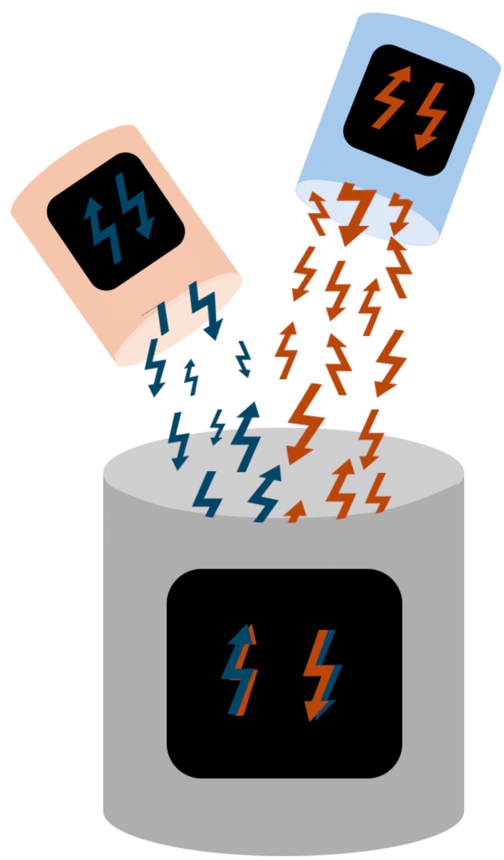
The operational potential of an integrated flexibility market for Dutch system operations

A PROOF-OF-CONCEPT STUDY

By

Tim Alex Stroomer



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Type:	Master Thesis
Author:	Tim Alex Stroomer
Student number:	5629616
Defended on:	September 26th, 2024
Program:	MSc. Complex Systems Engineering and Management
Institution:	Delft University of Technology
External client:	TenneT TSO B.V.
Confidentiality level:	Public
1st Supervisor:	Dr. P.W.G. (Pieter) Bots
2nd Supervisor:	S. (Sander) Renes PhD LLM
External Supervisor:	M. (Martijn) Ophuis

Preface

Before you lies the master thesis 'The operational potential of an integrated flexibility market for Dutch system operations'. The delivery of this thesis marks the end of my 2-year learning development within the Master Complex Systems Engineering and Management at Delft University of Technology. The project was carried out between February and September of 2024.

Reflecting on my academic journey, I can recognize a tendency to challenge myself with new experiences, enjoying learning new knowledge fields and skills. And this project was nothing different. I learned new concepts of electricity markets, modelling, the optimization software Linny-R and a fast-growing organization with lots of amazing smart people. Therefore, this thesis has provided me with valuable lessons both personally and professionally.

However, this novelty came with some significant challenges and setbacks. This led to moments in which I strongly questioned the rationale behind my efforts and almost wanted to quit the task. Fortunately, I held on to my motivation and finished this research you are about to read. Before diving into the details, I would like to express my gratitude to all those who supported me throughout this journey.

I would like to thank my parents, brother, and girlfriend for their unwavering support and encouragement. Special thanks to my external supervisor, Martijn Ophuis, for his guidance and valuable insights, as well as my 1st academic supervisor, Pieter Bots, for his support during the modeling process and upgrading the optimization software. I also appreciate my 2nd supervisor, Sander Renes, for his helpful feedback and deep insights into market dynamics.

Executive summary

A transmission system operator (TSO) is responsible for managing, maintaining, and developing the high-voltage electricity grid. This includes two important functions: balancing (BA) and congestion management (CM). BA matches the supply and demand ensuring a constant grid frequency, while CM alleviates congested lines ensuring the save transport of electricity. Both functions use upward or downward reserve capacities from connected parties, called flexibility. Currently, a TSO procures this flexibility through five distinct markets trading a specific flexibility product: Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), manual Frequency Restoration Reserve directly activated (mFRRda), Reserve Other Purposes (ROP), and Capacity Restriction Contracts (CRCs). FCR, aFRR, and mFRRda are used for BA, while ROP and CRCs are used for CM. Each product fulfills a different purpose, acts on a different timeframe and therefore has distinct bid requirements and renumeration schemes. For instance, ROP and CRC require location-specific bids which affect bid effectiveness. Whereas FCR requires bidders to have local-frequency control and faster response times than aFRR and mFRRda. Therefore, flexibility providers commit their capacity to specific markets in advance according to their needs and capabilities. Consequently, a TSO lacks the ability to address potential flexibility shortfalls in one area by drawing on capacity reserved for another. Mismatches can arise, possibly leading to stressful situations for operators, higher costs, and even regional power outages. In addition, the various market options create complexities for participants potentially increasing the likelihood of inefficiencies and misallocations of flexibility resources.

To address this issue and improve system efficiency, this study explored the possible integration of these markets, combining two or more of the current products into a single flexible reserve product, which offers can be used universally. This provides TSOs with more leeway to mix and match, increasing the use of the available capacity, and simplifies the offering process for market participants. The study specifically analyzed a combination of the capacities currently offered through aFRR and ROP in context of the Dutch system operations. These products turned out to have notable similarities, including moderate response times, overlapping procurement timelines, and comparable system properties, which increases the likelihood that their capacities can be used universally. In addition, these products had the highest accessibility of historical data, which was important for the proposed quantitative analysis, an area identified as a significant gap in the existing literature. mFRRda also shared strong similarities with aFRR and ROP, but due to the limited availability of data, it was not included in the analysis.

A modeling approach was adopted to compare the technical and economic performance of the current separated and the proposed combined system. The separated system involved aFRR and ROP bids solving their distinct BA and CM problems, while the latter allowed interchangeable use of aFRR and ROP for BA and CM. The performance was measured through problem-solving capacity, frequency of failures, capacity consumption for both BA and CM, and costs. To achieve this, a simulation was run, optimizing congestion and imbalance issues at the lowest cost by utilizing the merit order of aFRR and ROP capacity offers. Five days of historical data were used, covering various imbalance and congestion scenarios along with corresponding aFRR and ROP bids. The simulation maintained the existing sequence of market clearing, prioritizing CM before BA. This reflects the current preventive and reactive approaches of these operations in time.

The simulations showed a significant improvement in operational performance. Both the BA and CM costs were reduced in the combined design by 70% and 80% respectively (as shown in the table below). By merging ROP and aFRR capacities, the availability and use of low-priced bids increased. Only a few actions of BA resulted in minor cost increases, which can be explained by the priority given to CM, but overall costs consistently decreased. Technically, the combined design eliminated initial system failures and significantly boosted problem-solving capacity. The latter was particularly visible in the upward balancing direction, which showed a capacity increase of over 360%. This increase can be explained by the complementary upward and downward reserve capacities of ROP and aFRR. The system showed only a modest 11% increase in CM capacity usage. This was due to the availability of extremely low-priced aFRR bids for CM, which outweighed the benefits of more effective bids.

Key performance indicators	Unit	Separated market design	Integrated market design	Difference (%)
BA costs	€/min	589	177	-70
CM costs	€/min	561	95	-83
Total costs	€/min	763	73	-90
Frequency of BA failures	%	1.6	0	-100
Frequency of CM failures	%	0.21	0	-100
Upward solving capacity BA	MW/min	526	2451	366
Downward solving capacity BA	MW/min	1083	1628	50
Solving capacity CM	MW/ISP	184	550	198
CM reserves used	MW/min	13.4	14.8	11

Overall, combining ROP and aFRR results in significant cost savings, improves grid efficiency, and enhances resilience to peak loads and disruptions. However, it is unlikely that the same added value will be generated by other forms of integration. aFRR, mFRRda and ROP share strong similarities, which makes the capacity currently offered through these products highly interchangeable. In contrast, FCR and CRC have highly specific and different characteristics, making them less suitable to be combined into one product. A more likely option is the partial integration of flexibility markets, combing the more generalizable products into a single reserve, while maintaining the highly specific products as they are. This will still increase the options for TSO's to mix and match and simplifies market structures, without compromising the unique benefits of a specialized product like FCR.

A partial or full integration of the various markets still poses several challenges. First, all bids should include locational information for CM, something currently not required for aFRR, mFRRda, or FCR. This study assumed a proportional distribution of effectivities to simulate their locations. In reality, geographic locations may be more concentrated or strategic bidding will occur, which could change this distribution and lower the generalizability of this study's results. Future research with real locational data could offer a more accurate assessment. Additionally, merging flexibility markets raises questions about the required auction structures, including pricing systems. For example, marginal pricing, used by aFRR, typically results in lower bid prices compared to the pay-as-bid system used by ROP. This study assumed historical bids, which were made under the existing separated market structure; hence, altering the auction design could lead to changes in bid sizes and prices. Further research is necessary to find the most effective auction structures for an integrated market design. Finally, dealing with the preventive nature of CM and the reactive nature of BA remains a challenge. This study maintained the existing sequence, but alternative operational rules, such as shifting market clearing timeframes and introducing a co-optimization strategy, could further enhance efficiency. Future research should explore these options to maximize the benefits of an integrated market design.

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List of abbreviations

aFRR.........................Automatic Frequency Restoration Reserve

BRP...........................Balancing Responsible Party

BSP...........................Balancing Service Party

CoSEM......................Complex Systems Engineering and Management

CRC..........................Capacity Restriction Contract

CSP...........................Congestion Service Party

FCR...........................Frequency Containment Reserve

IP..............................Imbalance Price

ISP............................Imbalance Settlement Period

KPI............................Key Performance Indicator

MILP..........................Multiple Integer Linear Programming

mFRRda.....................Manual Frequency Restoration Reserve directly activated

ROP...........................Reserve Other Purposes

TSO...........................Transmission System Operator

UCP...........................Unit Commitment Programming

1. Introduction

1.1. Problem formulation

On July 14, 2020, the 'ALERT' state was declared by the Dutch transmission system operator (TSO) TenneT. A temporary condition allowing the operator to request immediate adjustment of power flows to and from connected parties to restore any imbalance between supply and demand or prevent lines from overloading, albeit at undisclosed costs. Months after the incident, requiring hours of negotiations, a settlement on the costs was reached. €321,000 for the temporary deactivation of a power plant, enabling the TSO to redistribute the power flow to prevent one of its transmission lines from overloading. The bitter irony? While there was a shortage of flexibility capacity offered for solving overloaded lines at the time of incident, there was a surplus of capacity offered for balancing purposes available. If this balancing flexibility had been activated to prevent the line from overloading, the TSO would have settled at a cost of €155,000 without any negotiations [1].

A TSO is responsible for managing, maintaining, and developing the high-voltage electricity grid. This includes two important functions: balancing (BA) and congestion management (CM), both of which require short-term flexibility [2]. On one hand, the TSO must maintain a consistent balance between supply and demand to maintain the grid frequency of 50 Hz. To achieve this, the TSO can activate flexibility resources up and down, adding electricity to or removing electricity from the grid. Secondly, the TSO ensures that energy is safely transmitted from production points to consumption areas. If the market outcomes exceed the available transmission capacity, the TSO may need to redispatch generation units or loads by decreasing output upstream and increasing it downstream of the congestion point, which is called CM. This ability to quickly and effectively adjust supply and demand in the electricity grid is called flexibility.

To obtain this flexibility, most European TSO's depend on their connected parties. These parties own assets that often do not (have to) run on full capacity. Consequently, they can provide flexibility by deviating from their normal production levels. This capacity can be offered in various short-term flexibility markets [3]. In these markets, parties can choose whether their flexibility can be used for BA or CM by offering their capacity on a range of flexibility products. These bids are then placed on several bid ladders to create a merit orders. The TSO then evaluates the ladders with the goal of minimizing costs of operation.

Currently, five markets exist trading five different products: Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), manual Frequency Restoration Reserve directly activated (mFRRda), Reserve Other Purposes (ROP), and Capacity Restriction Contracts (CRCs). FCR, aFRR, and mFRRda are used for BA, while ROP and CRCs are used for CM. Each product fulfills a different purpose, acts on a different timeframe and therefore has distinct bid requirements and renumeration schemes. For instance, ROP and CRC require location-specific bids to effectively solve congestion. Whereas FCR requires bidders to have local-frequency control and faster response times then aFRR, mFRRda, ROP and CRC. These factors influence the decision of parties when offering their flexibility on a particular product, allowing them to choose the option that best aligns with their needs and asset capabilities. Additionally, this structure ensures that the TSO can rely on the capacity offered through these products to meet the necessary technical and operational standards.

However, once a party commits their capacity on one of these products, it cannot be utilized on another, even if there is an excess of bids and not all bids are used. This restriction exists, despite the fact that the same asset could also meet the requirements of other flexibility products. As a result, TSOs are limited in their ability to mix and match, which can lead to unsolved mismatches between flexibility demand and supply, similar to the incident described in the introduction of this section. These mismatches can create stressful situations for operators of power systems and potentially higher costs because more expensive emergency flexibility must be called upon. In extreme cases, the operator even has to shut down (parts of) the electricity grid to prevent damages, resulting in (regional) power outages [4].

In addition, this strict separation of flexibility markets also challenges the parties themselves. They face different qualification processes, distinct market requirements, and diverse input obligations when offering their capacity [5][6]. This fragmented landscape adds an administrative burden and requires significant coordination efforts. Each market has its own set of rules and procedures, making it cumbersome for participants to navigate and comply with multiple regulatory frameworks. This complexity not only deters participation but also increases the likelihood of inefficiencies and misallocations of flexibility resources.

To address these issues and improve system efficiency, a possible solution is the integration of these flexibility markets, combining two or more of the current products into a single reserve product that can be universally applied to an imbalance or congestion issue. This allows for more leeway to mix and match by the TSO increasing the use of the available capacity, while also simplifying the offering process for market participants.

1.2. Literature review

To date, the integration of flexibility markets has received little attention in literature. Research has primarily focused on the challenges and benefits of the individual markets of BA and CM [18][19][20]. However, one of the few studies that did address market integration was conducted in 2017 [3]. This research developed a conceptual framework and a criteria catalog for evaluating an integrated approach between BA and CM, focusing on market liquidity, price formation, participant impacts, responsibilities, market power, and operator capabilities. The study highlighted the benefits of an integrated market, such as increased efficiency and availability of flexibility, but noted that legal and regulatory adjustments are needed. Accordingly, the study mentioned that the Electricity Balancing Guideline (EBGL) restricts balancing energy bids used for redispatch to influence the imbalance price, which would be a direct consequence of combining the bid ladders. The imbalance price is a key metric that reflects the cost incurred by the system operator when balancing. Moreover, countries like Germany, currently prohibit the use of BA reserves for CM. Future research recommendations from this study include a quantitative analysis to validate their findings and assess the potential economic impacts.

Separately, but also on integration, is a 2020 study [17] that critically analyzed existing approaches to BA and CM, focusing on their effects on service provider incentives and the potential for market-based solutions. The researchers introduced three interaction models, with the third model (CMB) most closely relating to the integration of BA and CM markets, as suggested in this research. They argued that CMB offers significant availability gains and a lower susceptibility for gaming (the leverage market parties can exercise on the market results) since the market parties do not know in advance for which purpose their bid will be used. However, the study points out that CMB necessitates a careful market design to ensure transparent cost allocation. Similar to the 2017 study [3], this research primarily conducted a qualitative analysis but underscored the importance of future quantitative research to better understand the efficiency and economic impacts of the proposed integration models

A few more studies have been executed at the interface of integrating BA and CM, however these studies keep the markets separate and therefore take a different approach. Instead, these studies discuss various forms of co-optimizations. Co-optimization in these studies appears in two primary forms: either by simultaneously selecting the necessary bids within the same timestep to enhance efficiency, or by considering the congestion impacts of activating balancing bids.

For instance, a 2016 study [22] examines the effect of locally (instead of globally) resolving an imbalance, showing an overall higher flexibility requirement for BA but less grid congestion. Another study from 2024 [23] explores filtering BA bids by placing some bids higher on the bid ladder according to their additional grid costs. A similar approach is taken by a 2018 study [24], which applies locational marginal pricing to bids, allowing congestion costs and energy losses to be considered in the bid selection process. Finally, a 2017 study [25] models a co-optimization with simultaneous selection for redispatch and BA reserves, incorporating expected imbalances (making BA preventive) to minimize the total reserve requirement for imbalance.

1.3. Knowledge gaps

The literature scan reveals that the integration of BA and CM markets has not been extensively explored. Only two studies conceptualized the idea of an integrated market design, leaving significant knowledge gaps in practical and empirical research on this topic:

1. The study from 2017 discussed a potential integration of BA and CM on market segment level [3]. The researchers did not discuss the specific products traded in these segments and how their different characteristics can shape opportunities for an integrated design. Exploring the specifics of these design options is highlighted as one of the main directions for future research.

