Functionality of Network Elements in the Cooperative Maximum-Flow Problem: Sustainable Development in Natural-Gas-Transmission Networks

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Abstract

Modeling the cooperative maximum flow problem (CMFP) in transmission and transportation networks (transnetworks) requires nodes and edge functions to enhance realism and accuracy. Several complex decision-making situations arise when functionality is considered. This functional approach considers the quantity and multiple qualities of transporting items, fluids, communication signals, and power, thereby increasing consumer satisfaction. Different functions and operators, such as attenuators, amplifiers, summation, multipliers, and dispatchers, affect network performance and transferability. In the current unstable world, where there are conflicts between countries, the collaborative modeling of nations, in addition to optimum utilization and increasing the use of existing capacities, is a strategic and practical step toward sustainable development. This study investigates the ways in which the owners of various multi-input and multi-output (MIMO) networks with different functions in nodes and edges can collaborate and benefit equitably. This paper proposes an all-inclusive model for transmission and logistical flow issues. These approaches and analyses are evaluated using two numerical examples before being reviewed in the context of a multifaceted examination of the natural gas transmission networks (NGTNs) of three European nations,

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including collaborative outputs, two scenario sensitivity analyses, and essential management insights. Real-world cooperative game-theoretical revenue-sharing methods are also examined.
Keywords: functionality in nodes and edges, cooperative maximum-flow problem, multiple-owners network, sustainable energy, natural gas-transmission network
2010 MSC: 00-01, 99-00

1. Introduction

Currently, transportation and transmission networks (TrNs) with multiple functions at the nodes and edges face intensifying competition, political conditions, international conflicts, globalization, rapid environmental and technological change, and expanding consumer demands. Transnetworks, such as network utilities, face two primary risks to their long-term viability: inadequate infrastructure for expanding the capacity and consumer demand [36, 39]; and the rapid growth of the market and low CO_2 fossil fuel supply to businesses and consumers present difficulties for companies. Businesses employ innovative technologies to increase their network capacities to circumvent this issue [46, 69]. Many studies have taken advantage of the potential of network collaboration to achieve this goal and have neglected the modeling accuracy to simplify modeling. Inaccuracy and realism in functional functions in nodes and links lead to unreliable modeling, and this unreliability and a lack of incentives can lead to failure in network cooperation [25, 27, 58] .

In practice, each commodity transferred into a network must adhere to specific quality factor requirements such as gas market pressure and volume [7, 43]. Consequently, the equation and relationship between each component must be considered when developing an operational model. In addition, various functions, such as the mathematical functions used in this article and other functions, such as activities and tasks performed in manufacturing factories, may be considered nodes and edges. This study particularly focuses on mathematical functions such as attenuators and amplifiers in the edges as well as dispatching, summing, and multipliers in the nodes. By introducing the concept of functionality, this study provides a new path for future research on maximum flow problems. The multi-input multi-output (MIMO) structure in this study raises additional network flow considerations.

According to the Sustainable Development Goals (SDGs)[42], global changes in energy management are needed to provide access to affordable, consistently available, and environmentally friendly energy by 2030. Climate Change was ratified during COP21 in Paris under the Paris Agreement [56]. These international initiatives underscore the requirement for a sustainable energy transition [1, 30].

Natural gas (NG) has undergone significant global changes. Owing to industrial development, substantial investments in supply networks consisting of pipelines and pressure compressor stations (CS) are required to effectively reach the global NG supply [51]. NG is a high-quality, environmentally friendly energy source which use is increasing due to the need to reduce carbon (CO_2) emissions [5, 17]. NG can be used as a short-to medium-term transitional energy source because it releases less CO_2 per unit of energy than petroleum, coal, or lignite, and the infrastructure is already in place.

In February 2022, the Russia–Ukraine conflict triggered a gas crisis, which resulted in several market modifications [2, 68]. Owing to its high prices and limited supply, NG consumption has decreased in most regions. From January to August 2022, the EU's gas consumption, which was immediately susceptible to the impact of Russian gas supply reductions, decreased by approximately 10% annually. All gas-importing regions experienced the effects of the crisis as Europe's rising demand for liquefied natural gas (LNG) caused supply problems and spiraling spot prices for competing buyers [28].

According to the Europe Gas Tracker Report, the EU gas infrastructure has grown significantly and continuously over the past few years [3]. The EU's gas import capacity will increase by 10 bcm/y in 2020 and by the same amount in the first quarter of 2021. Despite this decrease in the import capacity, the COVID-19 pandemic may have affected project completion [3, 15]. The possibility of improving and benefiting from the maximum transmission power of connected networks between European countries by considering functions in nodes and edges, as well as MIMO, is a challenge that requires modeling to continue previous research in the field of maximum flow problems with double precision and comprehensive care to reduce the countries' errors in the area of justice in the income-sharing sector.

Cooperative game theory (CGT) provides potential solutions to these problems; however, it is also critical to address the equitable distribution of regular funds. Several studies show that business owners can share resources and infrastructure with firms in the same class and industry [6, 12, 26]. The infrastructure of utility companies operating in different industries, such as transmission networks for oil and gas, water, and power, is often shared [8, 11]. Establishing fair revenue distribution is essential to avoid the negative effects of unanticipated political events and organizational process changes while maintaining long-term partnerships. Despite numerous studies attempting to divide income equally [6, 67], this study provides a detailed structure in terms of the functional functions of the nodes and links. This structure will enable us to improve justice in the collaboration between network transportation and transmission chains.

Flow games manage the flow conditions [29, 40]. Individuals, companies, and governments own different portions of their networks in the real world. The literature on capacity-enhancing cooperative maximum-flow problem (CMFP) initiatives seeks to demonstrate the increasing synergy and distribute it equitably [22, 24], albeit to simplify the modeling of the scope of functionality in any omitted network components. This paper presents a comprehensive model for maximizing flow using a mixed-integer nonlinear problem (MINLP), considering the functionality of MIMO networks.

Optimal outcomes, which serve as an embodiment of decision makers' contentment when confronted with alternative options, constitute pivotal notions in economics and game theory. Thus, a favorable option meets the decision-makers' needs and offers a positive outcome [25]. In this situation, the function of each network element must be examined. The following three questions are addressed using the cooperative maximum-flow problem (CMFP) in transmission and transportation networks (transnetworks), which requires nodes and edge functions.

1. How can we construct and solve a model for CMFP-TrN states that considers the operational functions in the nodes and edges?
2. How can transmission networks leverage CGT to form coalitions and share revenue while considering their functionalities?

3. What are the ramifications and sustainability effects of the proposed model on the natural gas transmission networks (NGTNs)?

This paper is arranged as follows: Section 2 presents an in-depth literature review. Section 3 delineates the fundamental requirements and assumptions underlying the proposed model and presents two illustrative numerical instances of the cooperative utility approach. Furthermore, the optimization framework introduced in Section 4 is subjected to a comprehensive assessment through a case study and sensitivity analysis. Management insights derived from the findings are expounded in Section 5, and Section 6 critically appraises and suggests potential avenues for future research based on these insights.

2. Literature Review

Considering these obstacles, a comprehensive analysis of the existing research landscape can be conducted using multiple vantage points. These encompass the realms of the cooperative game theory, maximum-flow problem, trans-network optimization, and optimization and sustainability aspects pertaining to NGTNs.

