3: CREATION OF THE DOMAINS

As the market simulation performed in Step 1 creates an estimation of the dispatch and corresponding initial loadings within CE for each hour of the simulated year, this would result in 8760 different flow-based domains. For the present study, the number of flow-based domains is limited for each time horizon in order to obtain feasible computation times by reducing the complexity of the simulations.

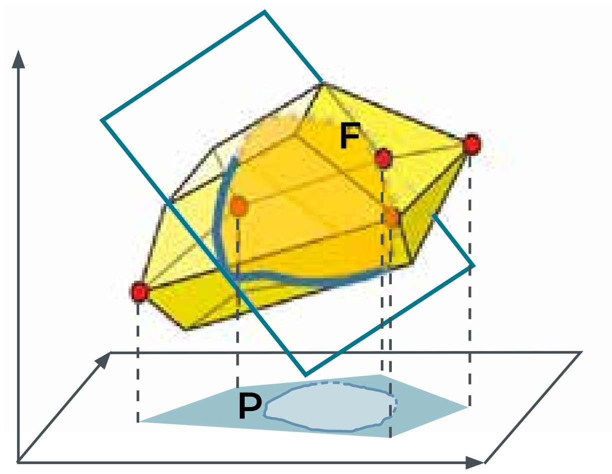
Step 3.1: Smart-Slicing

Explanation of smart-slicing

As the number of dimensions in the flow-based domain increases, so does the complexity. It is therefore necessary to use simplifications in order to represent the flow-based domains in a human readable way e.g. by 2D projection.

Figure L-9 illustrates the concept of smart slicing. The blue square represents a hyperplane that would cut the multi-dimensional polytope fixing hence the net positions of the other dimensions. Applying this so-called smart-slicing reduces the degree of freedom and results in the grey projections as 2D representations. Of course, the way the smart slicing is applied, i.e. which net position are chosen will visually affect the 2D representation. While building the flow-based domain, the net position chosen for the smart slicing were the ones from the market simulations at the precise hour considered.

FIGURE L-9 — FLOW-BASED DOMAIN – SMART SLICING



Use of smart-slicing

Smart-slicing can also be used for other purposes than visualisation. Enumerating full-dimensional polytopes is impossible with the domain dimensionality used in this study (14 CE biding zones + ALEGrO + (if applicable) AHC dimensions). Five dimensions (5D) were deemed most relevant to Belgian security of supply (CWE + ALEGrO). The positions of the other dimensions were considered by the procedure of 'smart slicing' and thus fixed for each hour to the market simulation results obtained in Step 2. Through 'smart slicing', the full dimensional polytope was then reduced to a 5D polytope describing the feasible net positions of these five most relevant dimensions for Belgium. Vertices enumeration was then performed by considering these five-dimensional polytopes at each hour.