2. Both 2017 and 2020 studies included a qualitative assessment of the integration concept, based on the several performance criteria [3][17]. However, both lack a quantitative evaluation of possible integration designs for BA and CM, which is empathized as an important direction for future research. The 2020 study highlights a specific need for more insight into efficiency, distribution of costs, and incentives.

1.4. Aim of this research

To bridge these knowledge gaps and extent current literature, this study focused on providing more quantitative insight into the operational benefits of an integrated flexibility market for a TSO system operation. The insights can help TSO's, policymakers, and industry stakeholders make more informed decisions on the implementation of integrated flexibility markets. Additionally, they can deepen the understanding of the implications and opportunities associated with market integration, identifying areas that require further investigation. Accordingly, the following main research-question has been formulated:

What is the operational benefit of integrating the flexibility markets for Dutch TSO system operations?

To address this overarching question, the study will explore the following sub-questions:

SQ1: Which of the current flexibility products are most suitable to be combined into an integrated market structure, considering their different characteristics?

The potential of an integration largely depends on the interchangeability of the products to be combined. This interchangeability in turn largely depends on their characteristics.

SQ2: What technical performance improvements for system operations can result from integrating flexibility markets?

This sub-question aims to identify potential enhancements in system efficiency and effectiveness that could arise from the integration of flexibility markets, focusing on how combining different products might improve operational performance.

SQ3: What are the economic implications of integrating flexibility markets on system operations?

This sub-question examines the cost impacts and economic feasibility of integrating flexibility markets, assessing whether the anticipated benefits justify the associated costs and exploring the overall economic viability of such integration.

1.5. Thesis outline

The report is divided into multiple sections to fully answer the research questions. The next chapter will provide the methodology used, elaborating on the research approach and tools. Chapter 3 will discuss the built of the model according to the modelling cycle. The empirical results are given in Chapter 4. Chapter 5 will provide a conclusion and a discussion is given in Chapter 6.

2. Methodology

2.1. A comparative study

To assess the operational benefits of integrating flexibility markets for system operations, a comparative study has been conducted. The evaluation process of flexibility bids for imbalance and congestion issues under the current separated structure has been compared to a scenario with an integrated market structure, see Figure 1. A comparative study is useful as it directly contrasts the performance of the current versus an integrated structure.

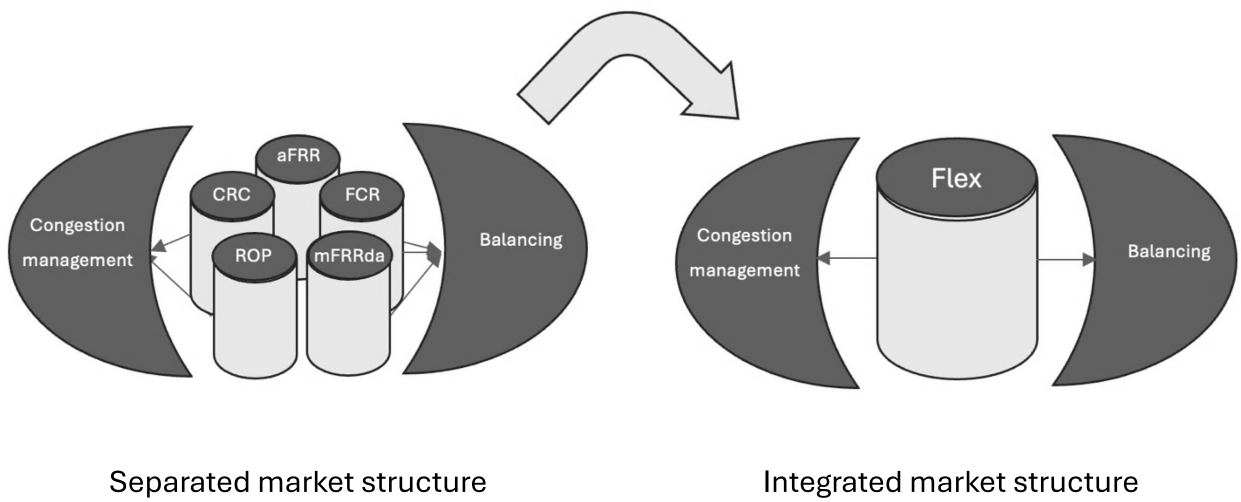

Figure 1: The evaluation process will be examined under and separated (left) and an integrated (right) structure

Currently, five evaluation processes exist within system operations, one for each flexibility product. These processes represent the systems of matching the received bids with the imbalance or congestion problems against the lowest price. This study specifically used only two of these products and their respective evaluation processes: aFRR and ROP. The greatest potential was observed in the combination of these two products.

Namely, the potential of an integration largely depends on the interchangeability of the products to be combined. For example, whether the capacity currently provided through the aFRR product can also fulfill the requirements of the ROP product and vice versa. This interchangeability, in turn, is determined by the differences in characteristics between the products.

Based on these characteristics aFRR, mFRRda and ROP shared the most features. They all have moderate ramp speeds and reaction times compared to FCR (see Table 1), show overlapping procurement timelines (see Figure 2), and comparable system properties, such as the activation by the TSO [8][9][10][11]. These similarities enhance the likelihood of universal use of capacities and require fewer adjustments in the event of a potential integration. In addition, these products had the highest accessibility of historical data, which was important for the proposed quantitative analysis. mFRRda was also a product with strong similarities, but due to the limited availability of data, it was not included in the analysis.

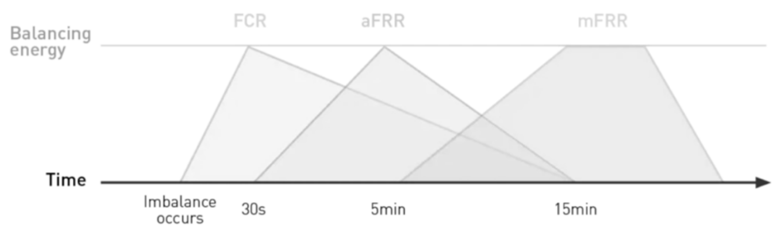

Figure 2: Three BA products in order of activation [12]

In contrast, FCR and CRC are more specialized products with unique characteristics presenting more significant challenges for integration. FCR demands much faster ramp speeds (up to 200%/min) as it is used for immediate imbalance correction [10] (see Figure 2), which capacity of other products may not meet. In addition, FCR is the activated by a local frequency control and not by the TSO. This ability is a significant technical requirement, not all assets are equipped with the necessary sensors and control systems to perform this function. Moreover, FCR is symmetric, meaning it requires assets to offer and deliver equal upward and downward power output, necessitating a specific set of assets like batteries or running loads.

CRC on the other hand acts one a different procurement timeline, called in several days or weeks before the incident, because they are often used to solve congestion caused by grid maintenance [16]. Integrating CRCs with other products would require market parties to submit their bids much earlier, reducing their flexibility to adjust to real-time market conditions and unforeseen changes in supply and demand. Moreover, CRC capacity is the only product that is procured through bilateral agreements with no standard renumeration and not through an auction (see Table 1), which would make integration with the other products harder.

Table 1: Comparison of the current flexibility products

Product characteristics	**FCR [source]**	**AFRR [source]**	**mFRRda [source]**	**ROP [source]**	**CRC [source]**
Activation	Local	TSO	TSO	TSO	Local
Reaction speed	2 seconds	30	N.A.	At least 1 hour	At least 12.5 hours
Ramp speeds	30 seconds	5 minutes	Up to 15 min.	N.A.	N.A.
Renumeration through	Capacity reservation	Capacity reservation and Energy spend	Capacity reservation and Energy spend	Energy spend	Varies
Market style	Auction	Auction	Auction	Auction	Bilateral contract
Timeline of market	8:00	9:00 and 14:45	9:00	N.A.	N.A.
Procedure	Reactive	Reactive	Reactive	Preventive	Preventive
Bid valid	4 hours	15 minutes	15 minutes	15 minutes	N.A.
Dimensioning level	110 MW	350 MW	1100 MW	N.A.	N.A.
Capacity valid	4 hours	24 hours	24 hours	N.A.	N.A.

Nevertheless, aFRR and ROP still share differences that have consequences when used combined under the integrated market structure. Firstly, ROP is a product used for CM, which is a preventive measure. Therefore, the bid evaluation process acts before real-time, up to 45 minutes in advance, also shown in Figure 3. In contrast, aFRR is used for BA and is evaluated near real-time.

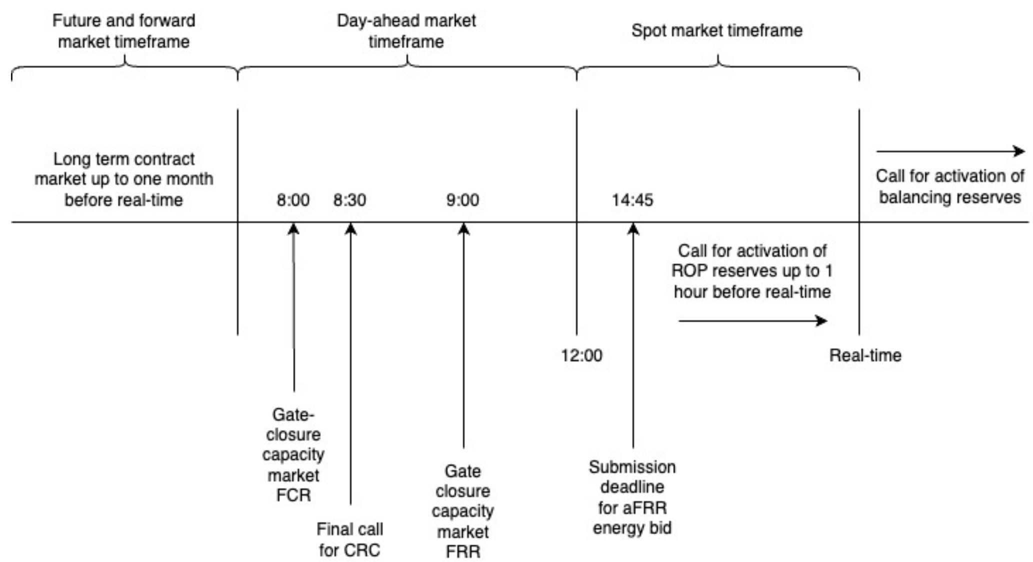

Figure 3: Timeline of market closures and calls for activation of BA and CM markets [14; edited].

This difference between time dimensions is not necessarily an important aspect to consider in the current system, since the use of aFRR and ROP reserves are strictly separated. However, when integrating the reserves into one pool of bids, this time dimension becomes a crucial point of discussion. Three designs for the evaluation process seemed possible:

- Unified Evaluation Timeframe

One approach could be to standardize the evaluation timeframes for all reserves. This would mean that either BA has to become preventive or CM reactive. A form of co-optimization would be formed.

- Staggered Evaluation Timeframe

Another option is to maintain individual evaluation processes for BA and CM but ensure that the results are coordinated. Meaning that BA can only use those reserves that have not been used for CM.

- Hybrid Evaluation Timeframe

A hybrid approach could be introduced creating a flexible evaluation system. This approach maintains the preventive and reactive nature of CM and BA respectively, but allows for real-time adjustments of reserves initially activated for CM.

The first and third options are likely to enhance the efficiency of reserve consumption. However, they would also necessitate substantial changes in system design. Additionally, the first option would alter the fundamental nature of both functions: transitioning BA to a preventive role could increase unnecessary interventions, while making CM reactive could increase the risk of late problem detection. While these considerations do not inherently disqualify these options, they represent significant trade-offs. This study has therefore opted to focus on the second option, which maintains the current evaluation order and limits the scope to a single system change at the time.

A second difference deals with the evaluation frequency. While aFRR evaluates every 4 seconds, the ROP product is only evaluated every 15 minutes [15]. When combined into one product, ROP will have to be evaluated for every 4 seconds and aFRR for every 15 minutes.

Another difference is the fact that every ROP bid contains a locational component. This location is important, as it represents it effectiveness, expressed between -1 and 1, to solve the congestion problem. BA does not require a bids location: frequency restoration can be done anywhere in the grid. When both ROP and aFRR bids are combined into one pool and used for both BA and CM, aFFR bids would require a locational component.

Finally, aFRR is different from ROP as it always contains a minimum amount of bid volume. This is called the dimensioning level, and it acts as a capacity reservation [13]. It is written by law that the TSO always has to have 350 MW upward and downward aFRR available for BA. In case of the integrated market structure, CM must therefore make sure this amount is left after evaluating the combined pool of bids.

2.2. Research approach

To compare the evaluation process of ROP and aFRR under the separated and integrated condition a modelling approach has been used. A modelling approach deemed particularly suitable due to several reasons:

- A modelling approach can enable quantitative analysis of a system, providing insights into potential cost savings, system stability improvements, and operational efficiencies.

- Modelling provides a safe environment to test the integration concept without any real-world risks. Potential pitfalls and challenges can be identified informing future implementation.

- The modelling framework allows for the exploration of different scenarios, which is crucial for understanding the conditions under which the integrated market would be most beneficial.

However, a modelling approach also has limitations. It often relies on simplifying assumptions and may not capture the full complexity of real-world operations. Additionally, it relies heavily on the available data, and missing or inaccurate data can significantly impact the results. Therefore, the potential consequences of the data gaps in this research have been discussed to elaborate on how these might skew the conclusions. Moreover, several scenarios have been executed to demonstrate how variations in some parts of the data can affect the outcomes, providing a clearer picture of potential real-world implications and (data) uncertainties.

2.3 Modelling cycle

To structure the modelling process, a framework has been used. The literature distinguishes various way to describe the modelling cycle, but in this thesis the six steps used in the TU Delft course ‘Systeemmodellering 1’ are adopted and described below [27].

1. **Formulating the question(s):** The first step in the process is to clearly define the research question(s) that you want to be answering using the model and which system these question(s) are about. This step has been previously covered.
2. **Conceptualization:** Next a conceptual model of the system can be developed. Key terms and relationships necessary from the research questions shall be explained. This creates a delineation of the system.
3. **Operationalization:** The third step is choosing an appropriate model type to translate conceptual model. In case of a quantitative model the concept and relationships have to be translated into measurable variables and equations.
4. **Implementation:** Then a software platform has to be identified that suits the requirements of the operational model in order to build a computational model. This also entails ensuring its accuracy through verification.
5. **Application:** The fifth step is performing the experiments with the model. Repeated model calculations can be executed to explore the systems behavior.
6. **Interpretation**: The final step is to analyze the results to answer the research question(s), acknowledge model limitations, and identify new research questions.

The steps above are part of a cyclic process, meaning that it is an iterative process. Therefore, in case something changes along the execution of the research, previous steps can be repeated to accommodate this.

2.4 Key performance indicators

Key Performance Indicators (KPIs) have been defined to measure the performance of both structures. These KPIs have been carefully selected to evaluate both technical and economic aspects.

2.5.1 Technical performance indicators

The main goal of introducing a more flexible reserve is to better match the supply and demand of flexibility. This has been evaluated by three technical KPIs which are discussed below.

KPI-tech 1 The frequency of system failures

A system that frequently needs to call in additional reserves to address operational issues may indicate a potential deficiency in its capacity, which could lead to increased operational costs. The frequency of system failures reflects this issue directly. System failures have been assessed by counting the number of times additional reserves were necessary to resolve the imbalance or congestion issue. Therefore, this KPI is measured separately for the BA and CM processes. The frequency of system failures has been expressed in percentage of time.

KPI-tech 2 Problem-solving capacity

The capacity to resolve imbalance or congestion issues can give an indication of a system's resilience, providing insights into both its current capabilities and its potential to handle future changes, such as increased congestion levels. The problem-solving capacity, as this KPI is called here, has been measured as the maximum size an imbalance or congestion problem can be at which the offered reserves were still sufficient to resolve the issue. Thus, without the need of additional (more expensive emergency) reserves. This has been evaluated separately for both the BA and CM processes.

For BA, problem-solving capacity can be divided into negative capacity and positive capacity requiring respectively upward and downward flexibility reserves. The total available volumes in megawatt (MW) of these reserves resemble these capacities.

Defining the problem-solving capacity for CM is a more complicated tasks due the involvement of reserve effectivities. Hence, the location of the congestion problem and bids affect the problem-solving capacity. Consequently, to measure this capacity multiple simulations have been used. The process included replacing the actual congestion problem in the model by a set of steps increasing in congestion volume repeating for every 15 minutes. These 15 minutes is also called Imbalance Settlement Period (ISP). To measure the capacity, the congestion volume of the step before failure was recorded in MW. Fifteen steps (equaling to the amount of timesteps a bid is valid) have been used ranging between 50 to 1900 MW to give this estimate. The actual steps can be found in Appendix B. Smaller, and more steps would have result in a better estimate, but this would have required a significant model rebuilt.