2.1. Cooperative Game Theory and the Maximum-Flow Problem

The CMFP is a prevalent issue utilized by numerous businesses and networks to increase transmission volume and capacity. This strategy leverages the network communication link synergy by utilizing a centralized solution. Earnings are evenly distributed using Shapley, τ-value, and the core-center [25, 41, 49, 64]. Hafezalkotob [23] formulated competition and cooperation models that encompass price and energy-saving dynamics within two distinct green supply chains (SCs) under the influence of government financial intervention. A water distribution pipeline's maximum flow was determined using the Ford-Fulkerson algorithm by Kyi and Naing [31]. Using the CGT, Kellner and Schneiderbauer [30] studied streamlined Greenhouse Gas (GHG) declarations in supply chains by identifying the optimal EN-16258 allocation unit for measuring a shipment's emissions and comparing them with the Shapley value. A framework for contractual backup reserves sharing has been proposed by Hou et al.

[26] for small/local operators and more resourceful operators with surplus capacity. In the design stage of fiber optic networks, a maximum green reliable flow (MGRF) reduces greenhouse gas emissions and maximizes network value [35]. Csercsik et al. [13] calculated power-structured payoffs for a gas pipeline system with third-party-controlled access. An evolutionary game model developed by Song et al. [53] was utilized to examine cooperative alliance organizers, institutional investors, upstream operators, and downstream operators. In our previous study, we presented an MINLP model to maximize reliability, allocate maintenance teams, and explore the edge status in network utility issues, focusing on cooperative transmission and maintenance planning [36].

In addition, research has been conducted using the CGT strategy to combine various energies. A power-to-gas station, an NG system, and an electricity system were integrated in a game-theoretic planning model developed by Zhang et al. [66]. Several studies [32, 62, 67] have investigated the cooperation and energy optimization of electricity and gas networks. The concept of incorporating diverse functionalities within the nodes and edges of a transnetwork has not received adequate attention or scrutiny in the existing body of scholarly research. Extensive exploration and comprehensive examination of this concept, along with its associated implications and potential benefits, are yet to be thoroughly investigated and addressed within the scientific community.

2.2. *Trans-network optimization*

Numerous studies have examined the optimization of trans-networks, such as telecommunications, electricity, water, gas, and transportation of commodities, from the perspectives of design and operation, as well as capacity enhancement [34]. To examine the effects of gas composition fluctuations on the operating strategy of the pipeline system, Chaczykowski et al. [9] developed a comprehensive pipeline flow model that involves tracks of gas composition resulting from mass and chemical energy transfer coupling. The pipeline network model designed by Mikolajková et al. [37] considered gas supply as a requirement for the gas distribution network model. Using nonlinear network flow models, D'Ambrosio et al. [14] examined mathematical programming approaches to optimize drinking-water distribution networks, highlighting the

MINLP's common structure in explaining the dynamics of water in pipes while covering design and operation problems. As a consequence of considering integrity, contiguity, balance, and independence criteria in railway transportation networks, Wang et al. [57] introduced a study on simultaneous districting of nodes and links. Their approach incorporated an MINLP model with a network-flow-based technique, utilizing valid inequalities and column generation-based algorithms for model enhancement. Additionally, a hybrid algorithm and iterative search algorithms were proposed as efficient solutions for the train dispatcher-desk districting problem, and their effectiveness was evaluated through various examples. By discussing power system issues and employing theoretical operations research methodologies, Skolfield and Escobedo [52] strengthened the bonds between communities. In addition, they examined applications such as expansion planning, regular operations, markets, network resilience, and unit commitment in order to find optimal power flow solutions. While the topics and formalizations related to trans-networks have been extensively studied in a wide range of articles, cooperative approaches and the ability to share networks simultaneously, considering functional requirements as well as the fair allocation of benefits among participants in coalitions, have not been thoroughly investigated.

2.3. Sustainability and Optimization of a Natural Gas Transmission Network

Numerous NGTN simulations, modeling, optimization, and efficiency enhancement studies have been conducted [9, 16, 18, 37, 54, 60]. Fodstad et al. [19] presented a modelling methodology that demonstrates how interruptible transportation services can boost throughput and revenues in natural gas transportation systems. Chen et al. [10] presented a formulation for optimizing detailed schedules for multi-product pipeline networks and achieving the shortest distance across a pipeline network. The bi-objective optimization of high-pressure gas networks was modeled by Osiadacz and Isoli [44] to ensure greater system efficiency than scalar optimization. For power production scheduling, Ordoudis et al. [43] introduced a novel volume-based method that improved intertemporal coordination and reduced system costs based on natural gas volumes. The study compared this approach to a price-based coordination alternative and utilized a stochastic bilevel program formulation that was compatible with dayahead and real-time markets in the natural gas system. To maximize the total profit, minimize both GHG emissions and water consumption, and optimize both strategic and tactical decisions, Zarei et al. [65] aimed to design and plan an optimal SC for NG components. Sukharev and Kulalaeva [55] examined the problem of estimating the state and parameters of NG pipeline systems under stationary and nonstationary gas flows. Liquefied natural gas (LNG) LCSA was performed by Al-Yafei et al. [4], who evaluated the performance of LNG from extraction and regasification after delivery by sea. Diverse fields, including gas storage, the development of optimization models, and increasing the utilization of existing capacities of NGTNs to combat energy crises, have been the main subject in research [59, 69]. Considering the two aforementioned research streams and numerous concerns surrounding sustainable energy supply in the global community, the simultaneous integration of the aforementioned approaches within NGTNs poses a highly challenging aspect that has not been adequately investigated in this field of research.

2.4. Research gap and contributions identified

A thorough examination of the aforementioned research streams revealed several comprehensive gaps that must be addressed. This study integrates insights derived from Csercsik et al. [13], Woldeyohannes and Majid [60], Fodstad et al. [19], and Hafezalkotob and Makui [25]. The identified issue emerged during the network collaboration design and redesign phases in 2021, independent of node and edge functionality [35]. Csercsik et al. [13] simplified their analysis by disregarding the operational functions of the nodes and edges. Hafezalkotob and Makui [25] investigated transshipment concerns using flow game models.

Although cooperative transferable utility (TU) games were advocated in Fossati et al. [20], the evaluation of coalition earnings was limited to a single numerical measure. Additionally, Peters [47] emphasizes the potential for alliances to allocate numerical resources, such as money, among their members. Conversely, Fodstad et al. [19] and Woldeyohannes and Majid [60] did not explore CGT strategies. Consequently, a comprehensive investigation of these favorable outcomes, particularly the collaboration of networks considering operational functions, remains insufficient. Notably, no prior studies have analyzed the influence of functionality within CMFP nodes and edges. Moreover, no research has been conducted on practical cooperation in the context of the NGTN aimed at mitigating the risks outlined by the International Energy Agency, 2022; Mehryar et al., 2021; Mohammad et al., 2021; ONU, 2022; UNFCCC, 2015, thereby promoting sustainability.

This study aims to investigate the functional capabilities of nodes and edges in networks by analyzing the interplayer cooperative maximum flow. We focused on examining the synergistic effects that emerged under different cooperative conditions. Although previous research has explored aspects of company cooperation, the evaluation of the desired synergistic effects has been overlooked, mainly because of the diverse range of collaboration sizes and functional approaches that have not been adequately addressed. Furthermore, this study not only examines cooperative aspects and strategies to minimize disruptions while enhancing transmission and transportation capacities but also identifies potential collaboration hotspots where businesses are more inclined to cooperate and mutually incentivize each other. A sensitivity analysis was performed to identify stable cooperation spaces, and the allocation of revenue to network owners was analyzed using various methods within the framework of coalition games.