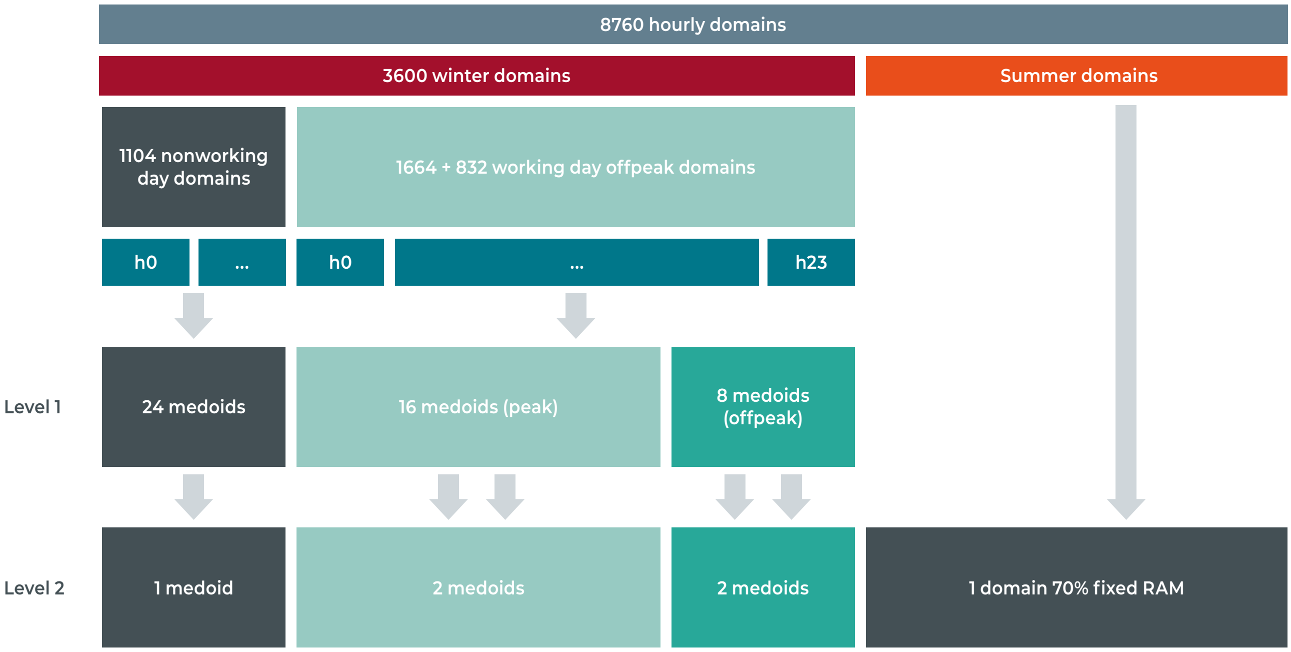
Step 3.2: Clustering of domains

Applying a clustering algorithm requires a metric that can be used to assess the similarity of domains. The clustering of the 8760 domains is based on their geometrical shape by means of comparing the Euclidian distance between vertices. A pre-cluster data split is applied to reduce cluster groups size and hence computational complexity whilst respecting time-related trends. In this split, summer and winter domains are separated, weekends and weekdays are separated, and within the weekdays, the peak and off-peak hours are separated as well. This resulted in the creation of 6 groups to be clustered individually.

Next, the number of centroids to retain are defined. For weekends, one centroid is calculated to represent the entire group, whereas for weekdays, per group, 2 clusters are created, each with its own centroid (see Figure L-10). The clustering was performed by means of a k-medoid algorithm. Here the centroids were elements which were part of the initial domains, and therefore had physical meaning. This process was performed in two steps in order to be able to reduce the set and ultimately find the representative centroids.

The level 1 clustering produced a first set of medoids that were further refined in level 2 in order to reach the targeted number of clusters.

FIGURE L-10 — FLOW-BASED DOMAIN CLUSTERING PROCESS



Step 3.3: Resizing and approximating the domains for computational efficiency

The domains are subsequently restored back to their full dimensions of 14 CE biding zones + ALEGrO + (*if applicable*) AHC dimensions prior to plugging them back into the Antares model. In general, the number of CNECs in the framework's domains is too large to be of practical use in market simulations.

A flow-based domain is defined by a certain number of inequality constraints representing the limits of critical network elements at a given time. Keeping the complexity at an acceptable level is key to successfully carry out the simulations. A simplification algorithm is therefore chosen based on the Manhattan distance of two hyperplanes. This step allowed the identification of the smallest set of CNECs that could be used to describe the entire domain, without any loss of quality or representativeness. Finally after this step, the final set PTDF-RAM linear constraints where defined and set into the model.

L.4.4. STEP 4: INCORPORATING MULTIPLE FLOW-BASED DOMAINS INTO ADEQUACY ASSESSMENT

The 'Monte Carlo' approach used in this study generates multiple possible future states, called 'Monte Carlo' years. The method used for relating Flow-based typical days to the climatic conditions within the different the 'Monte Carlo' years was originally developed by the French TSO RTE (see reference documents [ANT-3] and [ANT-4]), was also implemented in RTE's adequacy study (*Bilan Prévisionnel* since 2017 [RTE-2]), as well as in the Pentalateral Energy Forum - GAA 2020 Report (PLEF 2020).

This method can be understood as follows. The k-medoid algorithm not only selects the representative domains for each of the clusters, but also identifies for each day the cluster to which it belongs. Thus, for the climatic variables in scope, thresholds can be defined (typically at the 33rd and 66th percentiles) which lead to the creation of climatic groups. As such, it is possible to identify, for every day, the climatic group to which it belongs. By counting the amount of times a domain appears in a specific climatic group, it is possible to define a probability matrix. This matrix represents the probability of being in a given cluster of domains under certain climatic conditions. Using the climatic conditions encountered at a given hour in the model, clusters can then be mapped back to the hours in the model. It is this interpretation that is used when mapping the typical days onto the 'Monte Carlo' years.

This kind of systematic approach makes it possible to link specific combinations of climatic conditions expected in future target years, e.g. high/low wind infeed in CE (Germany, France...) or high/low temperature and demand in France and Belgium, with the representative domains for these conditions.

L.5. EVOLUTION OF THE FLOW-BASED METHODOLOGY

Elia is a pioneer in the flow-based approach for adequacy studies and has developed a methodology to model exchanges between countries in the capacity calculation region that replicates the day-ahead operation. In fact, NTC only modelling of exchanges has not been used since 2015 and the introduction of flow-based methodology in CWE. In the first flow-based assessment of winter 2016-17 (the strategic reserve volume evaluation published end of 2015) only one domain was used to represent the entire winter. That domain was based on an historical situation. Since then, leading up to the present study, Elia has since improved its modelling by:

- adding more historical domains;
- relating the domains to the climatic variables in a systematic way;
- incorporating minRAM evolutions within those historical domains;
- correcting historical domains for historical grid outages;
- correcting historical domains for future grid upgrades;
- integrating the breakup of the DE-AT bidding zone on 1 October 2018;
- recalculating the domains to include the planned HTLS upgrade of the 380-kV Belgian backbone;
- modelling the ALEGrO interconnector, which provides additional freedom for the flow-based domain.
- development a flow-based framework which does not rely on historical data and instead mimics the operational flow-based capacity calculation workflow while allowing calculation of flow-based parameters for market and adequacy (mid- and long term) studies.
- adding the flow-estimation step in the process in which internal controllable elements' set points are estimated prior to simulating the flow-based process by mimicking the operational behaviour in D2CF;
- integrating the Advanced Hybrid Coupling (AHC) for any external border to the CCR considered (e.g. Core);
- Extension of the studied CCR to Central Europe region