KPI-tech 3 Efficiency of congestion management

By combining the reserves currently offered through aFRR and ROP products, reserves with different effectivities become available for CM. Unlike with BA, this can affect the total consumption of reserves and therefore the efficiency of the system. The efficiency can be measured by comparing the consumption of reserves for CM against the size of the congestion problem. This KPI therefore has no unit. Moreover, a shift in consumption for CM, can also give some qualitative information about the type of bids used.

2.5.2 Economic performance indicators

The costs of operation under the integrated market structure will be different from current separated design. This is a direct effect of integrating the pool of aFRR and ROP reserves. To get an idea of the size and direction of this change, the economic performance will be assed using three KPI's.

KPI-eco 1 Balancing costs

The costs of BA are the income of Balancing Services Parties (BSPs) and are settled with the Balancing Responsible Parties (BSP), responsible for the imbalance issue [4]. A change of this costs will therefore directly affect the entire cost chain. The BA costs are normally equal to both the costs of capacity reservations and activated energy bids. However, this study will only consider the latter, because this study is only interested in changes. Capacity reservations costs are not dependent on the actual activation requirements. In addition, the ROP product currently has no capacity market in place, which makes a comparison that includes the capacity costs unfair.

To measure the BA costs resulting from the activated energy bids the current renumeration method for activating aFRR has been used: marginal pricing. Hence, the most expensive activated energy bid sets the price of renumeration for all bids. The BA costs over a certain timeframe are therefore equal to the total volume of activated bids used in that timeframe, times the highest bid of that timeframe. The timeframe used in this study was 1 minute, which was consequence of limited data available for the model. In reality, the activation of aFRR reserves for BA change every 4 seconds. This aggregation therefore automatically underestimates the real costs of BA. The BA costs have been calculated for both upward and downward activations, allowing to point out which is affected most when the respective imbalance problem is solved in a combined system.

KPI-eco 2 Congestion management costs

The costs of congestion management are not settled with any external party. These costs are paid by the TSO and are therefore socialized. Reduced costs will therefore directly be beneficial. For the same reasons as for BA costs only the costs made through the activation of energy bids have been included.

To measure the CM costs resulting from the activated energy bids the current renumeration method for activating ROP has been used: pay-as-bid. As the name suggests, the total cashflow is now simply the sum of each volumes bid times its price. The timeframe over which CM costs have been measured is 15 minutes. This is the time-block over which a congestion problem is measured and solved by the TSO. However, to more easily compare the CM costs with BA costs, the results have been transformed in €/min. The CM costs have been calculated for both upward and downward activations, allowing to point out which is affected most when the respective congestion problem is solved in a combined system.

KPI-eco 3 Total system costs

Currently, BA and CM are two distinct functions within system operations, therefore the associated costs are recorded separately. However, the subject of this study is the integration of flexibility markets, which mainly means the integration of BA and CM. Therefore, the total costs, resembling the sum of BA and CM costs, has also been added as an KPI for this study. To this end, the total costs have also been calculated for both upward and downward activations expressed in €/min.

3. The model

3.1 Conceptualization

As described in the previous chapters, this research specifically focuses on comparing the bidding evaluation process under the current separated market structure with the proposed integrated structure. This chapter will provide further insight into this system by defining various concepts and discussing necessary simplifications. This conceptualization establishes the scope of the research and forms the basis for model development.

3.1.1. Separated market structure

In the separated market structure, aFRR is responsible for BA, while ROP handles CM. There is no interaction between them. The evaluation process for these two products is as follows:

- **aFRR Bids**: Bids for aFRR are ranked from lowest to highest price on a bidding ladder and are valid for 15 minutes. Every 4 seconds, an automatic control signal is sent to participants based on measured imbalance, specifying a certain amount of activation. The bidding ladder determines who receives this signal, aiming for cost minimization. This process helps restore balance in the grid. If aFRR bid availability is insufficient, mFRRda is manually activated.

- **ROP Bids**: ROP bids, submitted for each quarter-hour, are assigned an effectiveness rating based on location and a power flow analysis. This rating indicates their impact on congestion issues. The price and effectiveness of each bid are integrated into an optimization program that matches regulation and de-regulation capacities. This prevents imbalance when managing congestion. ROP capacity is deployed based on forecasts and managed on a quarter-hourly basis.

3.1.2. Integrated market structure

In an integrated market structure, these processes remain the same. However, since they draw from the same pool of bids, they must take each other's choices into account. As a result, the evaluation process will resemble what is shown in Figure 4. CM will be prioritized in the selection process as it serves as a preventive measure.

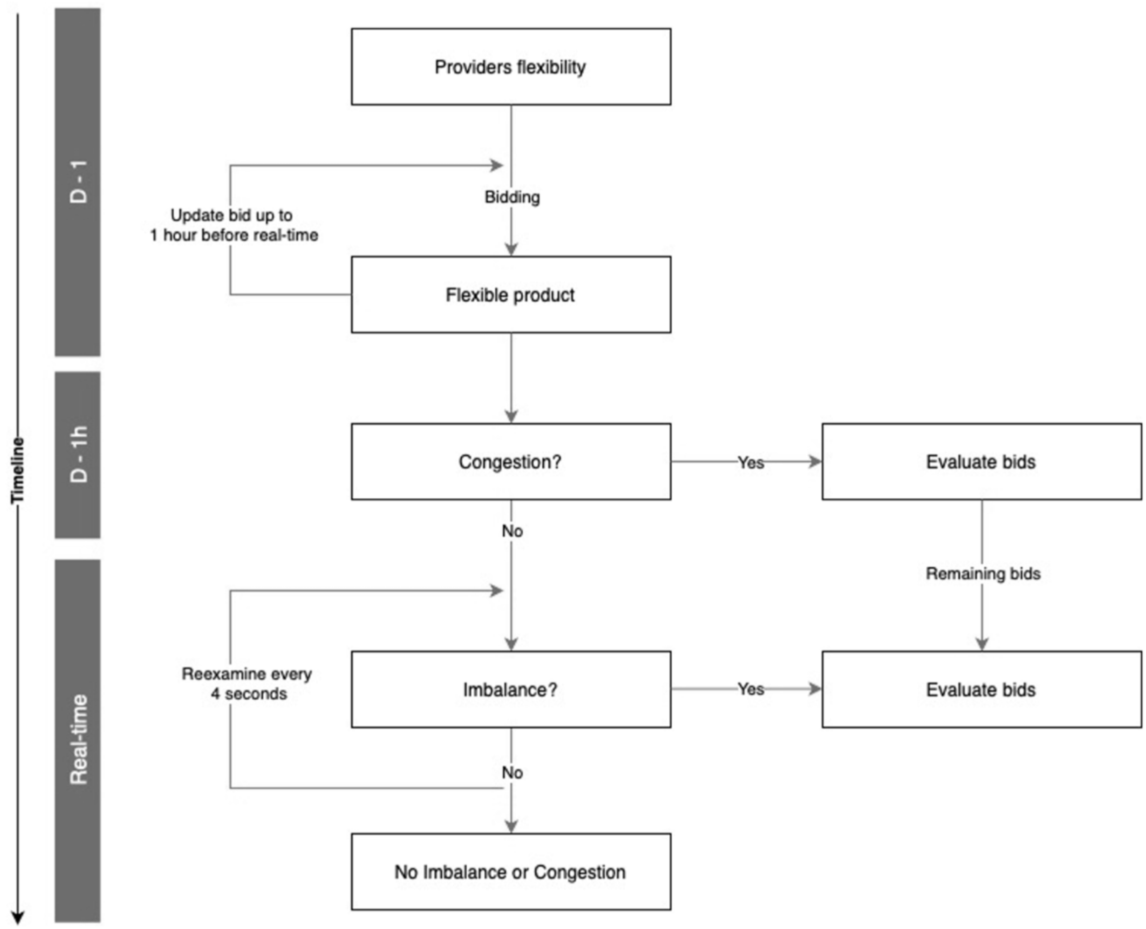

Figure 4: Evaluation of bids under an integrated market structure

3.3. Data

The concept has now been discussed. However, before explaining the operationalization phase, a discussion of the data used will be presented first. Data availability significantly influenced the subsequent steps in the modeling process and was a key factor in the numerous iteration cycles. Several simplifications of the system will be addressed.

3.3.1. aFFR prices and volumes

First, ideal would be to have available historical prices per aFFR bid. However, the available data was limited to four data points of the bid ladder, of which an example is shown in Figure 5. To preserve price levels and the shape of the bid ladder, bids were aggregated into four groups, each group taking on the price level of one of the four available data points. This aggregation resulted in less competition between bids on price levels in the model.

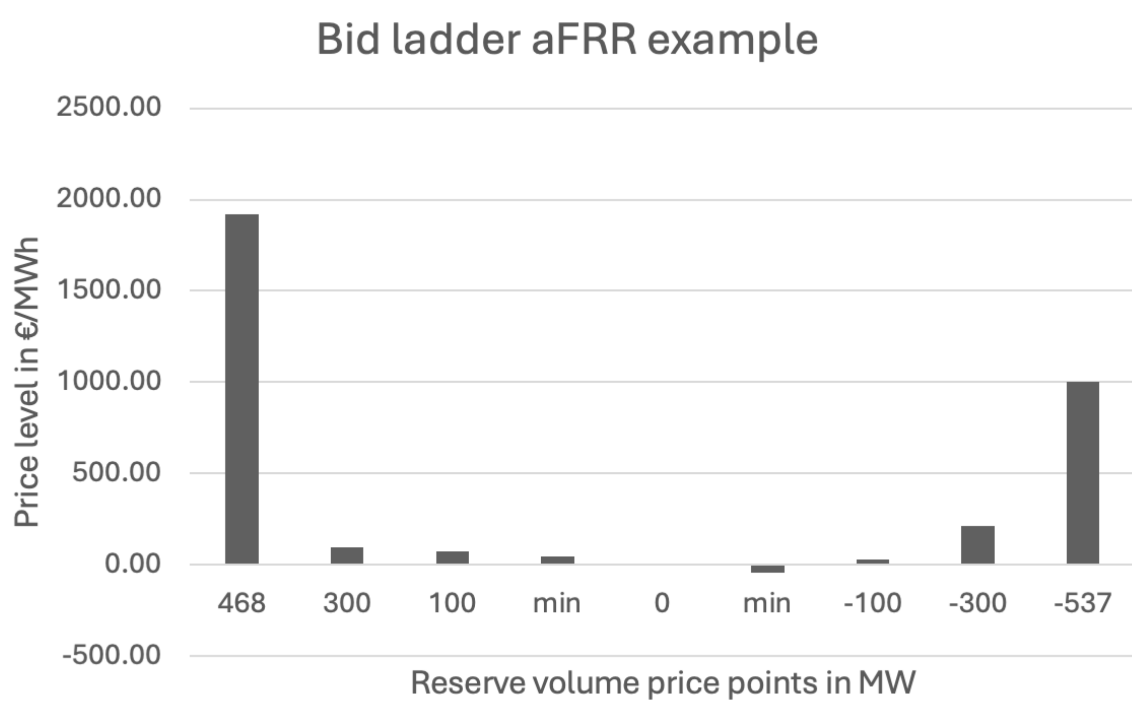

Figure 5: An example of the price points available (bid ladder)

Second, ideal would be to have available historical volumes per aFFR bid. However, the available data was limited to the sum of the bid volumes. To create four bids each with a set volume, the difference in volume between the price points on the ladder was appointed as bid volume, as explained in Table 2. This appointing resulted in a simplified system due to a smaller number of bids.

Table 2: From the total volume of bids to four bid groups

Price Level	*Offered Volume (MW)*	*Offer Price (€/MWh)*
A	100	Average of lowest and 100 MW price
B	200	Average of 100 MW and 300 MW price
C	≤300 if total offered volume > 600 MW, otherwise 0	Average of 300 MW and 600 MW price, unless offered volume < 600 MW, then zero
D	Remaining volume above 600 MW if total offered volume > 600 MW, otherwise remaining above 300 MW	Average of 600 MW and highest price if total offered volume > 600 MW, otherwise average of 300 MW and highest price

Data from the month of April 2024 has been used. The data is shown in Figure 6 and Figure 7. The dimensioning can be clearly seen as the minimal level of aFRR. Comparing both figures shows that there is double as much downward aFRR then upward aFRR, averaging at 1062 MW and 443 MW, respectively. This is because the assets capable of providing aFRR in an electricity system are often already operating at near full capacity for efficiency reasons as results from the spot and day ahead markets. This leaves less room to offer upward capacity, hence the difference.

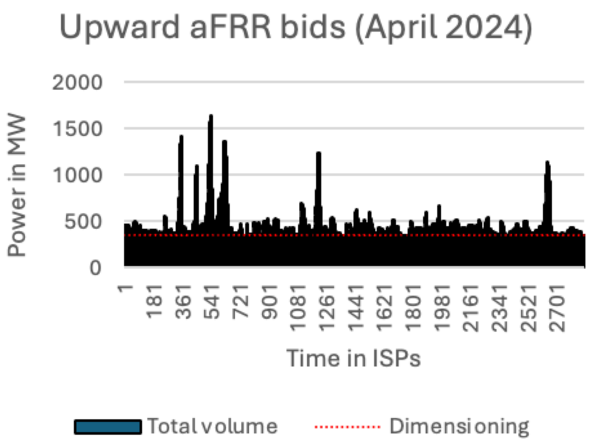

Figure 6: Upward aFRR bids from April 2024

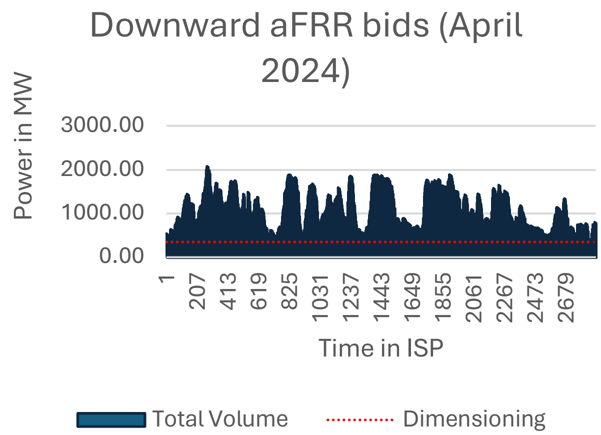

Figure 7: Downwards aFRR bids from April 2024

3.3.2. ROP prices and volumes

First, ideal would be to have available historical prices per ROP bid. Available data was limited to a number of historical acceptances of ROP bids on demand between 100 €/MWh and 500 €/MWh. To preserve similarity with aFFR, four price groups were created from the available data. This grouping of prices resulted in less competition on price levels but secured a symmetrical system.

Second, ideal would be to have available historical volumes per ROP bid. Available data was limited to the sum of the bid volumes. A similar relationship (exponential) as aFRR was assumed for these volume levels, resulting in the steps shown in Table 3. This appointing resulted in a simplified system due to a smaller number of bidders.

Table 3: Four types of redispatch bids, valid for up- and down-regulation

Price Level	*Offered Volume (MW)*	*Offer Price (€/MWh)*
A	15% of total	100
B	22.5% of total	200
C	22.5% of total	300
D	40% of total	500

Nevertheless, data from April 2024 has been used in this research to comply with the other datasets. The total volume of upward and downward ROP capacity is visualized in Figure 8 and Figure 9 respectively. An opposite observation can be seen here; downward volumes lack behind upward volumes. There is an average of 1515 MW of upward capacity and only 545 MW downward capacity available. This is the total opposite ratio as with the balancing reserves. This can be explained by the fact that legislation obliges market parties with connections to the grid larger then 60 MW to always offer their flexibility [34]. Hence ROP capacity is usually offered by large traditional thermal power plants which are generally have higher marginal prices then renewables, ending up higher in the bid ladder and are therefore often not running on full capacity or are even turned off, having upward flexibility left to offer more frequent than downward capacity.