The contributions of this study include: 1) the possibility of considering a variety of functions in nodes and edges within networks to establish cooperation between networks in flow problems, 2) creating a qualitative approach for optimizing networks by considering the different characteristics of the transferable material using different proportional relationships, and 3) identifying areas of higher stability within the CGT and fostering collaboration with utilities by leveraging the spectrum of synergy, considering the diverse functionalities exhibited by network elements.

3. Problem description and modeling

In this section, we comprehensively examine the key aspects of the study. Subsection 3.1 focuses on delineating the essential prerequisites and underlying assumptions that form the foundation of our analysis. Subsequently, in Subsection 3.2, we expound the requirements, variables, and formulation of the functionality approach within the maximum-flow model. Furthermore, the critical topic of coalition income sharing is thoroughly explored in Subsection 3.3, shedding light on its implications within the broader context of our study. Finally, in Subsection 3.4, we employ near-real numbers as a powerful tool for evaluating networks and facilitating consensus among network owners, as exemplified through the presentation of two illustrative examples.

3.1. Basic assumptions and prerequisites

This paper presents an illustrative demonstration of the model using a realistic example. Instead of merely expanding the network by introducing additional nodes and edges, our objective was to thoroughly investigate and enhance synergistic interactions by considering the functionalities of nodes and edges.

(1) Unlike previous research in this field, the relationship between the input and output value of nodes and edges in networks is governed by several defined functions [13, 25, 36]. The functions considered in this study are mathematical operators.

(2) Prior to initiating collaborative efforts, network owners engage in a meticulous assessment of the line capacity across each edge to ensure their ability to fulfill their obligations. Consequently, the decision-making process pertaining to capacity expansion or contraction is distinct from that for collaboration. Furthermore, the supplementary parameters are contingent on market constraints and prevailing link conditions, which effectively shape the course of action.

The indexes, parameters, and decision variables are utilized throughout the current study:

Indexes:

i, j	Nodes, which represent the originating or terminating points of links,
r	Routes,

m	Coalitions,
e	Edges,
A_m	All the links involved in the transmission between source node (s) and destination node (d),
n	Number of attributes,
q	Compressor stations,
Parameters:	
I_{A_m} min, I_{A_m} max	Matrixes of minimum and maximum input flows and their attributes,
D_{A_m} min, D_{A_m} max	Matrix of the minimum and maximum demand of output flow and their attributes,
P_S	Pricing associated with a single unit of a transmitted product when sold to a customer,
P_b	Price paid by a buyer to a producer for each unit of a transmitted commodity,
cap_{i-j}	Capacity link, which refers to the maximum number of flow units that can be transmitted through link (i, j),
D_{i-j}	Length of the edge (i, j) measured in kilometers,
C_t	Cost of 1km of 1 transmitter unit,
F	Maintenance and fixed cost of network elements,
α_{i-j}	Attenuation coefficient for each link (i, j),
d_{i-j}	Gas pipe diameter in link (i, j),
κ	Isentropic exponent,
$\lambda = (\frac{\kappa-1}{\kappa})$	Specific heat ratio,
Z	Compressibility factor,
R	Universal gas constant,
T_s	Suction temperature factor for compressors,
h_q	Adiabatic compression factor,
η_q	Isentropic compressor efficiency,
η_{m_q}	Mechanical efficiency of the compressor,

η_{d_q}	Driving efficiency of the compressor,
LHV	Compressor's low heating value,
A_H, B_H, C_H, D_H	Compressor constants,

Decision variables:

$\overrightarrow{X_{i-j}}$	Matrix of The amount of flow and its attributes that are transmitted from i to j, as stated in node i,
$\overleftarrow{X_{j-i}}$	Matrix of the amount of flow and its attributes that are transmitted from i to j, as stated in node j,
$\overrightarrow{x^1_{i-j}}$	Number of first attributes that are transmitted from i to j, as stated in node i,
$\overrightarrow{X_r}$	Matrix of the amount of flow and its attributes that are transmitted from the source to the destination while moving toward path r,
β_{i-j}	Dispatch coefficient for each link (i, j),
$\overrightarrow{P_{i-j}}$	Amount of gas pressure transmitted from i to j as stated in node i,
$\overleftarrow{P_{j-i}}$	The amount of gas pressure transmitted from i to j, as stated in node j,
k_{i-j}	Gas pressure-reduction factor based on the gas pipe's transfer volume for link (i, j),
$\overrightarrow{P_q}$	Gas pressure exiting from CS number q,
$\overleftarrow{P_q}$	Gas pressure entering CS number q,
x_{f_q}	Amount of gas used to increase the gas pressure in CS number q,
e_q	Number of active compressors working in parallel within the CS q,
n_q	Optimum compressor rotation per minute (RPM) in CS number q,
Ψ_{A_m}	The aggregate revenue generated by the network under the ownership of coalition m,

3.2. Functionality modeling the network

Let $G = (E, V)$ denote a directed multiowner network, where E represents the set of edges and V represents the set of vertices (nodes). $M(M \geq 2)$ is defined as a finite and non-empty set of players with network edges. In the network representation $G = (E, V)$, network edges $E = \{E_{\{1\}}, E_{\{2\}}, \ldots, E_{\{M\}}\}$ are jointly owned by M players, such that $\bigcup_{m \in M} E_{\{m\}} = E$ and $\bigcap_{m \in M} E_{\{m\}} = \emptyset$. Although game owners possess several advantages within the context of the CMFP-TrN, they also have opportunities to form coalitions. These independent players are characterized by unique advantages, and subsets of the player coalition, denoted by m, face distinct demands. In addition, each node or edge has a specific function for receiving or transmitting commodities through multiple input and output ports (Fig. 1–4 and Eq. (2)–(5)). Transferable materials possess a variety of qualitative parameters and characteristics that have been discussed in previous studies, primarily in terms of their reliability parameters [35, 63]. The $\overrightarrow{x^1_{i-j}}$ *or* $\overleftarrow{x^1_{j-i}}$ variables expressed in the equations are single attributes that considered the flux amount in previous studies. Transferable commodity variables with distinct characteristics and attributes are represented as a matrix with multiple rows and a single column ($\overrightarrow{X_{i-j}}$ *or* $\overleftarrow{X_{j-i}}$). Matrix writing was used to establish the model (Eq. (1)). Some inputs of functions in the nodes and edges are decision variables obtained by the element's owner from the network, whereas other inputs are the outputs of previous elements that have reached this element. Accordingly, the coalition is considered to own the edges of its members collectively. For example, the partnership formed by players one and three accesses the boundaries defined by $E_{\{1\}} \cup E_{\{3\}}$.

$$\overrightarrow{X_{i-j}} = \begin{bmatrix} \overrightarrow{x^1_{i-j}} \\ \overrightarrow{x^2_{i-j}} \\ \vdots \\ \overrightarrow{x^n_{i-j}} \end{bmatrix} \tag{1}$$

$$node\, i;\; f_i(\overleftarrow{X_{i-j}}, \overleftarrow{X_{i-j'}}, \ldots) = \overrightarrow{X_{i-j''}}, \overrightarrow{X_{i-j'''}}, \ldots;\; j, j', j'', j''', \ldots\; connected\, related\, nodes, \tag{2}$$

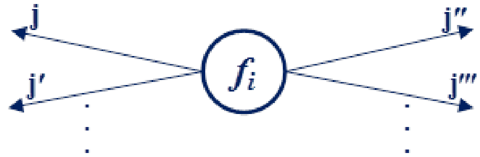


Figure 1: Functionality in a node

$$link\ i\ to\ j;\ \overrightarrow{f_{i-j}}\,(\overrightarrow{X_{i-j}}) = \overleftarrow{X_{j-i}}, \tag{3}$$

Figure 2: Functionality in a link

$$input\,node\,so;\ f_{so}\,(\overleftarrow{X_{so-out}}) = \overrightarrow{X_{so-j}}, \overrightarrow{X_{so-j'}}, \ldots, \tag{4}$$

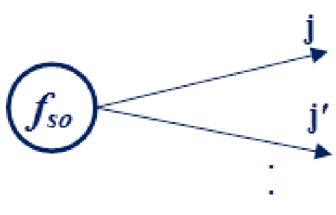


Figure 3: Functionality in a source node

$$output\,node\,d;\ f_d\,(\overleftarrow{X_{d-j}}, \overleftarrow{X_{d-j'}}, \ldots) = \overrightarrow{X_{d-out}}, \tag{5}$$

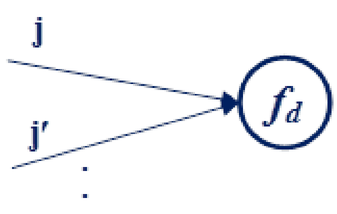


Figure 4: Functionality in a distention node

We consider the objective of transferring the supply of NG or other goods, signals, or commodities from source node s to destination node d within a network (as shown in Fig. 5). This network is owned by three individual players ($P = \{1, 2, 3\}$), where the set of edges is $E = \{(so, a), (so, b), (b, a), (b, d), (a, d), (so, d)\}$ and the set of vertices is $V = \{so, a, b, d\}$. The first player owns the upper link ($E_{\{1\}} = \{(so, d)\}$), second player owns the middle links ($E_{\{2\}} = \{(so, a), (a, d)\}$), and third player owns the bottom links ($E_{\{3\}} = \{(so, b), (b, a), (b, d)\}$). In the typical structure presented, node f, with two inputs and one output is owned by the second owner, whereas node a with one input and two outputs is owned by the third owner. Additionally, for each edge, the relationship between its input and output values was defined according to its corresponding function. This interpretation applies to all coalitions including $(2^3 - 1)$. Owners should determine several function-related variables to control and optimize the network transformation.

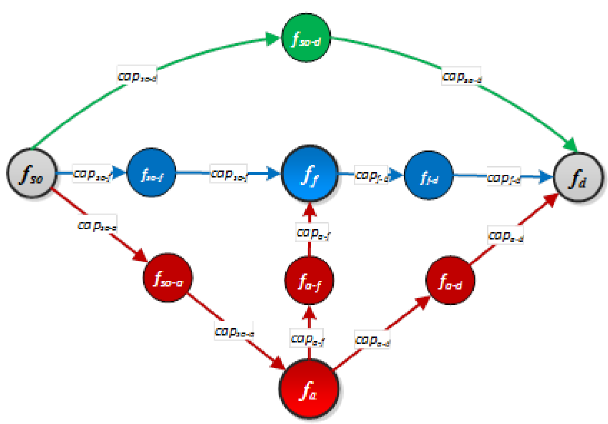


Figure 5: Typical structure of cooperative networks considering functionality in nodes and edges

Based on the CMFP-TrN approach employed in this study, the quantity of transmission required to satisfy the demands and surpass all attribute thresholds within each coalition was determined (Eqs. (6) and (7)). Matrices I_{A_m}, D_{A_m} are the minimum and maximum amounts of the transferable commodity plus all attributes that are entries and outputs in the network. Similarly, the capacity of each edge and route acts as a constraint, as specified in Eqs. (8) and (9), whereas the optimization objective focuses on the overall income encompassing the expenses associated with the supply, procurement, and transportation of materials and commodities across the network. Regardless of the current expenses, every operating network has maintenance and fixed costs based on the volume of transmission, Eq (10). The modeling can also be applied to multiple-input multiple-output (MIMO) networks.

$$I_{A_m} \min \leq \overleftarrow{X_{so-out}} \leq I_{A_m} \max; \tag{6}$$

$$D_{A_m} \min \leq \overrightarrow{X_{d-out}} \leq D_{A_m} \max; \tag{7}$$

$$\overrightarrow{X_{d-out}} = \sum_{r=1}^{R} X_r;\ r \in R = 1, 2, \ldots, R, \tag{8}$$

$$X_r \leq \overrightarrow{x^1_{i-j}}, \overleftarrow{x^1_{i-j}} \leq cap_{i-j}; \forall r \in (i, j), \tag{9}$$

$$\max\ \Psi_{A_m} = P_s \cdot \overrightarrow{X_{d-out}} - P_b \cdot \overleftarrow{X_{s-out}} - \sum_{e \in A_m} D_{i-j} \cdot C_t \cdot \overrightarrow{x_{i-j}} - F \cdot N_{A_m}, \tag{10}$$

To consider the relationships between the attributes of transferable materials, it is necessary to adapt the proposed model to specific problems. The manipulated variables encompass the quantities of items or commodities transmitted through individual edges or routes as well as multiple adjustable parameters associated with each function. Given the interplay between transmission and functionality, the problem is a challenging MINLP. To address this issue, the general algebraic modeling system (GAMS) offers the Branch-And-Reduce Optimization Navigator (BARON) [50], a powerful solver capable of addressing MINLPs. According to the superadditive property, the network flow income of each coalition must exceed its total income. Subsection 3.3 will discuss the use of shape values to allocate the network owners' excess income.

3.3. Multiple-owner Collaboration

There should be a coordination and awareness of market constraints in the CMFP-TrN model. For all two-owner coalitions, it was necessary to examine each owner's network separately to solve the models. In the next step, models and solutions were used to establish coalitions with the three owners. The process was repeated until a grand coalition was modeled and resolved. It's expected that the total network value of TU games will exceed the general network utilities of the coalition members, Eq (11);

that is,

$$\Psi_{A_m} \geq \sum_{p_i \subset m} \Psi(p_i), \quad \forall m \in P, \tag{11}$$

$EU(m)$ represents the discrepancy between the maximum income achieved by a coalition and the cumulative maximum income attained by each coalition member, Eq (12).

$$EU(m) = \Psi_{A_m} - \sum_{p_i \subset m} \Psi(p_i), \quad \forall m \in P, \tag{12}$$

The main and additional incomes of coalition members can be compared [33]. In consequence, the following formula can be used to measure the synergy of a coalition using Eq (13) to compare it to each coalition member's income:

$$Synergy\,(m) = \frac{EU(m)}{\Psi_{A_m}}. \tag{13}$$

Following the computation of income and synergy for all coalitions, the next step involves exploring the optimal benefit distribution. This task presents complexity in determining the individual contributions of each owner to the net income. To address this challenge, this study investigated various theoretical strategies for CGT. Building on prior research conducted by Csercsik et al. [13], Hafezalkotob and Makui [25], and Mehryar et al. [36], the Shapley values, τ-values, and core-center approaches were employed to assess the contribution of each coalition.

3.4. Numerical example

The methodology for the experimental evaluation of these two networks is described in the following subsection. During the operational phase of both projects, the three companies intend to work together to maximize their income. The first illustration shows a single-input single-output (SISO) network with distinct node and edge functions. A hypothetical SISO NGTN was also established and solved in the second example. The MIMO structure is considered in an NGTN application example.