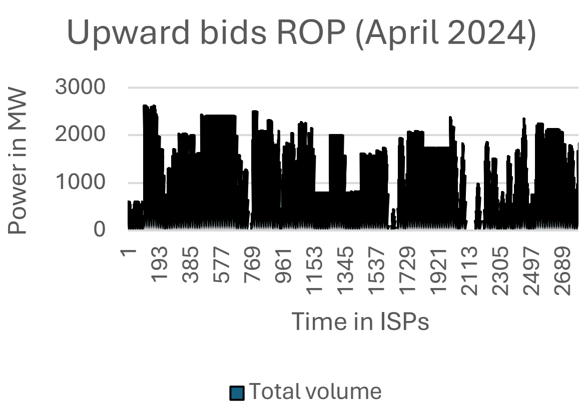

Figure 8: Upward ROP bids from April 2024

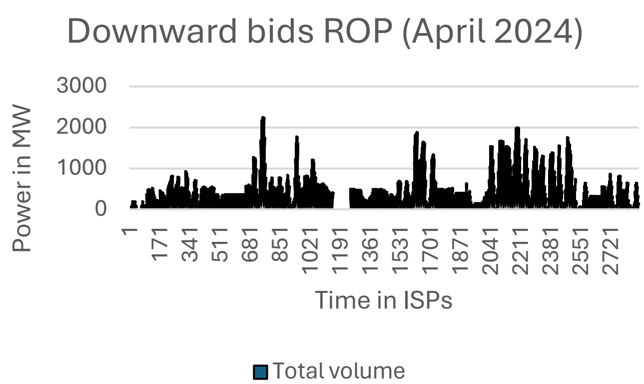

Figure 9: Downwards ROP bids from April 2024

3.3.3. Bid effectiveness

Ideal would be to have available the location of each historical individual bid. No data was available about this on aFFR nor on ROP bids. To still appoint a certain effectiveness to each bid, this was randomized appointed between -1 and +1 in a uniform way using the function RAND in Excel. This random appointed effectiveness was rated better than random appointed location, with would have involved power flow analyses utilizing laws of nature.

This has been the greatest iteration step of the study, going back from implementation to the operationalization phase. This random effectiveness resulted in a simplified system approach to achieve a simple minimal objective function.

This study is limited to four bids per flexibility product. In order to avoid that only high or low effectivities would be available in a certain price group of bids, 3 types of effectivity groups have been made. Each price level A-D is split up equally in size with an effectivity of the high, medium or low group. Effectivities were given to these group according to Table 4 below. This setup not only offers for more variation in bids, but also creates the opportunity to do experiments on volume to effectivity and price to effectivity ratios.

Table 4: Effectivity groups and their effectivities

Effectivity group	**High**	**Medium**	**Low**
Effectivity range	[-0.9 to -0.7]	[-0.6 to -0.4]	[-0.3 to -0.1]
	[0.7 to -0.9]	[0.4 to 0.6]	[0.1 to 0.3]

It should be mentioned that a bid with a high effectivity does not mean that the bid is necessarily chosen. Namely, redispatch requires both upward and downward adjustments. If a high effectivity downward adjustment is chosen, and only positive effectivities are available for upward adjustments to solve for a positive congestion problem, then the upward bid with the smallest effectivity will be chosen to form the counteraction. This is illustrated in an example in Figure 10.

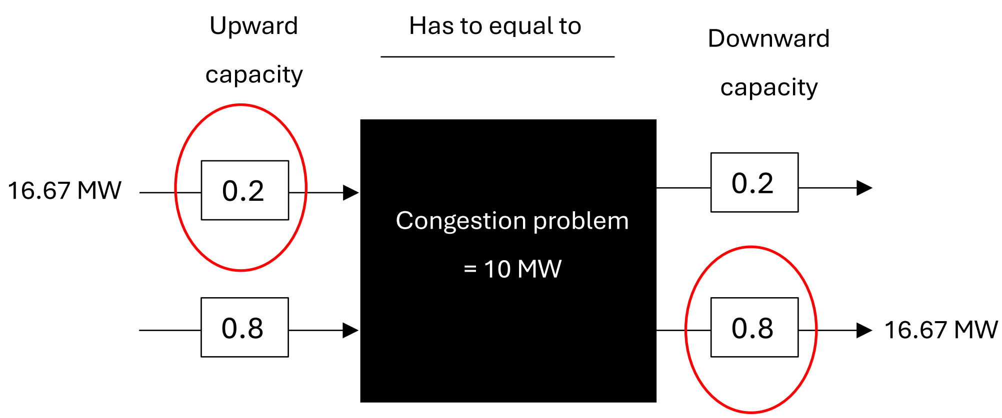

Figure 10: Example of the resulting bid evaluation process according to their effectivities

In addition, it is also not only positive effectivities that can be helpful to reduce congestion, as is illustrated by a simple example of a congestion problem shown in Figure 11. The adjustments that would solve the congestion most efficiently are indicated by a red circle. However, in practice this combination is not always available, therefore additional capacity is required to compensate as illustrated before in Figure 10.

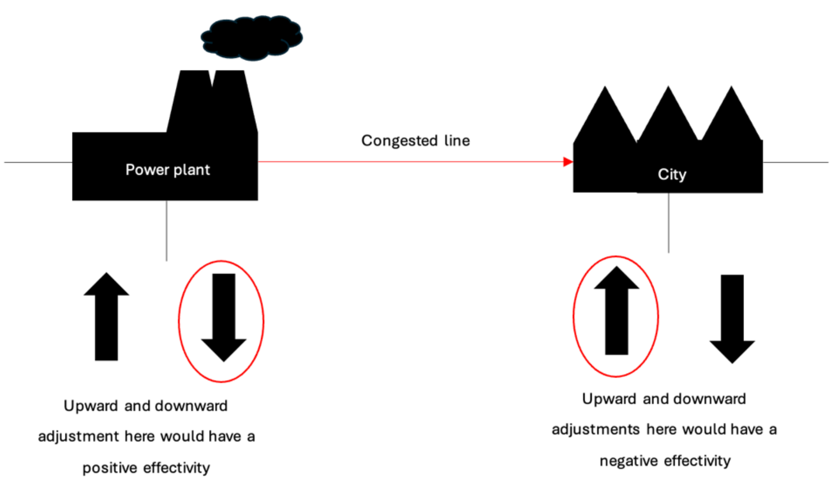

Figure 11: Both negative and positive effectivities can solve congestion

3.3.4. Imbalance

Ideal would be to have available historically measured imbalance for every 4 seconds. However, the available data was limited to historical applied aFFR capacity per minute, aggregated for upward and downward adjustments, as shown in Figure 12. To obtain a certain imbalance value, this aggregated data was used. This use of aggregated data results in less realistic volumes and costs, due to less detail of aggregated data on real fluctuations. Especially during a large number of successive upward and downward adjustments, the deviation from the real imbalance can be large.

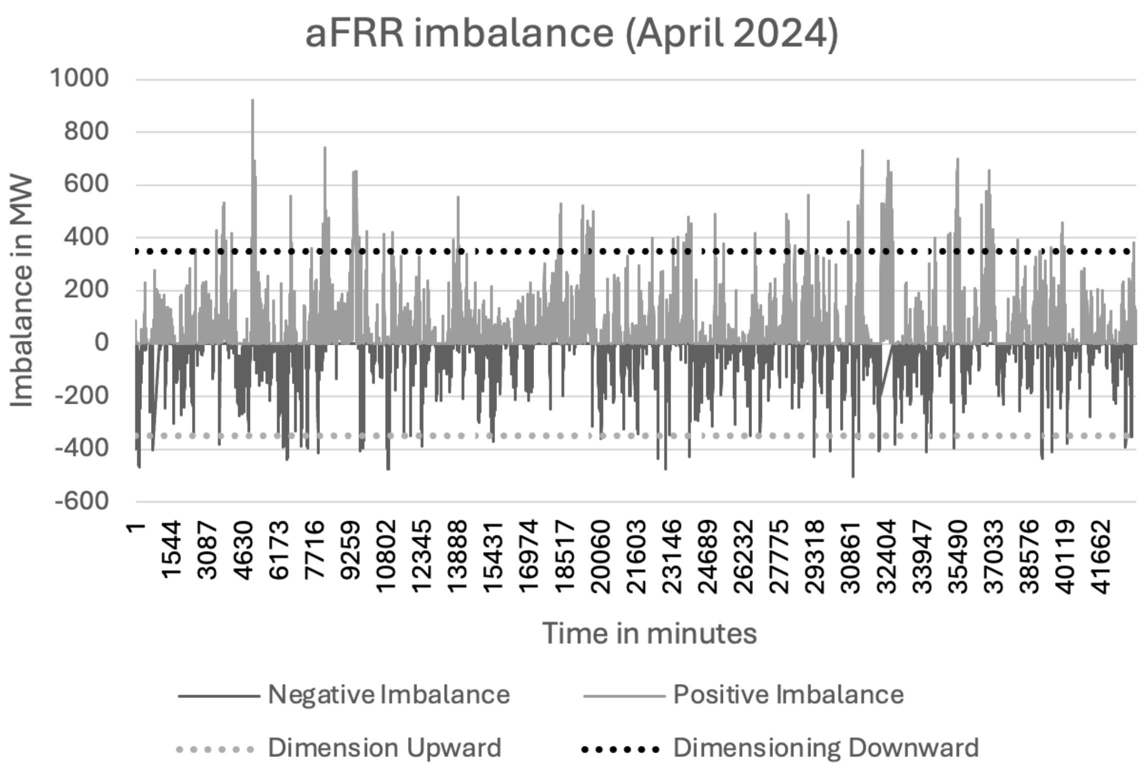

Figure 12: The aFRR imbalance data of April 2024

3.3.5. Congestion

Ideal would be to have available historical height, duration, direction and location of congestion on the electricity grid. However, available data was limited to the historical applied ROP product for up and down adjustments, without direction and location, as shown in Figure 13 below. It showed a number of accepted biddings with their average effectiveness (0,7). To still get an idea of the congestion problem, the historical deployment was divided by the average effectiveness of the historical applied biddings. This method lacks the location of the congestion, hence the approach of random appointed effectiveness and a more simplified system.

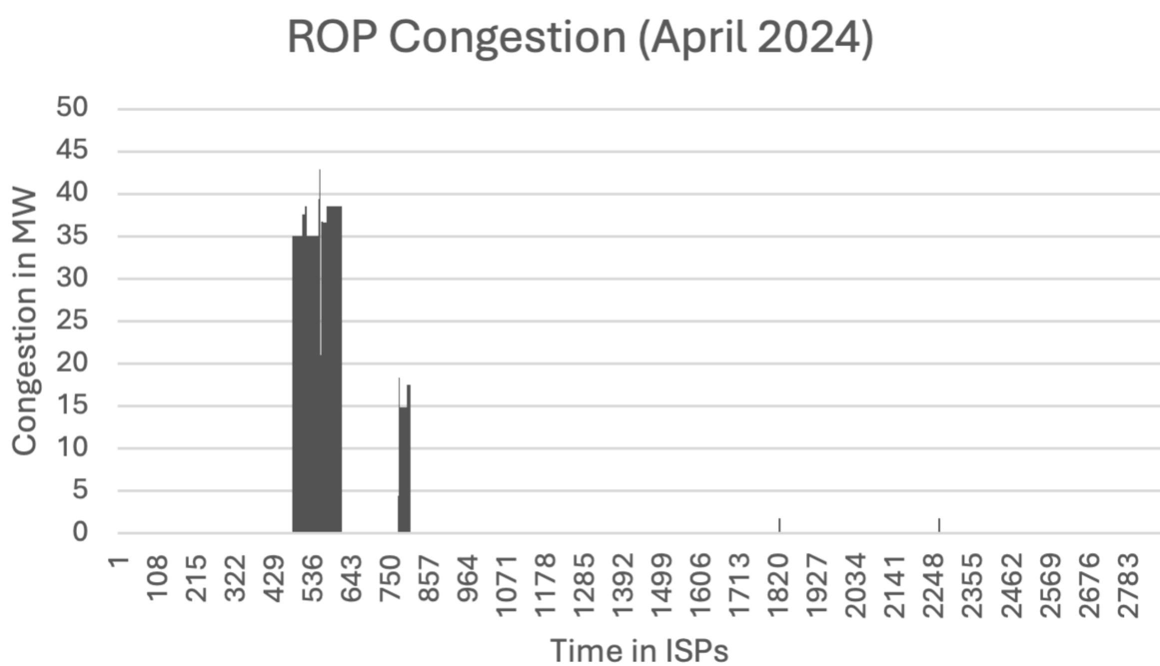

Figure 13: The ROP congestion data of April 2024

3.2 Operationalization process

The operationalization of the conceptual design involves translating the concepts and relationships introduced in the previous sections into measurable variables and equations. This translation is discussed below.

3.2.1 Flexibility reserves

The first concept of the system that should be translated are the flexibility reserves offered by BSPs and CSPs. These bids contain three pieces of information:

- The price at which they are willing to activate the flexibility which can be expressed as $P_{aFRR}(i,t)$ *and* $P_{ROP}(i,t)$ and is measured in €/MWh,
- The volume of the available reserve expressed as $V_{aFRR}(i,t)$ *and* $V_{ROP}(i,t)$ and is measured in MW,
- And the grid location of the asset that is providing the flexibility. This location is normally given as an EAN-code. However, as previously discussed, this has been simplified to the effectivities which can be expressed as $E_{aFRR}(i,t)$ *and* $E_{ROP}(i,t)$ and have no unit.

In these expressions i represents the specific bid of the BSP or CSP and t the ISP for which the bid information holds.

3.2.2 System problems

A second concept of the system entails the system problems. This can be divided into imbalance problems and congestion problems. A problem contains only one point of information:

- The size of the problem expressed as $S_{BA}(d,t_{min})$ and $S_{CM}(d,t_{ISP})$ in MW

In the BA expression d represent the direction of the problem, which can be either positive or negative. In case of BA this means that either downward or upward reserves are required respectively. The meaning of direction for CM is a bit different. It represents the direction in which the line is congested, which has a direct consequence on the effectivities of the bids. t_{min} represents the minute of time at which the imbalance problem is occurring, while t_{ISP} represents the ISP at which the congestion problem is occurring. The expression of these variables again shows the important difference in time dimension between the evaluation processes of BA and CM. The BA process in the model will evaluate 15 times more often than CM.

3.2.3 The costs

A third concept of the system are its costs. The main goal of the TSO is to solve the problems at lowest costs.

- The costs of each process can be expressed as $C_{BA}(d)$ and C_{CM} in €/min

The costs minimization of CM considers both the employment of upward and downward reserves for its solution. This is inherent to the redispatch process. In contrast, costs for BA are direction specific, specified with the letter d. Costs are optimized for negative and positive imbalance independently.

3.2.4 Emergency reserves

A special case of flexibility reserves that this study incorporates are the last resort reserves. This reserve replaces mFRRda or dialed-in reserves for ROP:

- This reserve will have a constant price P_{lt} of 10,000€/MWh
- The reserve volume can be expressed as V_{lt} and has an unlimited capacity for both the upward and downward direction

- Its effectivity E_{lt} has been randomized between -1 and 1

This reserve has constant parameters and is therefore independent of time.

3.2.5 Activated volumes

During evaluation process certain bids get activated up to a certain level of their capacity.

- This can be expressed as the activated aFRR volume $VA_{aFRR}(i,t)$ in MW
- This can be expressed as the activated ROP volume $VA_{ROP}(i,t)$ in MW
- This can be expressed as the activated emergency volume $VA_{lt}(t)$ in MW

In which i represents the specific bid of the BSP or CSP and t the time at which the bid is activated.

3.2.6 Activation duration

The offered volume is activated for a certain amount of time. This time is dependent on the period for which the problem is determined and therefore the evaluation frequency. As mentioned earlier, this is different for BA, CM and the additional lastresort reserve:

- The duration for BA can be expressed as T_{BA} and is always equal to 1/60 hour
- The duration for CM can be expressed as T_{CM} and is always equal to ¼ hour
- The duration for lastresort can be expressed as $T_{lt\ (BA)}$ and is always equal 1/60 hour
- The duration for lastresort can be expressed as $T_{lt\ (CM)}$ and is always equal to ¼ hour

3.2.7 Objective functions and constraints separated market structure

The system evaluates the problems and bids. These evaluations can be translated into objective functions, which use the variables defined in the previous sections. Three objective functions have been defined:

- Minimizing the costs of upward BA:

$$Min\ C_{BA}(neg) = \sum_{i,t}(P_{aFRR}(i,t) \cdot VA_{aFRR}(i,t)\ \cdot T_{BA}) + \sum_{t}(P_{lt} \cdot V_{lastresort}(t) \cdot T_{lt\ (BA)})$$

- Minimizing the costs of downward BA:

$$Min\ C_{BA}(pos) = \sum_{i,t}(P_{aFRR}(i,t) \cdot VA_{aFRR}(i,t) \cdot T_{BA}) + \sum_{t}((P_{lt} \cdot V_{lastresort}(t) \cdot T_{lt\ (BA)})$$

- Minimizing the costs of CM (redispatch):

$$Min\ C_{CM} = \sum_{i,t}(P_{ROP}(i,t) \cdot VA_{ROP}(i,t) \cdot T_{CM} \cdot E_{ROP}(i,t)) + \sum_{t}((P_{lt} \cdot V_{lastresort}(t) \cdot T_{lt\ (CM)} \cdot E_{lastresort}(t))$$

These functions only hold for the separated market structure, since aFRR can only be used for BA and ROP can only be used for ROP. The decision variables are the sizes of the activated volumes. These objective functions are subjected to various constraints. The most important constraint is that the solution solves for the problem.