3.4.1. Numerical Example 1

This example is comparable to that of SISO networks for telecommunications and electrical transmission (Fig. 6). At the edges of the network, signal loss and attenuation functions were implemented using a reduction factor. This example employs Eq. (6)–(10); However, Eq. (1)–(5) relating to the edges and nodes, must be rewritten. In this instance, only the signal is transmitted and no other characteristics are considered (Eq. (14)); thus, $\overrightarrow{X_{i-j}} = \overrightarrow{x^1_{i-j}} = \overrightarrow{x_{i-j}}$. At the central node of F, a multiplier with two inputs and one output is considered (Eq. (15)). The decision-maker controls a distributor or dispatcher at node A (Eq. (16)). Additionally, the sum of the node outputs equals the total input to the network (Eq. (17)). Furthermore, the sum of the input signals at node D yields the output value (Eq. (18)). The minimum output and input were considered zero. Tables A-1 and A-2 present the network and market parameters, respectively.

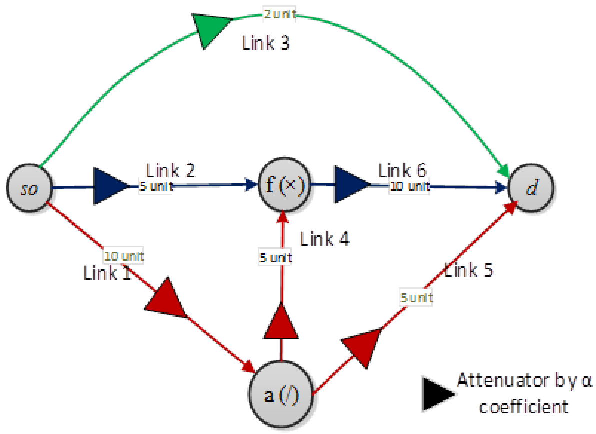


Figure 6: Example 1 according to functionality in nodes and links

$$\begin{cases} \overleftarrow{x_{j-i}} = \alpha_{i-j} \cdot \overrightarrow{x_{i-j}} \\ 0 \leq \alpha_{i-j} \leq 1 \end{cases} \quad ; \forall (i-j) \in A_m \ , \tag{14}$$

$$node\ f;\ \overrightarrow{x_{f-d}} = \overleftarrow{x_{f-so}} \times \overleftarrow{x_{f-a}} \ , \tag{15}$$

$$node\ a;\ \begin{cases} \overrightarrow{x_{a-f}} = \beta_{a-f} \cdot \overleftarrow{x_{a-so}} \\ \overrightarrow{x_{a-d}} = (1-\beta_{a-f}) \cdot \overleftarrow{x_{a-so}} \\ 0 \leq \beta_{a-f} \leq 1 \end{cases} \ , \tag{16}$$

$$node\ so;\ \overleftarrow{X_{so-out}} = \overrightarrow{x_{so-d}} + \overrightarrow{x_{so-a}} + \overrightarrow{x_{so-f}}\ , \tag{17}$$

$$node\ d;\ \overrightarrow{X_{d-out}} = \overleftarrow{x_{d-s}} + \overleftarrow{x_{d-f}} + \overleftarrow{x_{d-a}}\ , \tag{18}$$

Table 1 lists the results of these calculations. One of the critical points in the cooperation of the grand total (cooperation of all network owners) is that, in node A, the input values are not equally distributed between the two outputs, and the optimal mode is to transfer 0.281 from the input to the a-f edge. The collaboration of Network 3 with Network 1 produced 0.000738 synergies, whereas its collaboration with Network 2 produced 0.384097 synergies. As shown in Table 2, the income of each network owner was calculated using the three aforementioned methods.

Table 1: Results of Example 1

	$C_1 = \{1\}$	$C_2 = \{2\}$	$C_3 = \{3\}$	$C_4 = \{1,2\}$	$C_5 = \{1,3\}$	$C_6 = \{2,3\}$	$C_7 = \{1,2,3\}$
$\overrightarrow{x_{so-d}}$, $\overleftarrow{x_{d-so}}$	2,1.4	0,0	0,0	2,1.4	2,1.4	0,0	2,1.4
$\overrightarrow{x_{so-f}}$, $\overleftarrow{x_{f-so}}$	0,0	5,4.5	0,0	5,4.5	0,0	5,4.5	5,4.5
$\overrightarrow{x_{f-d}}$, $\overleftarrow{x_{d-f}}$	0,0	4.5,3.375	0,0	4.5,3.375	0,0	8.621,6.466	8.621,6.466
$\overrightarrow{x_{so-a}}$, $\overleftarrow{x_{a-so}}$	0,0	0,0	5.263,5	0,0	5.263,5	7.321,6.955	7.321,6.955
$\overrightarrow{x_{a-d}}$, $\overleftarrow{x_{d-a}}$	0,0	0,0	5,4.95	0,0	5,4.95	5,4.95	5,4.95
$\overrightarrow{x_{a-f}}$, $\overleftarrow{x_{f-a}}$	0,0	0,0	0,0	0,0	0,0	1.955,1.916	1.955,1.96
β_{a-f}	0	0	0	0	0	0.281	0.281
$\overleftarrow{X_{so-out}}$	2	5	5.263	7	7.263	12.321	14.321
$\overrightarrow{X_{d-out}} = \sum_{r \in C_m} X_r$	1.4	3.375	4.95	4.775	6.35	11.416	12.816
Π_{A_m}	11882	28690	14703.632	40592	26605.632	70455.337	82357.337
$EU(A_m)$	0	0	0	20	19.6320	27061.705	27081.71
$Synergy(A_m)$	0	0	0	0.000493	0.000738	0.384097	0.328832

Table 2: Using different methods for allocating coalition payoffs in Example 1

Owner	Shapley	τ-value	core-center
{1}	11895.33	11892	11892
{2}	42224.19	42225.85	42225.85
{3}	28237.82	28239.48	28239.48
Stable	YES	YES	YES

3.4.2. Numerical Example 2 – Natural Gas Transmission Network

This example is similar to the SISO NGTN (Fig. 7). Two characteristics were considered in the transmission of NG: gas volume and acceptable pressure. The volume of NG transported with the defined pressure limits at the origin and destination was adequate. This example uses Eq. (6)–(10); However, Eq. (1)–(5) relating to the edges and nodes, must be rewritten. The matrix-related gas pipeline is expressed by Eq. (19), and the matrix-related CS is expressed by Eq. (20), with the owner determining the three variables (x_{f_q}, n_q, e_q). The relationship between the gas pressure reduction and transferred volume is given by Eq. (21). The relationship between the outlet and inlet pressures CS is given by Eq. (22). All equations related to NGTN were derived from Refs. [18, 51, 60]. The output gas volume equation at nodes s, a, and b is considered with the operator's decision (β_{i-j}) to determine the amount of gas dispatching Eqs (23)–(25).

In addition, at nodes f and d, the volumes received from different lines are automatically added using Eqs. (26),(27), leaving no decision variables for the operator. Each CS has a unique gas-transfer capacity (Eq. (28)); a portion of the input gas was also used to provide energy to the CS (Eqs. (29),(30)). Furthermore, it is necessary to use Eqs. (31)–(33) to ensure that the gas pressure along the network and at the intersection of the lines remains constant (the pressure can be reduced by using pipeline pressure breakers). The minimum NG output and input were considered zero. Tables A-3 and A-4 present the network and market parameters, respectively.

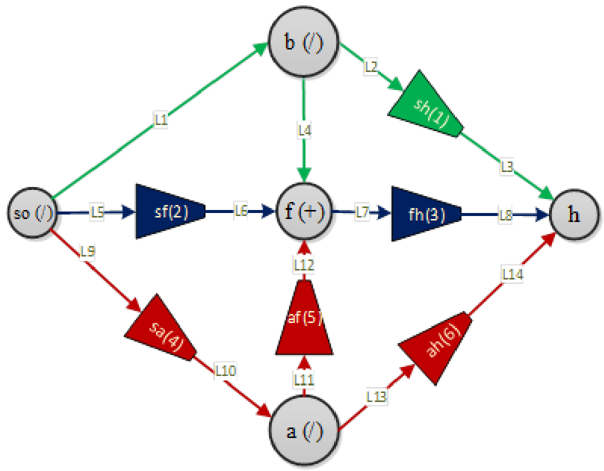


Figure 7: Example 2 functionality in gas transmission network

$$\overrightarrow{X_{i-j}} = \begin{bmatrix} \overrightarrow{x_{i-j}} \\ \overrightarrow{P_{i-j}} \end{bmatrix}; \forall (i,j) \in A_m, \tag{19}$$

$$\overrightarrow{X_q} = \begin{bmatrix} \overrightarrow{x_q} \\ x_{f_q} \\ \overrightarrow{P_q} \end{bmatrix}; \forall q \in A_{m,} \tag{20}$$

$$Pressure\,in\,Links: \begin{cases} (\overrightarrow{P_{i-j}}^2 - \overleftarrow{P_{j-i}}^2) = k_{i-j} x_{i-j}{}^2; \\ k_{i-j} = \frac{6.4575\times10^7}{2.4\times10^9} \frac{D_{i-j}}{d_{i-j}{}^5} = 0.027 \frac{D_{i-j}}{d_{i-j}{}^5}; \end{cases} \quad \forall (i,j) \in A_m; \tag{21}$$

$$(\frac{\overrightarrow{P_q}}{\overleftarrow{P_q}})^{\lambda} = \frac{\lambda . n_q{}^2}{ZRT_s}[A_H + B_H(\frac{(x_q/e_q)}{n_q}) + C_H(\frac{(x_q/e_q)}{n_q})^2 + D_H(\frac{(x_q/e_q)}{n_q})^3] + 1; \forall q = 1, 2, \ldots, q_{A_m}; \tag{22}$$

$$flow\,in\,node\;\;so: \begin{cases} \overleftarrow{x_{so-out}} = \overrightarrow{x_{so-b}} + \overrightarrow{x_{so-sf}} + \overrightarrow{x_{so-sa}}; \\ \beta_{so-b} + \beta_{so-sf} + \beta_{so-sa} = 1; \\ \overrightarrow{x_{so-b}} = \beta_{so-b} \cdot \overleftarrow{x_{so-in}}; \\ \overrightarrow{x_{so-sf}} = \beta_{so-sf} . \overleftarrow{x_{so-in}}; \\ \overrightarrow{x_{so-sa}} = \beta_{so-sa} \cdot \overleftarrow{x_{so-in}}; \end{cases} \tag{23}$$

$$flow\,in\,node\ b: \begin{cases} \overleftarrow{x_{b-so}} = \overrightarrow{x_{b-sh}} + \overrightarrow{x_{b-f}}; \\ \beta_{b-sh} + \beta_{b-f} = 1; \\ \overrightarrow{x_{b-sh}} = \beta_{b-sh} \cdot \overleftarrow{x_{b-so}}; \\ \overrightarrow{x_{b-f}} = \beta_{b-f} \cdot \overleftarrow{x_{b-so}}; \end{cases} \tag{24}$$

$$flow\,in\,node\ a: \begin{cases} \overleftarrow{x_{a-sa}} = \overrightarrow{x_{a-af}} + \overrightarrow{x_{a-ah}}; \\ \beta_{a-af} + \beta_{a-ah} = 1; \\ \overrightarrow{x_{a-af}} = \beta_{a-af} \cdot \overleftarrow{x_{a-sa}}; \\ \overrightarrow{x_{a-ah}} = \beta_{a-ah} \cdot \overleftarrow{x_{a-sa}}; \end{cases} \tag{25}$$

$$flow\,in\,node\ f: \left\{ \overrightarrow{x_{f-fh}} = \overleftarrow{x_{f-b}} + \overleftarrow{x_{f-sf}} + \overleftarrow{x_{f-af}}; \right. \tag{26}$$

$$flow\,in\,node\ d: \left\{ \overrightarrow{X_{d-out}} = \overleftarrow{x_{d-sh}} + \overleftarrow{x_{d-fh}} + \overleftarrow{x_{d-ah}}; \right. \tag{27}$$

$$C.S \cdot \ flow: \ \overrightarrow{x_q} = x_q \leq cap_q;\ \forall q = 1, 2, \ldots, q_{A_m}; \tag{28}$$

$$\overleftarrow{x_q} - \overrightarrow{x_q} = x_{f_q}; \forall q = 1, 2, \ldots, q_{A_m}; \tag{29}$$

$$x_{f_q} = \frac{10^6 \overrightarrow{x_q} h_q}{\eta_q \eta_{m_q} \eta_{d_q} LHV} = 0.486 \overrightarrow{x_q}\left(\left(\frac{\overrightarrow{P_q}}{\overleftarrow{P_q}}\right)^{\lambda} - 1\right); \forall q = 1, 2, \ldots, q_{A_m}; \tag{30}$$

$$Pressure\,in\,node\ b: \begin{cases} \overrightarrow{P_{b-sh}} + \overrightarrow{P_{b-out}} = \overleftarrow{P_{b-so}}; \\ \overrightarrow{P_{b-f}} = \overrightarrow{P_{b-sh}}; \end{cases} \tag{31}$$

$$Pressure\,in\,node\ f: \begin{cases} \overleftarrow{P_{f-b}} = \overrightarrow{P_{f-fh}} + \overrightarrow{P_{f-out}}; \\ \overleftarrow{P_{f-b}} = \overleftarrow{P_{f-sf}}; \\ \overleftarrow{P_{f-b}} = \overleftarrow{P_{f-af}} \end{cases} \tag{32}$$

$$Pressure\,in\,node\ a: \begin{cases} \overleftarrow{P_{a-sa}} = \overrightarrow{P_{a-af}} + \overrightarrow{P_{a-out}}; \\ \overrightarrow{P_{a-af}} = \overrightarrow{P_{a-ah}}; \end{cases} \tag{33}$$

Table 3 lists the computations that were performed. The flows and pressures of each pipeline, node, and CS are listed in Table A-5. Part of Table A-5 illustrates compressor RPM and the number of active compressors for each CS; Some compressors that do not transmit gas flow are turned off, and others in the transmission path that do not affect gas pressure are bypassed. Despite working together, Networks 1 and 3 generated less income than when they operated independently. This is owing to fixed costs. Indeed, an increase in network elements does not lead to an increase in network gain, necessitating a change in network topology. The collaboration of Network 2 with Network 1 produced 0.32894 synergies, whereas its collaboration with Network 3 produced 0.29664 synergies. Table 4 depicts the income calculated for each network owner using the three aforementioned methods to share revenue.