- In the case of BA this equals to the following two function:

$$S_{BA}(d, t_{min}) = \textstyle\sum_{i,t}(VA_{aFRR}(i,t))$$

- In the case of CM, the effectivity gets involved resulting in:

$$S_{CM}(d, t_{ISP}) = \textstyle\sum_{i,t}\big(VA_{aFRR}(i,t) \cdot E_{ROP}(t)\big)$$

A second constraint in the system requires that the total upward activated volumes must equal the total downward activated volumes in the case of CM. This balance is necessary for the redispatch process to prevent creating additional imbalances. In practice, this balance is not always perfectly maintained due to slight variations in ramp rates between upward and downward delivering assets. However, the latter has been neglected in the model, to avoid the need of more complex model structures. The condition can be expressed as:

$$\sum_{i,t}(VA_{ROP}(i,t)) = 0$$

3.3.8. Objective functions and constraints integrated market structure

The previous functions and constraints only hold when the system operates with the current separated market structure. Combining the products into an integrated market structure will lead to different functions and constraints. To form these, some additional variables have to be introduced.

As mentioned in the conceptualization, an integrated market structure will have to deal with the timing difference between CM and BA. To avoid flexibility is used twice, the leftover available capacity has to be calculated after the execution of CM. This can be expressed as:

$$VA_{aFRR}(i,t) - V_{aFRR}(i,t) = V_{aFRR_{left}}(i,t)$$

for BA and

$$VA_{ROP}(i,t) - V_{ROP}(i,t) = V_{ROP\_left}(i,t)$$

for CM.

Additionally, a variable must be introduced that expresses the level of activation of this leftover capacity during BA.

$$AV_{aFRR\_left}(i,t)$$

for aFRR and

$$AV_{ROP\_left}(i,t)$$

for ROP. Accordingly, the objective functions can be realized:

- Minimizing the costs of upward balancing

$$Min\ C_{BA}(neg) = \sum_{i,t}(P_{aFRR}(i,t) \cdot VA_{aFRR\_left}(i,t)\ \cdot T_{BA}) + \sum_{t}((P_{lt} \cdot V_{lt}(t) \cdot T_{lt\ (BA)}) + \sum_{i,t}(P_{ROP}(i,t) \cdot VA_{ROP\_left}(i,t)\ \cdot T_{BA})$$

- Minimizing the costs of downward balancing

$$Min\ C_{BA}(pos) = \sum_{i,t}(P_{aFRR}(i,t) \cdot VA_{aFRR\_left}(i,t)\ \cdot T_{BA}) + \sum_{t}((P_{lt} \cdot V_{lt}(t) \cdot T_{lt\ (BA)}) + \sum_{i,t}(P_{ROP}(i,t) \cdot VA_{ROP\_left}(i,t)\ \cdot T_{BA})$$

- Minimizing the costs of congestion management (redispatch)

$$Min\ C_{CM} = \sum_{i,t}(P_{ROP}(i,t) \cdot VA_{ROP\_left}(i,t) \cdot T_{CM} \cdot E_{ROP}(t)) + \sum_{t}(P_{lt} \cdot V_{lt}(t) \cdot T_{lt\ (CM)} \cdot E_{lt}(i,t)) + \sum_{i,t}(P_{aFRR}(i,t) \cdot VA_{aFRR\_left}(i,t)\ \cdot T_{CM} \cdot E_{aFRR}(i,t))$$

The constraints have also been adjusted. The first constraint has been modified to:

- In the case of BA this equals to the following two function:

$$S_{BA}(d, t_{min}) = \sum_{i,t} \left(VA_{aFRR\_leftover}(i,t) \right) + \sum_{i,t} \left(VA_{ROP\_leftover}(i,t) \right)$$

- In the case of CM, the effectivity gets involved resulting in:

$$S_{CM}(d, t_{ISP}) = \sum_{i,t} (VA_{ROP}(i,t) \cdot E_{ROP}(t)) + \sum_{i,t} (VA_{aFRR}(i,t) \cdot E_{aFRR}(t))$$

The second constraint results in:

$$\sum_{i,t} (VA_{ROP}(i,t)) + \sum_{i,t} (VA_{aFRR}(i,t)) = 0$$

Additionally, a third constraint will be required in this market structure. This constraint makes sure that CM is limited in its consumption of reserves up to the required dimensioning level required by law for BA, which is equal to 350 MW.

$$\sum_{i,t} (VA_{ROP}(i,t)) + \sum_{i,t} (VA_{aFRR}(i,t)) < 350\ MW$$

3.4 Implementation phase

The third step of the modelling cycle is the translation of these variables and formulas into a computational model. To this end, this section will introduce the modelling tool that has been used and explain the model as a result from this phase.

3.4.1 The modelling tool

For this thesis the modelling tool Linny-R has been used. Linny-R is an executable graphical specification language for mixed-integer linear programming problems (MILP), particularly Unit Commitment (UC) problems [28]. Linny-R was useful for this research due to the following reasons:

1. Linny-R can optimally dispatch energy systems
2. MILP allows to include variables that change for each timestep. This is advantageous in this study since imbalance, congestion and offered flexibility vary for each timestep.
3. Linny-R provides the option to work with experiments, which can be useful to deal with potential uncertainty in data.
4. Linny-R offers a graphical programming approach, making it relatively easy to use by someone with limited programming skills.

However, Linny-R is still under development and therefore some new features have not been undergone extensive testing. In addition, a comprehensive and clear guide is still not available. To overcome these limitations, Pieter Bots (the developer of this software) provided extensive guidance during the modelling process in case something was unclear or not working.

3.4.2 Settings of the models

For each model in Linny-r different settings can be chosen that influence the outcome of a simulation. Important settings for this research included the timestep and the amount of optimization timesteps.

- **A timestep** of one minute has been taken for the model. Meaning that processes are optimized for every minute. This came in handy for the optimization of the BA problem, since imbalance data was provided per minute. However, congestion, as mentioned earlier, is optimized for every 15 minutes. To accommodate this, Linny-R provides a setting to restrict processes to take decisions only once every N timesteps. In this N case was put at 15 for CM.

- **The model is run** with 5 days of data from the 5th up to 10th of April 2024. As a result, the optimization period was set from timestep 5761 to 12960, requiring that one day consists of 1440 minutes.

3.4.3 Working principles of Linny-R

A model in Linny-R can be constructed from 4 type of building blocks: products, processes, links and clusters [11]. Below is a brief overview of what each building block entails and how they have been used in the model:

- **Products** are units that represent raw materials or finished products and are represented by ovals. A special form is the data product, which does not represent a physical entity, but serves purely form as an information point or limiting factor. A data product is marked by dotted edges. In this research mostly data products have been used, representing prices of bids, system problem goals and various summations.

- **Processes** take products and convert them into other products, visualized by rectangles in a model. This research uses processes to represent the bid utilization process by the TSO, deciding the level of activation of flexibility services. These processes therefore have upper and lower bounds. In addition, processes are used to represent the measurement and expectation of system problems.

- **Links** are the connections between products and processes and can indicate the direction, efficiency or condition to the flow. In the model proposed here, the effectivities for redispatch have been placed as rates on the links between reserves and congestion problems.

- **Clusters** in Linny-R are purely for organizational means, indicated by a large square. Parts of model consisting of products, processes and links can be placed in a cluster to provide a clearer overview. Clusters have been extensively used in the model to group the various bid and process categories (A-D & aFRR-ROP).

3.4.4 The model mechanism and structure

The building blocks previously mentioned have been used to build a model in Linny-R. All graphical parts of the model will be discussed below. In addition, it will be shown how the two market structures, separated and integrated, are implemented in the model.

3.4.4.1 Top-level model

The top-level model shown in Figure 14 illustrates the two evaluation systems for BA with aFRR and CM with ROP (which is called redispatch here, since that is the actual function of ROP). The model is based on a system of rounds in which each actor (redispatch and balancing) can change the levels of its processes. Two rounds A and B alternate for each one-minute timestep. Redispatch can change its levels in round A, while balancing is frozen. Then balancing can evaluate in round B and redispatch is frozen. However, this balancing round has to take into account the results of round A. Additionally, in the model normal conditions are assumed for balancing, in which the ramp rates of the various bids are no activation parameters or constraints within the system. This assumption is justifiable because the imbalance used refers to the historic aFRR activations.

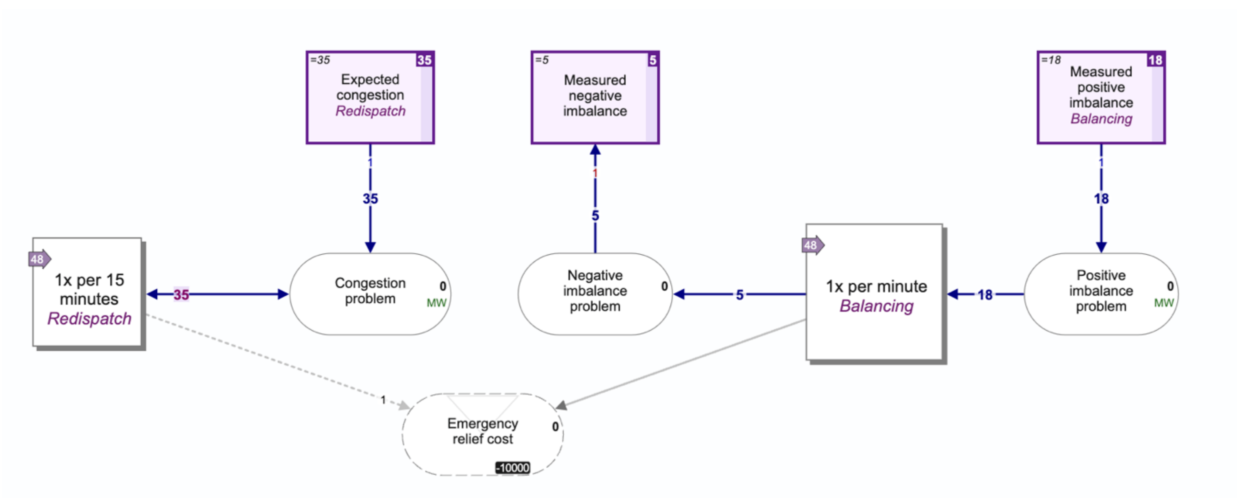

Figure 14: Top-level model, showing both the BA and CM processes

Redispatch is placed on the left, changing its decisions only once every 15 minutes. It's doubly linked with the congestion problem, implying that upward (feeding) and downward (withdrawing) reserves are required to solve. In turn the congestion problem is linked to the expected congestion, which holds the dataset for historic congestion. The BA process can be seen on the right side and is connected to a negative and positive imbalance. The BA system updates every minute, according to the datasets held by the measured imbalance.

Both the redispatch and balancing cluster use the same emergency relief product, ensuring the model will always run.

3.4.4.2 The redispatch evaluation process

Clicking on the redispatch cluster will lead to the level shown in Figure 15. Here the various flexibility clusters are provided and connected to the congestion problem on the right. These clusters contain all the bids (divided among the four price levels) provided for each product. On the left the total consumption of upward and downward bids is calculated and constrained to zero. This is necessary to ensure that redispatch does not create additional imbalance. Finally, the emergency relief process for redispatch is shown, which is an unlimited resource of downward capacity for an extremely high price. This high price ensures that it will only be used when the ROP or aFRR are actually insufficient in capacity.

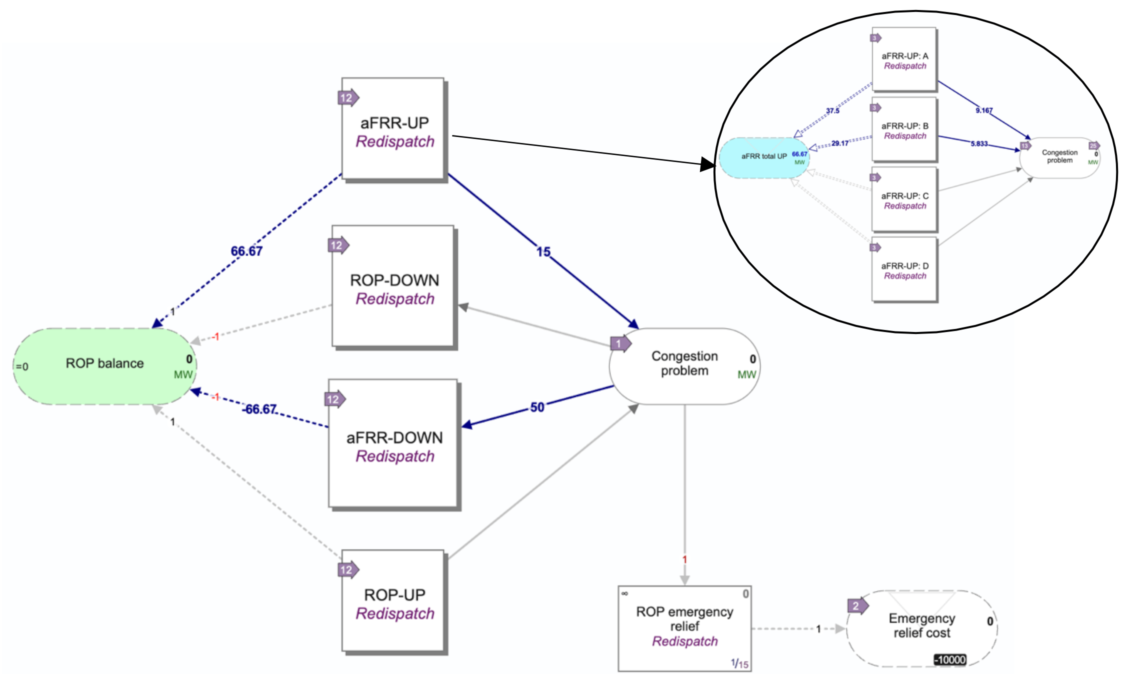

Figure 15: Inside the redispatch cluster

3.4.4.3 Utilization of redispatch bids

Two levels deeper in the model and the actual activation of bids can be seen, as shown in Figure 16. On the right the effectivities can be seen as rates on the links between the bid utilization processes and the congestion problem. In addition, the frequency at which these processes can change their decision is shown here, indicated by the 1/15 on the right bottom corner.

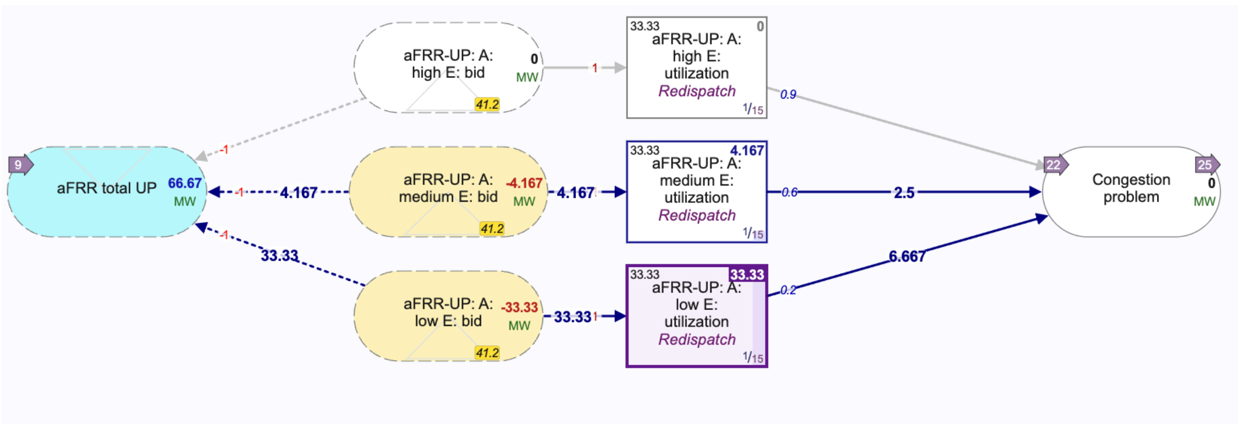

Figure 16: Utilization of bids for redispatch

3.4.4.4 The balancing process

Zooming back out to the top-level model and going into the cluster of the balancing process, the structure shown in Figure 17 can be seen. Upward reserves are connected to the negative imbalance problem, while downward reserves are connected to the positive imbalance problems. Clicking on these reserve clusters will again lead to the various bid groups as shown below.