Table 3: Results of Example 2

	$A_1 = \{1\}$	$A_2 = \{2\}$	$A_3 = \{3\}$	$A_4 = \{1,2\}$	$A_5 = \{1,3\}$	$A_6 = \{2,3\}$	$A_7 = \{1,2,3\}$
$\beta_{so-b}, \beta_{so-sf}, \beta_{so-sa}$	1,0,0	0,1,0	0,0,1	0.665,0.335,0	0.487,0,0.513	0,0.335,0.665	0.399,0.201,0.400
$\beta_{b-sh}, \beta_{b-f}$	1,0	0,0	0,0	0.503,0.497	1,0	0,0	0.503,0.497
$\beta_{a-af}, \beta_{a-ah}$	0,0	0,0	0,1	0,0	0,1	0.479,0.521	0.496,0.504
$\overleftarrow{X_{so-out}}$	14	14	14.74	41.81	28.78	41.81	69.62
$\overrightarrow{X_{d-out}} = \sum_{r \in C_m} X_r$	13.30	13.31	14	39.71	27.26	39.55	65.65
Π_{A_m}	8350678	8376483	8791453	24926420	16947298	24408527	40051470
$EU(A_m)$	0	0	0	8199259	-194833	7240591	14532856
$Synergy(A_m)$	0	0	0	0.32894	-0.01150	0.29664	0.36285

Table 4: Different methods used for allocating coalition payoffs in Example 2

Owner	Shapley	τ-value	core-center
{1}	12115504	11970928	11998336
{2}	15859021	16144770	16093554
{3}	12076945	11935772	11959580
Stable	YES	YES	YES

4. Case Study

4.1. Problem statement

In this Section, a practical example is used to evaluate the network–owner synergy. According to goal 7 of the Sustainable Development Goals, providing more energy is one of the goals of sustainable development [1, 42]. Detailed information on gas pipelines and the European gas network is provided by [15]. Hence, part of the database was selected and used to implement the proposed modeling.

Owing to the large number of gas pipelines and gas-pressure boosting stations, the critical and central portions of the European Union, including portions of the networks in Poland (PL), Germany (GE), and the Czech Republic (CZ), were selected. After Ukraine, Poland experienced unique regional geopolitical circumstances in its western energy corridors. In the network under consideration, Input 1 is the gas pipeline that passes through the Ciechanow station. In addition, the city of Łódź, one of the MIMO network outputs, is considered output 6. Another network entrance was Entrance 19, which was under Poland's control.

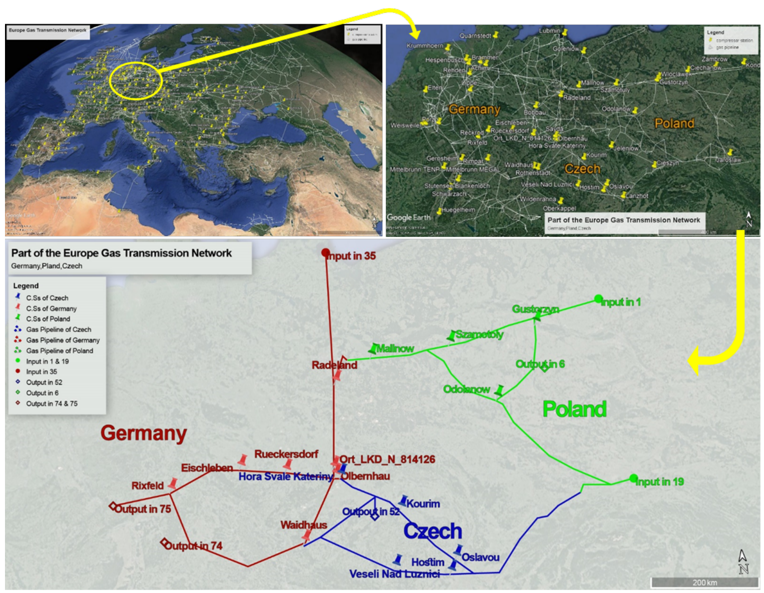


Figure 8: Part of Europe's gas transmission network (Germany, Poland, and Czech Republic)

The NGTN is routed from the Czech Republic to Germany. A portion of this network connects with Germany through Poland. As shown in Fig. 8, the Czech Republic's network is only a transmitter and consumer, and the gas input is not considered. With Exit52, Prague, the capital of the Czech Republic, was regarded as a consumption destination. Owing to its limited domestic NG resources, Germany imports more than 90% of its NG via pipelines from Russia, Norway, and the Netherlands [21]. In this example, an entrance from the north after the Lubmin CS (entrance number 35) was considered; the other entries were from Poland and the Czech Republic. Two exits (75 and 74) were planned in the cities of Koblenz and southern Frankfurt. The parameters associated with the CS and gas transmission pipelines are listed in Tables A-6–A-8 of Annex. The market parameters resemble those in the second numerical example (see Appendix, Table A-4).

4.2. Cooperative and non-cooperative problem solving

The model was solved for all potential coalitions, including individual players ({1}, {2}, {3}), pairs of players ($\{1, 2\}$, $\{1, 3\}$, $\{2, 3\}$), and the entire coalition ($\{1, 2, 3\}$). Therefore, it is necessary to calculate the total synergy and network worth $\Pi(C_m)$, as well as any relevant extra value. Tables A-9 and A-10 in the Annexure display the results of gas pressure flow in the gas pipelines. The input and output CS flow and pressure values are listed in Tables A-11 and A-12 of the Annexure, respectively. Annexure Table A-13 lists the compressor RPM values and the number of active compressors. Each CS, in which the compressors are disabled and bypassed, is shown. Table 5 presents the outcomes of each coalition and the resulting synergies. When owners' operations are performed individually, the supplementary utilities and synergies are equal to zero.

This finding demonstrates that coalition members receive different types of collaborative benefits. As shown in Table 5, the Czech Republic faces only maintenance and fixed costs owing to the lack of gas entry into the network. In addition, Germany and Poland's cooperation is accompanied by losses owing to the provision of maintenance and fixed costs. However, the collaboration between Poland and the Czech Republic achieved a synergy of 0.21759% while the collaboration between the three countries achieved a synergy of 0.14067. Multiowner networks have their own benefits and payoffs, and each scenario has its own structure.

In this section, alternative approaches are employed to determine fair income allocation. The methodologies are listed in Table 6. The core-center, τ-value, and Shapley value are among the considered methods. The analysis was conducted using the TUGlab platform [38], and interesting similarities emerged between the different methods when imputations were considered.

Table 5: Results of the case study

	$A_1 = \{GE\}$	$A_2 = \{PL\}$	$A_3 = \{CZ\}$	$A_4 = \{GE, PL\}$	$A_5 = \{GE, CZ\}$	$A_6 = \{PL, CZ\}$	$A_7 = \{GE, PL, CZ\}$
input in 1		29.196		29.191		29.197	29.191
input in 19						8.411	8.406
input in 35	20.937			20.975	20.937		20.910
output in 6		27.809		27.804		27.809	27.804
output in 52						7.977	7.768
output in 74	13.682			19.920	13.682		14.453
output in 75	6.235			27.809	6.235		5.643
$\overleftarrow{X_{so-out}}$	20.937	29.196	0	50.166	20.937	37.607	58.507
$\overrightarrow{X_{d-out}} = \sum_{r \in C_m} X_r$	19.916	27.809	0	47.724	19.916	35.786	55.668
Π_{A_m}	12297054	17602429	-7500	29823700	12289554	22488074	34785346
$EU(A_m)$	0	0	0	-75783	0	4893145	4893363
$Synergy\,(A_m)$	0	0	0	-0.00254	0	0.21759	0.14067

Table 6: Results for different methods used for allocating coalition payoffs in the reality problem

Owner	Shapley	τ-value	core-center
{1}	12284496	12297162	12256798
{2}	20036444	20030257	16116157
{3}	2464406	2457927	6412391
Stable	YES	YES	YES

4.3. Sensitivity analysis

The sensitivity of the expressed model is analyzed in two different scenarios in the following sections. In the first scenario, changes in the total income across all coalitions based on changes in the purchase price of 1MCM of NG versus the proportion of this amount paid for maintenance and repair costs were analyzed. The second scenario analyzed the variances between the acceptable input and output gas pressures. In both scenarios, the Shapley, core center core-center, and τ-values were used to determine the synergy spectrum and values shared by the countries.