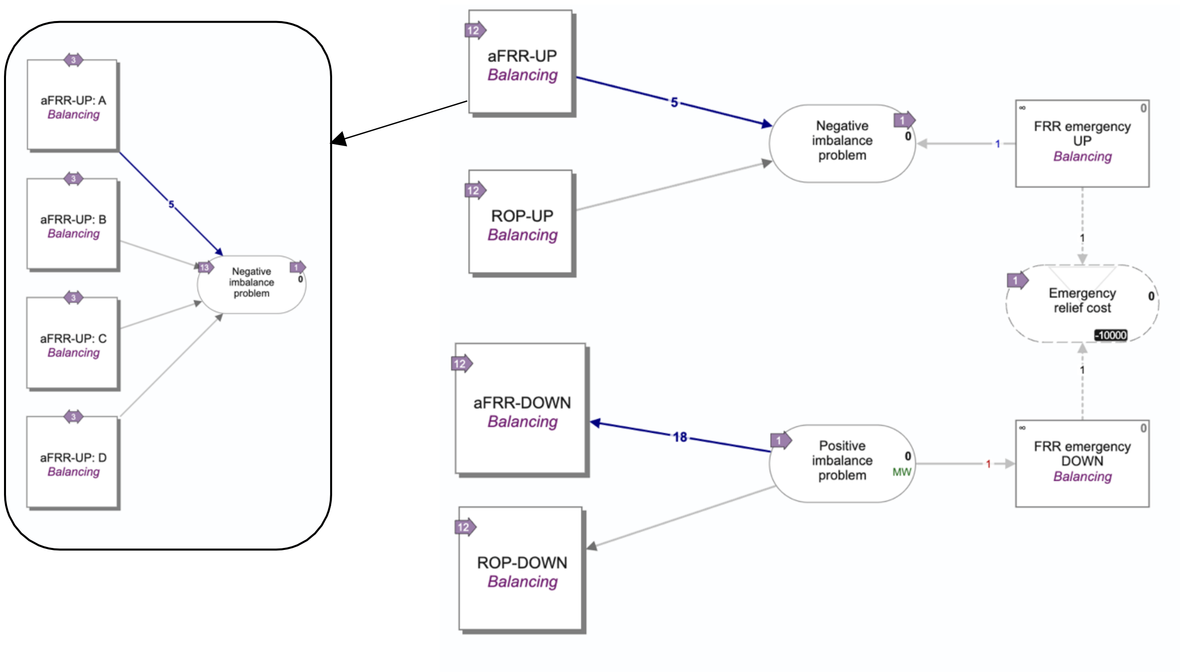

Figure 17: Inside the balancing cluster

3.4.4.5 Utilization of balancing bids

The deepest level of the balancing side of the model will lead to the utilization process of the balancing bids as shown in Figure 18. This is a bit different from the redispatch side, since a structure had to build in place to consider the results of the redispatch round. The volume bid product is referring to the dataset. The bid product is the same product as shown in Figure 19. If something is consumed from this bid it will get a negative value and together with the volume bid, this will lead to the availability product, representing the left-over to be used by the balancing round.

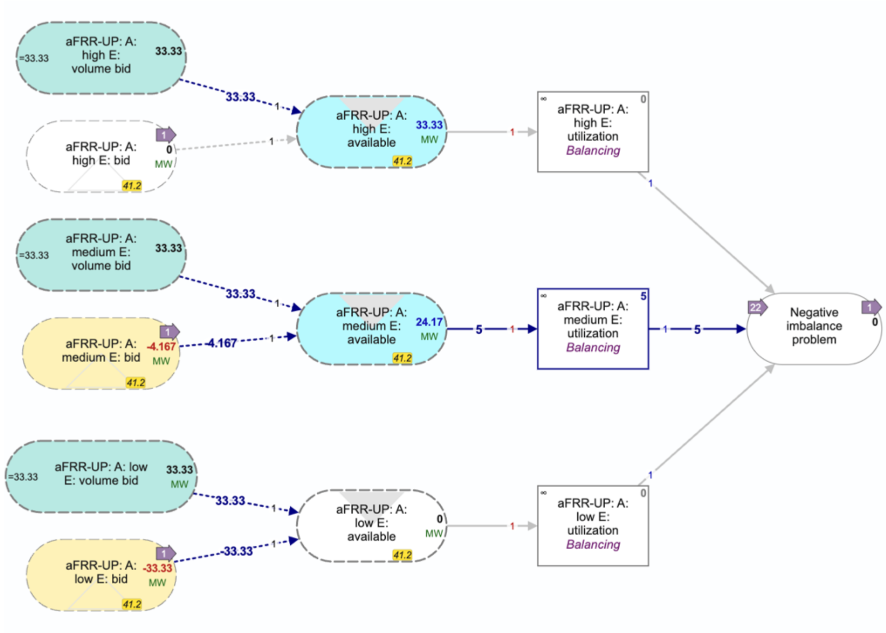

Figure 18: Utilization of bids for balancing

3.4.4.6 Implementing the two market structures

The model structure discussed above represent the concept of an integrated market structure as explained in the operationalization phase. To accommodate a simulation of the separated market structure the connection between aFRR with CM and ROP with BA has to be removed. This can be done model by turning off the reserves in the respective evaluation processes, resulting in Figure 19.

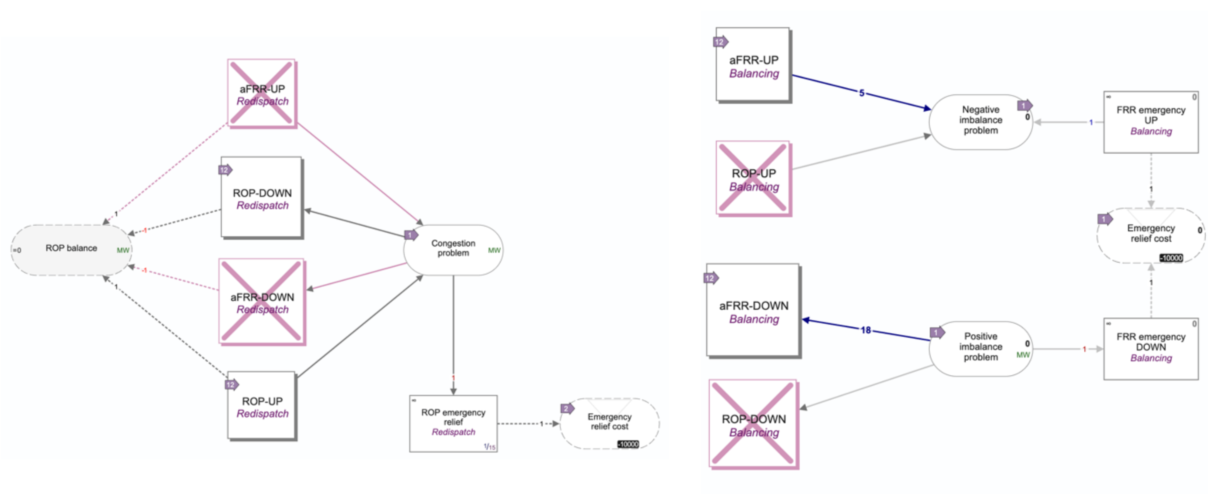

Figure 19: ROP bids for balancing and aFRR bids for redispatch are ignored in separate mode

3.4.5 Model validations

The validation of a model is a crucial step to ensure its accuracy in representing the system under consideration. Without proper validation, a model can lead to incorrect conclusions and inefficient processes, compromising the quality of insights and actions derived from them. To this end, this chapter will present a validation process based on the logical choices that it is expected to be made following from the lowest price objective used by TSO's. An empirical validation was not possible due to the lack in historical data.

3.4.5.1 Validation of balancing

In Figure 24, the activated reserves (y-axis) are plotted against the positive imbalance (x-axis) over a 5.5-hour period from the model's results. The different colors represent various types of reserves, stacked in the graph. Although the legend is incomplete, two key observations can be made that validate the model's functionality.

Firstly, when a positive imbalance occurs, one would expect the system to activate an equal number of reserves to offset this imbalance. Looking at Figure 20, we indeed see that this happens: the total amount of activated reserves exactly matches the level of imbalance but is mirrored along the x-axis. This confirms that the model correctly activates reserves to restore balance in the grid.

Secondly, one would expect that the lowest-cost reserves are activated first. In the graph, we observe that price-level A reserves from aFRR are consistently activated first, as expected. As the demand for reserves increases, more expensive reserves, such as price-level A from ROP, are activated later. This is evident in periods where price levels A and B from aFRR are cheaper than those from ROP, explaining why these reserves are prioritized.

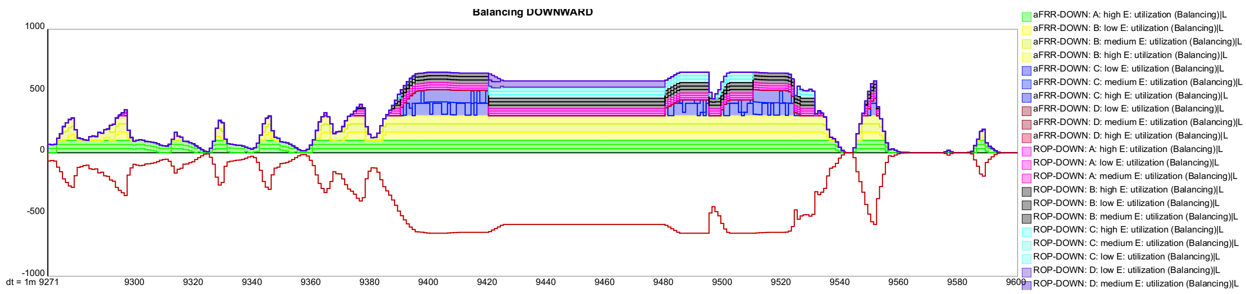

Figure 20: Activated reserves against positive imbalance (y-axis in MW)

A similar result is observed when addressing a negative imbalance, as illustrated in Figure 21. The same principles apply here: the total volume of activated reserves aligns with the negative imbalance, mirrored along the x-axis, confirming that the model effectively balances the system.

Additionally, the graph demonstrates that the lowest-cost reserves are activated first. Just as with the positive imbalance scenario, the reserves with the lowest price are prioritized, and more expensive reserves are activated only as needed. This confirms that the model optimally uses reserves based on cost-efficiency, maintaining consistent application of the economic dispatch principles.

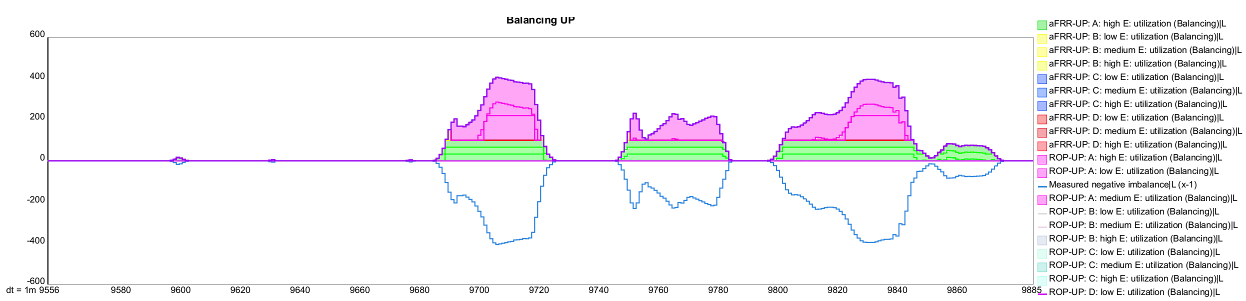

Figure 21: Activated reserves against negative imbalance (y-axis in MW)

3.4.5.2 Validation of congestion management (redispatch)

The validation of the redispatch part of the model is quite a bit harder due the interference of effectivities of reserves next to their price characteristic. Choosing the bids with the lowest price would not necessarily mean that the total solution is lowest. To this extend two graphs have been made to investigate the models' choices for redispatch. The first graph is presented in Figure 22, showing a similar chart as provided for positive balancing. In all cases the lowest priced bids were still taken first. This is because of the even distribution of effectivities among price-levels. The legend is incomplete, but in blue is price level A of aFRR reserves and the orange line is the congestion level multiplied by -1.

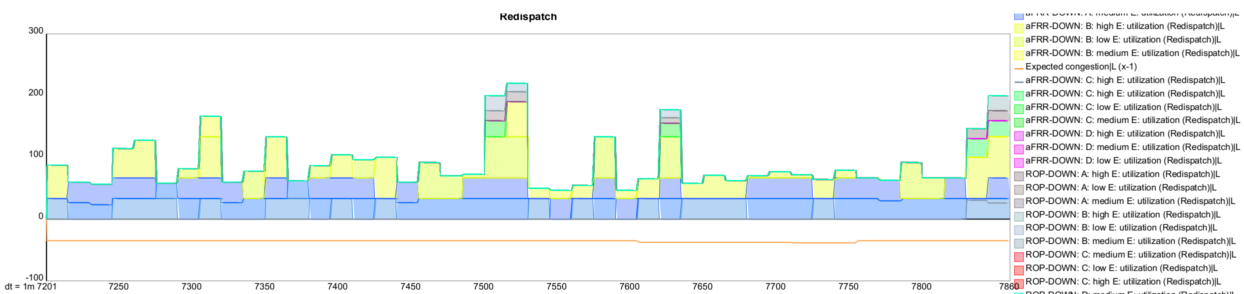

Figure 22: Activated downward reserves for redispatch (y-axis in MW)

The second graph is bit more complicated and is shown in Figure 23. It presents the same reserves but now stacked together per effectivity type. In addition, three different lines can be seen, which are the actual effectivities of each group multiplied by 100 for better visibility. In black the high effectivity, in pink the medium one, and in green the low effectivity. From this graph, containing downward reserves, a logical set of choices can be seen. The reserves with low effectivity are only used when the high effectivity is negative. Using downward reserves with high negativity would not be expected, since this would only increase the congestion problem. Together with the first graph it can therefore be seen that those reserves are taken that lead to the best economical solution, as demanded from the objective functions given.

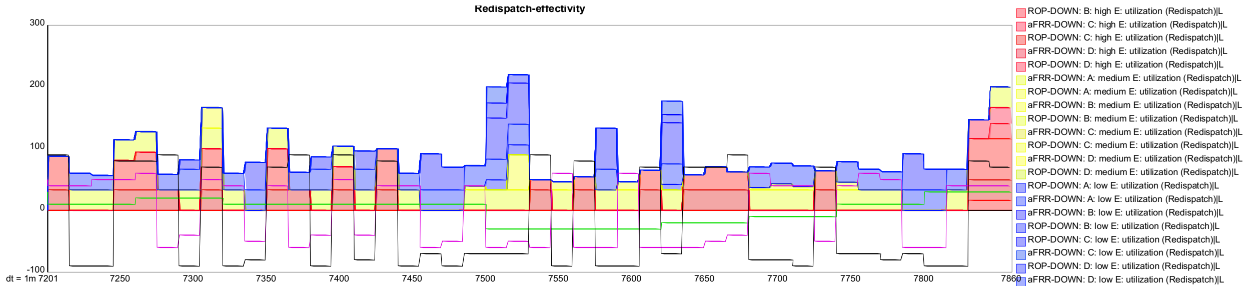

Figure 23: Activated downward reserves stacked per effectivity group (y-axis in MW)

4. Results

The results of the simulation including the outcomes of the experiments are discussed in this chapter. First the overall results will be presented. Consequently, each specific KPI is discussed in more detail with the help of a graph. The graphs in this section are showing the difference in results between the separated market structure and integrated market structure, unless otherwise stated.

4.1. Overall results

The simulations show a significant improvement in operational performance. Economically, both the BA and CM costs have been reduced under the integrated structure by 70% and 83% respectively, as shown in Table 5 below. Technically, the integrated structure eliminates initial system failures and significantly boosts problem-solving capacity. The latter is particularly visible in the upward balancing direction, which shows a capacity increase of over 360%. The system showed only a modest 11% increase in CM capacity usage. Which is an interesting fact, considering that more bids with various effectivities became available under the integrated design. However, this can be explained by the extremely low-priced aFRR bids, which outweighed the benefits of more effective bids.

Table 5: Overall results

		Separate market structure				Integrated market structure				Difference
Key performance indicators	**Unit**	**Min**	**Max**	**σ**	**μ**	**Min**	**Max**	**σ**	**μ**	**μ (%)**
BA costs	€/min	-148	16225	2172	589	-63	792	163	177	-70
CM costs	€/min	0	7539	882	561	0	534	107	95	-83
Total costs	€/min	-148	16225	2142	763	-63	792	158	73	-90
Frequency of BA failures	%	N.A.	N.A.	N.A.	1.6	N.A.	N.A.	N.A.	0	-100
Frequency of CM failures	%	N.A.	N.A.	N.A.	0.21	N.A.	N.A.	N.A.	0	-100
Upward solving capacity BA	MW/min	350	1648	276	526	350	3979	769	2451	366
Downward solving capacity BA	MW/min	451	1884	432	1083	21	2931	526	1628	50
Solving capacity CM	MW/ISP	0	600	114	184	0	1300	265	550	198
CM reserves used	MW/min	0	117	23	13.4	0	108	25	14.8	11

4.3. Economic performance

4.3.8. Balancing costs

The difference in balancing costs has been calculated based on the marginal pricing method as explained in section 2.5. The result is shown in Figure 24. A positive y-value indicates a net profit when using the integrated market structure. From the graph, mostly large positive values can be seen, the costs of BA decrease for the TSO. This can be explained by the increased volume of cheap bids available to solve imbalances. In addition, it can be seen in Figure 24 that the balancing costs only increase when a congestion problem is solved simultaneously, which is approximately between t = 1600 and t = 3300. The priority of redispatch resulted in less capacity of the lowest price levels for balancing measures.

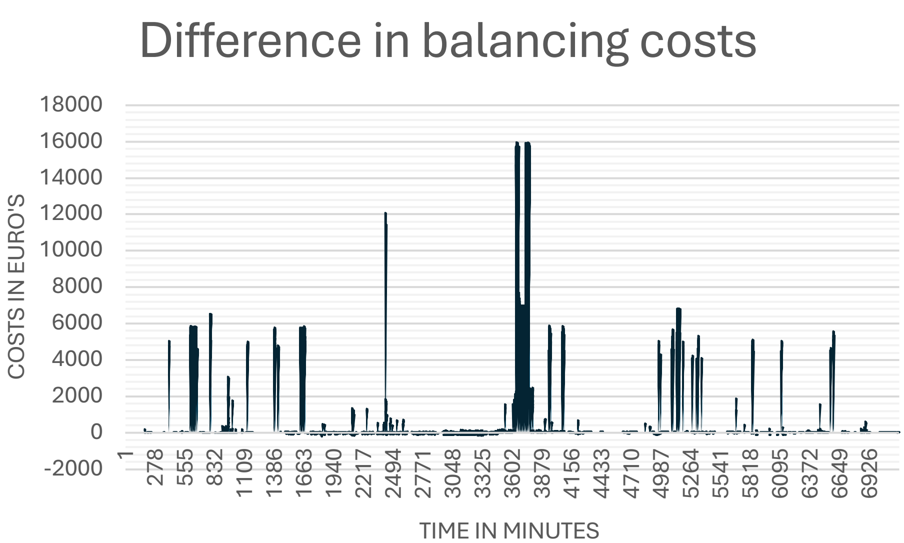

Figure 24: Difference in balancing cost between the separated and integrated market structure

4.3.9. Redispatch costs

A similar trend can be seen when looking at the redispatch costs, presented in Figure 25. The costs for a TSO for managing congestion decrease under an integrated market structure. The overall decrease in costs can be explained by the large volume of cheap aFRR bids. The CM costs reduced with about 83% when running the evaluation under the integrated market structure.

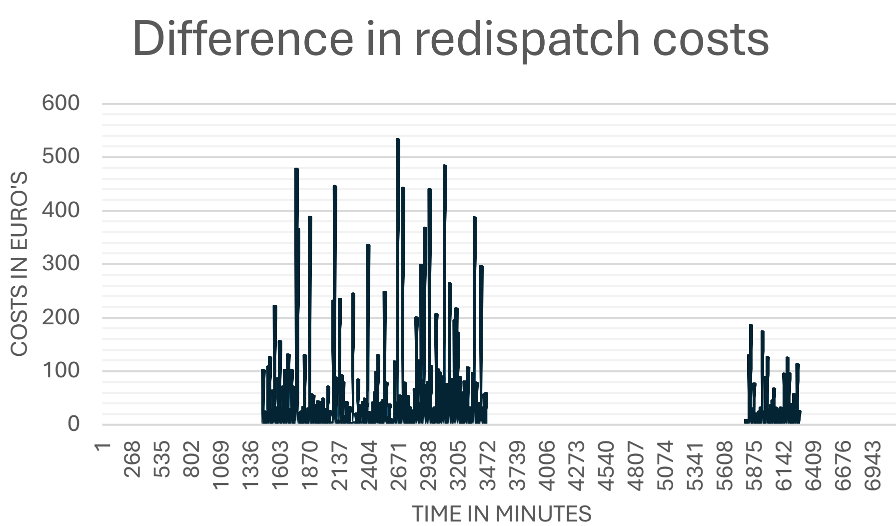

Figure 25: Difference in redispatch cost between the separated and integrated market structure

4.3.10. Total costs

In the final graph on costs the total difference is presented, see Figure 26. An overall net decrease in costs can be seen. The increase in balancing costs during congestion have been compensated by a greater decrease in redispatch costs during this congestion. Only around timestep 2244 a net decrease is spotted, resembling an event with both a congestion of 35 MW and a relatively high positive imbalance of over 320 MW.

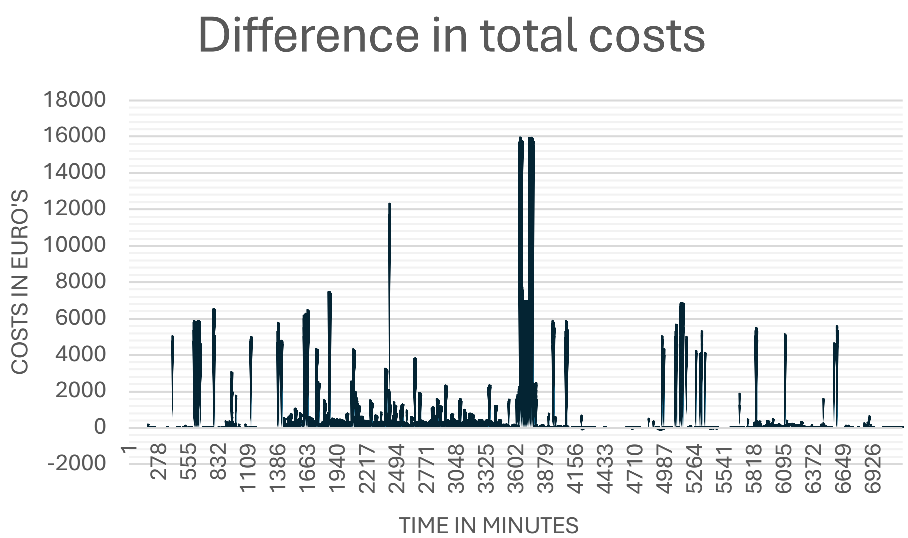

Figure 26: Difference in total cost between the separated and integrated market structure

4.4. Technical performance

4.4.8. The frequency of system failures

The frequency of system failures is a direct indication of the systems technical performance. Only a few timesteps resulted in a system failure as shown in Figure 27. However, those of BA should not have happened, as this study used historic aFRR activation as the imbalance level, meaning that historically there was sufficient aFRR capacity. Nevertheless, all shortages causing the system to fail in the separate system have been solved under the integrated structure. It is clear that a flexible reserve under an integrated market results in less frequent system failures compared to the current system, due to the ability of interchangeable use of capacity.

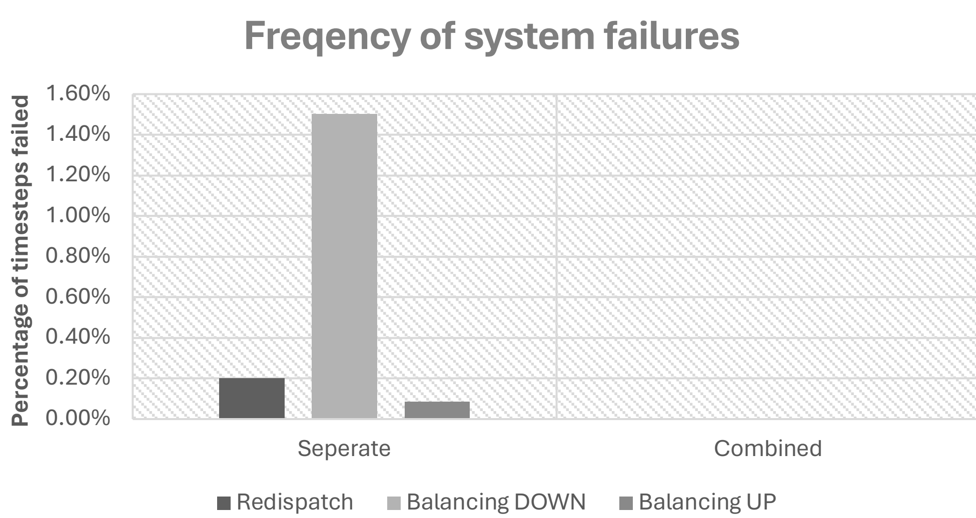

Figure 27: The frequency of system failures of the system under the two market structures

4.4.9. The solving capacity

By combining the reserves of aFRR and ROP a new pool of bids is created. This can influence the power to solve imbalance and congestion problems: the solving capacity. As explained in section 2.5. the solving capacity of BA equals the amount of available reserve directly. This can split into upward and downward volumes. Under the separated market structure this equals the amount of aFRR reserves. And under the integrated design this equals the number of reserves left for BA, consisting of aFRR and ROP reserves.

The average solving capacity for BA increased by an average of 366% for the ability to solve negative imbalance and by 50% to solve positive imbalance. The extreme difference in the upward direction is caused due to the high amount upward ROP capacity available in the integrated market. This increase is so big, it totally changed the balance between upward and downward solving capacities. Now more upward capacity then downward capacity is available, averaging at 2450 MW and 1627 MW respectively.

The integration of flexibility markets also has an increasing effect on the solving capacity of congestion management. In Figure 28 this capacity is shown for the current separated design, while in Figure 29 this is shown for the integrated market structure. The average solving capacity (indicated by the orange lines) has more than doubled (550 MW versus 190 MW). There is one moment during the 5 days of data no upward ROP was available, hence no congestion can be solved, which can be seen in both graphs around ISP 365.

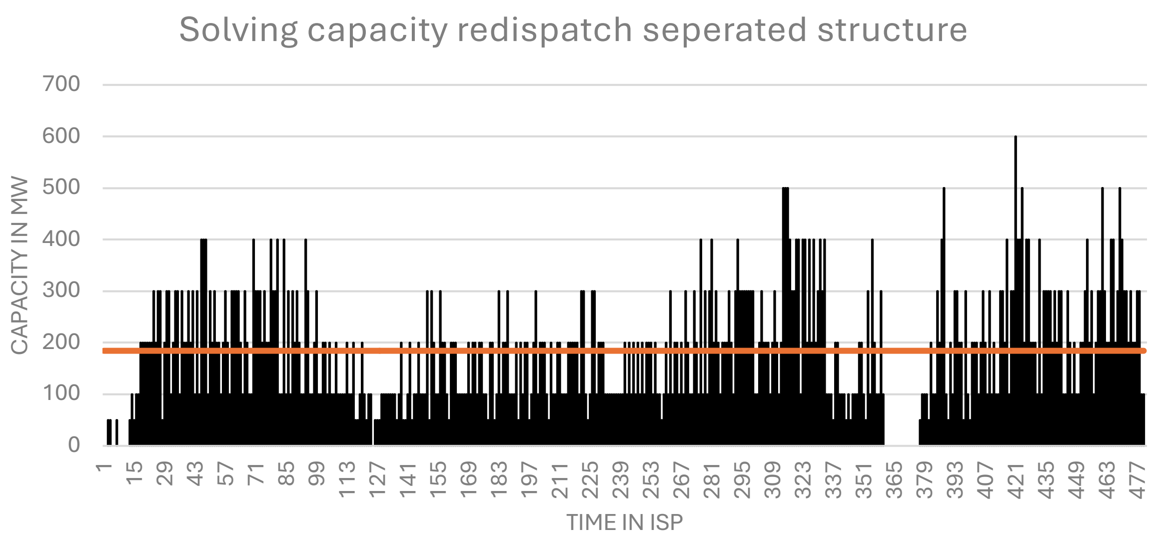

Figure 28: Solving capacity of redispatch under the separated market structure

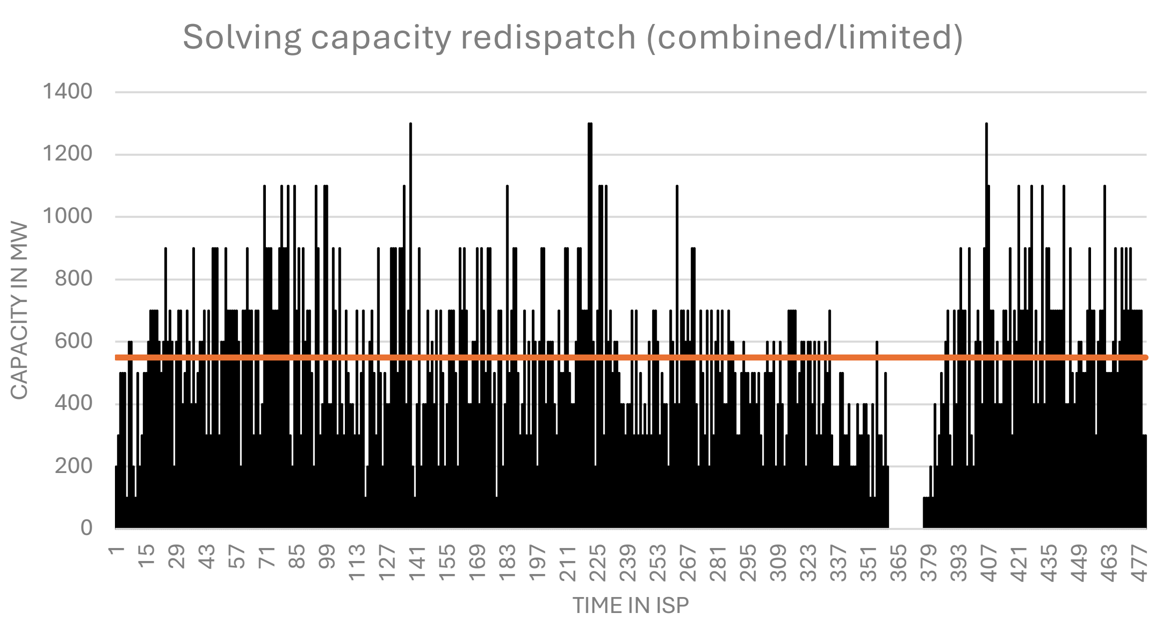

Figure 29: Solving capacity of redispatch under an integrated market structure

4.4.10. The consumption of reserves during redispatch

When both the ROP and aFRR products are combined in one bid ladder the availability of bids increases. This allows for different combinations to be made during the management of congestion. Figure 30 shows the effect of this change on the consumption of reserves during redispatch. On average, an increase in capacity is seen at most of moments. This can again be explained by the lower cost of the aFRR bids. Although more reserves with different effectivities become available, the significant lower cost of aFRR allows the system for finding better economic solutions in some cases, while increasing the capacity that is used to perform the action.

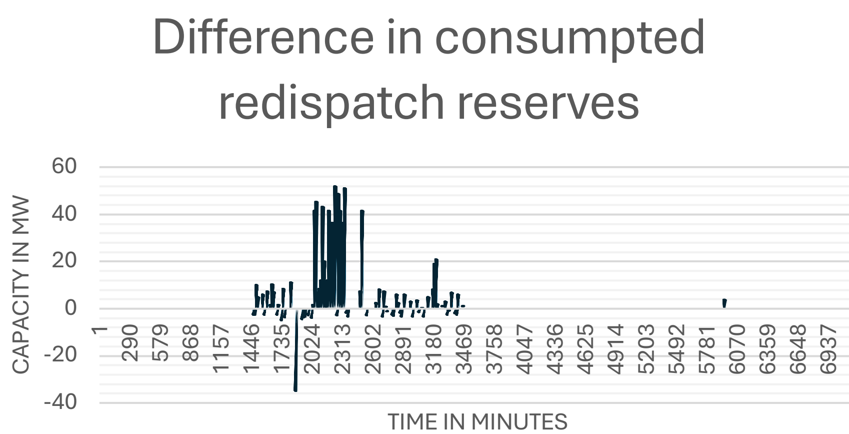

Figure 30: Consumed reserves for redispatch

4.6. Additional experiments

In addition to the main experiment presented in the foregoing, two supplementary experiments were conducted. These experiments were aimed to evaluate an uncertainty in the dataset and a change in system setting. The uncertainty concerned the interchangeability of reserves. The system setting was related to the dimensioning level.

4.6.1. Interchangeability

The first set of extra experiments examines the interchangeability of the capacity currently offered through the ROP product. The main experiment assumed that all ROP capacity under the separate market structure is fully available in the integrated design, with 100% interchangeability. It is thereby assumed that this capacity can meet the fast response rates required by the aFRR product in the combined design.

However, current ROP capacity is mostly offered by parties with connections larger then 60 MW. In practice this mainly entails large thermal power plants. It is well known that thermal power plants, cannot react quickly to demand changes due to mechanical inertia and combustion processes [35]. Therefore, in reality, the interchangeability of ROP capacity can be lower than 100%. And because this study assumes that the capacity supplied in the integrated market must be fully interchangeable, the overall pool of bids would be reduced. To examine the effect of this expectation 5 steps have been formed to measure the consequences gradually, which are shown in Table 6.

Table 6: The interchangeability experiment setup

Experiment names	Interchangeability level
No flex	0%
Low flex	25%
Medium flex	50%
Almost flex	75%
Full flex	100%

This issue is unlikely to affect aFRR capacity, as it already meets the quick response requirements. Using it for redispatch would simply provide additional time, which should not present any issues. However, whether the current aFRR capacity will continue to be offered in the integrated market will also depend on other factors, such as the compensation structure, which were not considered in this study.

The results of this experiment are presented Table 7. Only the problem-solving capacity were recorded, the scope was constrained by the project's time limitations. The increase in capacity for solving negative imbalance is more than the capacity for positive imbalances. This is caused due to the high amount upward ROP capacity now available in the flexible reserve product. This increase is so big, it totally changed the balance between upward and downward solving capacities. Now more upward capacity then downward capacity is available, averaging at 2450 MW and 1627 MW respectively. Only when no ROP capacity is offered into the flexible reserve product the solving capacity decreases, because aFRR than has to solve both congestion and imbalance.

Table 7: The difference in average balancing solving capacities in MW

Interchangeability level	Average solving capacity negative-BA	Average solving capacity positive-BA
No flex	-14	-15
Low flex	471	125
Medium flex	956	265
Almost flex	1441	405
Full flex	1926	545

4.6.1. With and without dimensioning

A second experiment that has been executed examines the effect of the changing the dimensioning requirement in the flexible reserve design. In the main experiment it is assumed that CM has to take into account the reservation requirement of BA, which is set at 350 MW for both upward and downward adjustments, called dimensioning. This implies that CM is seen as a less important function compared to BA.

However, both BA and CM are crucial for maintaining the overall stability and reliability of the power grid. One could argue that ensuring safe transport is just as important as maintaining balance. Allowing the imbalance to increase temporarily might be acceptable to prevent immediate congestion leading to physical damage to the grid infrastructure. To test this scenario, two experiments have been executed, one in which the dimensioning level is 350 MW and one without this dimensioning level to see the effect on both the technical and economical KPIs. Due to time constraints, only solving capacity and total costs have been examined.

The results are presented in Table 7 and Figure 36. Regarding costs, there is no visible effect across any one of the scenarios (Table 8). This lack of impact can be attributed to the fact that CM was never constrained by the availability of bid volume, thus not necessitating more resource-efficient choices. However, if congestion volume levels were to increase significantly, the dimensioning status would likely affect the costs, making CM more expensive and BA costs less expensive when activated.

Table 8: The effect of dimensioning on the total system costs

Interchangeability	Difference in system costs between active and non-active dimensioning
NoFlex	0
Lowflex	0
MediumFlex	0
AlmostFlex	0
FullFlex	0

The other result considers the solving capacity of redispatch (CM). When removing the dimension requirement under the integrated structure, the solving capacity increases, but only at this empty period of Figure 35. (comparison with Figure 36). This can be explained by the fact that the solving capacity was never limited by the amount of capacity available, only by the amount of 'good' capacity. Good meaning the combinations of capacities with complementary effectivities.

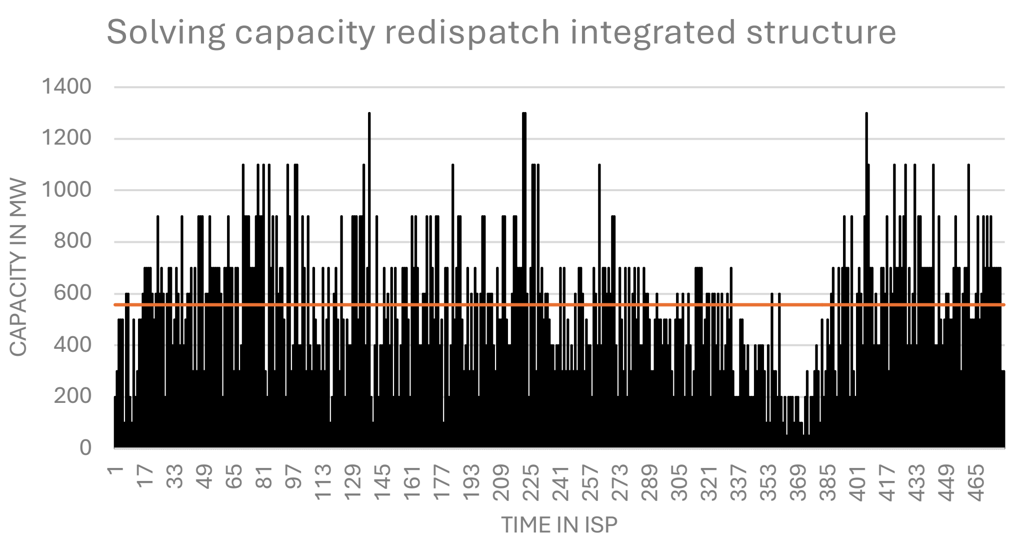

Figure 31: Solving capacity of redispatch in the combined setup without dimensioning

5. Conclusion

The integration of flexibility markets is seen as a possible solution to increase the efficient use of available flexibility. This study focused on the collection of quantative data on the operational performance of this solution in the Dutch electricity market. To achieve this goal, three sub-questions were addressed:

SQ1: Which of the current flexibility products are most suitable to be combined into an integrated market structure, considering their different characteristics?

The Dutch TSO TenneT currently utilizes three different products for balancing—FCR, aFRR, and mFRRda—and two different products for CM—ROP and CRC. Of these five products, the characteristics of aFRR, mFRRda, and ROP are the most similar. All three are activated by TenneT, the differences in response times are more plausible to overcome, their procurement timelines align closest, and they are all traded through an auction system including an energy price. FCR is challenging to integrate into the flexible product due to its different response requirements and activation methods compared to the other products. Meanwhile, CRC differs significantly in its timeline and procurement approach. By replacing aFRR, mFRRda, and ROP with the flexible reserve product, accessibility to this market will remain higher and it allows for both BA and CM to utilize the provided capacity.

SQ-2: What technical performance improvements for system operations can result from integrating flexibility markets?

The introduction of a flexible reserve product significantly enhances the technical performance of system operations. The frequency of system failures dropped to zero under the integrated market structure compared to the separated design, which experienced capacity shortages in 0.2% to 1.2%. This reduces its reliance on more expensive solutions like mFRRda or external agreements.

Furthermore, the solving capacity for imbalances significantly improved under the integrated market, particularly for negative imbalances, which almost quintupled to an average of 2450 MW in the full flexible scenario due to the substantial addition of upward ROP capacity. The solving capacity for CM also increased, with the redispatch capacity more than doubling to approximately 550 MW on average at any given moment. These increases demonstrate that a flexible reserve is more robust against potential future increases in congestion or imbalance problems.

Finally, the consumption of reserves during congestion management has overall increased unexpectedly by 11% when using an integrated structure. Although, the integrated market increases the likelihood of finding more effective bids, the results of this study show that these effectivities have been outweighed by the reduced prices of bids. In this case, the low prices of aFRR. This result has a negative effect on the availability of flexibility for other system problems.

SQ3: What are the economic implications of integrating flexibility markets on system operations?

The simulations showed a significant improvement in economic performance. Both the BA and CM costs were reduced in the combined design by 51% and 86% respectively. By merging ROP and aFRR capacities, the use of low-priced bids increased. BA experienced only minor increased costs during periods that required both BA and CM, which can be explained by the priority given to CM, but overall costs consistently decreased.

The additional experiments showed that the interchangeability level of an integrated market structure can significantly impact the cost savings. BA savings between the separated and integrated market structure reduced significantly with lower levels of interchangeability, but did not greatly affect redispatch savings. The latter was because ROP capacity was seldom used for redispatch under the integrated market structure, owing to its higher costs. Testing the influence of dimensioning levels on CM revealed no effect on cost savings nor solving capacity, as CM was never really limited by the availability of bid volume.

With these conclusions on the sub-questions, the main research question can be addressed, which is recalled:

What is the operational benefit of integrating the flexibility markets for Dutch TSO system operations?

Overall, combining ROP and aFRR results in significant cost savings, improves grid efficiency, and enhances resilience to peak loads and disruptions. However, it is unlikely that the same added value will be generated by other forms of integration. aFRR, mFRRda and ROP share strong similarities, which makes the capacity currently offered through these products highly interchangeable. In contrast, FCR and CRC have highly specific and different characteristics, making them less suitable to be combined into one product. A more likely option is the partial integration of flexibility markets, combing the more generalizable products into a single reserve, while maintaining the highly specific products as they are. This will still increase the options for TSO’s to mix and match and simplifies market structures, without compromising the unique benefits of a specialized product like FCR.

6. Discussion

6.1. Operational challenges

A partial or full integration of the various markets still poses several challenges. First, all bids should include locational information for CM, something currently not required for aFRR, mFRRda, or FCR. This study assumed a proportional distribution of effectivities to simulate their locations. In reality, geographic locations may be more concentrated or strategic bidding will occur, which could change this distribution and lower the generalizability of this study's results. Future research with real locational data could offer a more accurate assessment.

Additionally, merging flexibility markets raises questions about the required auction structures, including pricing systems. This study assumed historical bids, which were made under the existing separated market structure. It is well known for example that marginal pricing, used by aFRR, typically results in lower bid prices compared to the pay-as-bid system used by ROP [37]. Hence, altering the auction design could lead to changes in bid sizes and prices. Further research is necessary to find the most effective auction structures for flexibility market with an integrated market design.

Finally, dealing with the preventive nature of CM and the reactive nature of BA remains a challenge. This study maintained the existing sequence, but alternative operational rules exist as described in section 2.1, such as shifting market clearing timeframes and introducing a co-optimization strategy, which could further enhance efficiency. Future research should explore these options to maximize the benefits of an integrated market design.

6.2. Simplifications of the system

This study simplified several real system properties in the model, which could have influenced the performance. One of these simplifications is the use of infinite divisibility of bids. In reality, market participants' bids have limited divisibility, making it challenging to find a perfect match between upward and downward regulation during redispatch, possibly leading to additional imbalance. By not incorporating this limitation, the model gained more flexibility, likely resulting in higher estimated economic and technical performance than would be the case. However, this simplification applies to both the separated and combined systems in the model. The simplification could have a more significant effect on the separated market, as only a limited number of reserves are available. This requires further investigation, with more complex models.

6.3. Conflict of interest

This study found an economic benefit in implementing a flexible product. Both CM and BA costs seem to decrease, which is positive from the TSO's perspective but may have opposite effects on the revenue model of market participants providing the reserves. General revenues for this group decrease.

This is not always bad. If the BSP is the same entity as the BRP, the dynamics change slightly because the financial interests are consolidated within one organization. While revenues decrease for the BSP, costs for the BRP decrease, potentially leading to a neutral outcome.

However, it remains to be seen whether the concepts of BSP and CSP and their connection to the BRP will still apply when different markets are integrated. This is especially true if a form of co-optimization is chosen, making it challenging to attribute used reserves and incurred costs to one of the two goals.

6.4. Recommendations

An important step to better determine the functioning of the flexible reserve product is improving data availability and quality. There should be more insight into the background of various bids concerning location and ramp rate.

A second recommendation is to involve the current BSPs and CSPs in the design and rollout process of the product. They can provide practical tips on using a flexible product.

A third recommendation is to adapt or circumvent policies and regulations. This involves removing or designing around legal barriers that currently separate these markets, such as the rule that the imbalance price cannot be influenced by the use of reserves for CM, as stated by the 2017 study [x].

A fourth recommendation focuses on bringing the teams responsible for CM and those responsible for BA closer together. The two operations should be seen as a whole. This would allow partly economic disadvantages in one area to be not problematic if a more significant economic advantages exist in the other.

6.5. Alternative solutions

As mentioned at the start of this paper, integrating flexibility markets is an operational solution. A TSO can also look at other solutions to increase the availability or improve the distribution of reserves. One example is to change the compensation structures. As for ROP, it is the only auction-based product that is not renumerated through a reservation price. This can make the product less interesting for connected parties. Equalizing or controlling the compensation structures can influence bidding behavior and potentially prevent shortages.

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Appendix

A. Search strategy of the literature review

To search for articles, the comprehensive search system Scopus was used. The search terms 'balancing,' 'congestion,' 'integration,' and 'markets' were used in combination with the operator AND. This resulted in an output of 132 articles.

Due to this high number, the first screening focused on the title and abstract. Several inclusion criteria were applied: the articles must at least discuss interfaces, connections, or conflicts between the two services/markets. This left 7 articles. Five articles were ultimately included because they were publicly or freely accessible via the TU Delft library. Using the search engine Google Scholar, a sixth article was added. The search terms 'Balancing' and 'Redispatch' were used for this. Overlapping articles with Scopus were removed. The selection process is schematically represented below in Figure x. In Table x an overview can be found of the selected articles.

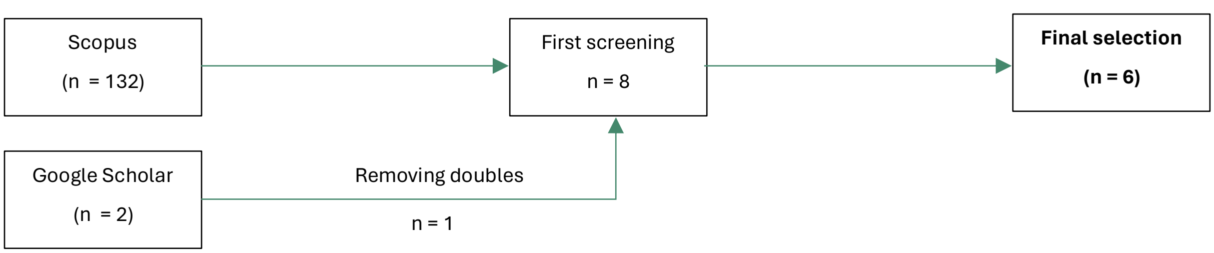

Figure 32: Literature search strategy

Table 9: Overview of selected articles

Number	Title	Author	Year of publication
1	Redispatch and balancing: Same but different. Links, conflicts and solutions	Poplavskaya et al.	2020
2	Integrating balancing reserves and congestion management to re-balance the German system	Horsch & Mendes	2017
3	Rethinking short-term electricity market design: Options for market segment integration	Rieß et al.	2017
4	Bid filtering for congestion management in European balancing markets – A reinforcement learning approach	Girod et al.	2024
5	Supply and demand balance control and congestion management by locational marginal price based on balancing market in power system with wind power integration	Bae et al.	2018
6	Integrated Balancing and Congestion Management under Forecast Uncertainty	Roald et al.	2016

B. Solving capacity of redispatch iterative process

To find the solving capacity of redispatch an iterative process has been used by increasing the congestion problem in small steps to find its 'breaking point'. The point at which the emergency relief had to kick in. After several tests of checking what step sizes and range of volumes to use for this test, the 15 steps are shown in Table x worked best. The third column gives an indication of the certainty range, which is derived from the step size. No certainty is given to the final step, because it would be infinite. However, none of the timesteps reached this level.

Table 10: Steps used for finding the solving capacity for redispatch

Step number	Volume (MW)	Certainty range
1	0	50
2	50	50
3	100	100
4	200	100
5	300	100
6	400	100
7	500	100
8	600	100
9	700	200
10	900	200
11	1100	200
12	1300	200
13	1500	200
14	1700	200
15	1900	n.a.