4.3.1. *Purchasing and Maintenance Cost Sensitivity Analysis*

In this sensitivity-analysis scenario, the effects of changes in the price of gas supply in the network's main areas and changes in maintenance and repair costs proportional to the amount of gas purchased on the profit of each coalition were investigated. The gas prices ranged between \$2,000,000 and \$4,000,000 with \$100,000 increments per 1MCM. The cost of repair and maintenance was between 60 and 80% of the amount of gas purchased at intervals of 2%. The total number of examined states was (21×11); Figure 9 depicts all seven types of cooperative alliances.

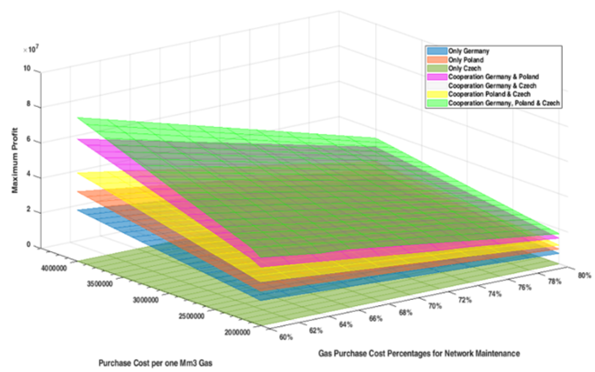


Figure 9: Gas purchasing and network maintenance cost sensitivity analysis–maximum profit for all coalitions combined

Fig. 10 depicts the spectrum of synergy resulting from international cooperation, concerning the sensitivity analysis. As shown in Table 5, there was no spectrum of synergy between Germany and the Czech Republic. According to Fig. 10, decision makers and owners of gas transmission networks can select a more stable and profitable space for cooperation.

In Figs. 12–14, the Shapley, τ-value, and core-center methods are shown to illustrate the spectrum of income shared by the NGTN owners of each country. As can be seen, the income from gas transmission networks increases as prices rise, and maintenance and repair expenses decrease. Poland had the highest profit among the three examined countries, whereas the Czech Republic had the lowest profit.

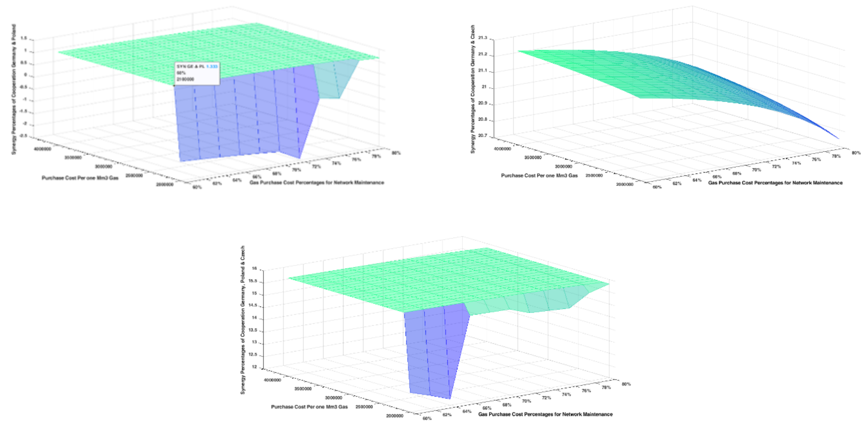
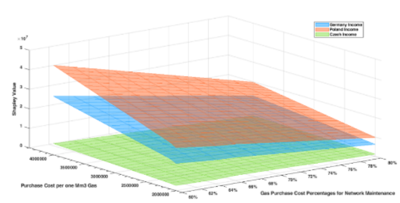
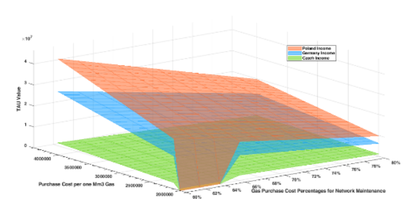


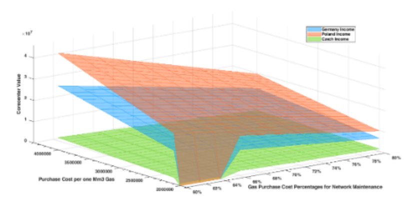
Figure 10: Gas purchasing and network maintenance cost sensitivity analysis–synergy spectrum of each coalition



(a) Shapley value



(b) τ-value



(c) Core-Center

Figure 11: Gas purchasing and network maintenance cost sensitivity analysis–income of each gas pipeline network by three methods

4.3.2. Allowable Input and Acceptable Output Gas Pressure Sensitivity Analysis

The second sensitivity analysis scenario examines the effects of changes in the allowable input gas pressure, acceptable output gas pressure, and each coalition's profits on the network. The minimum acceptable gas pressure for injection into the network was 44 bar, and the maximum pressure of the received gas was 45–55 bar at intervals of 1. The physics of the pipe determines the maximum acceptable gas pressure for output and consumption. The minimum acceptable gas pressure is considered to be between 58 and 68, with a difference of one between the two values. The total number of examined states is shown in Figure 12 as seven coalition states.

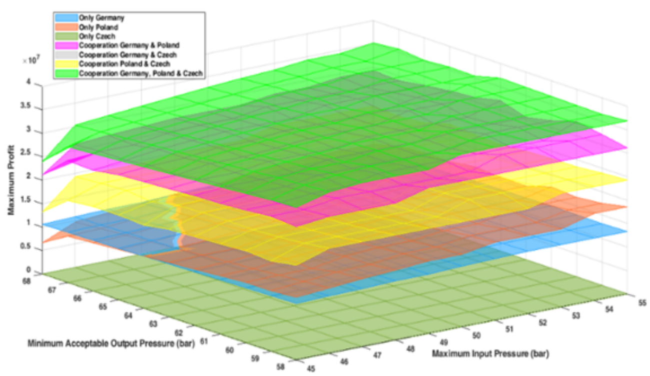


Figure 12: Allowable input and acceptable output gas pressure sensitivity analysis–maximum profit of all coalitions combined

Fig. 13 depicts the spectrum of synergy resulting from cooperation between countries, considering the changes described in this subsection. As stated in the previous section, Germany and the Czech Republic do not share a spectrum of synergy.

In Fig. 14, the Shapley, τ-value, and core-center methods are depicted to illustrate the income spectrum shared by NGTN owners in various countries as part of this subsection's sensitivity analysis. As shown, it is impossible to calculate the τ-value and core-center values when the maximum input pressure is high and the minimum acceptable output pressure is low. This indicates that cooperation conditions are not favorable during these intervals.

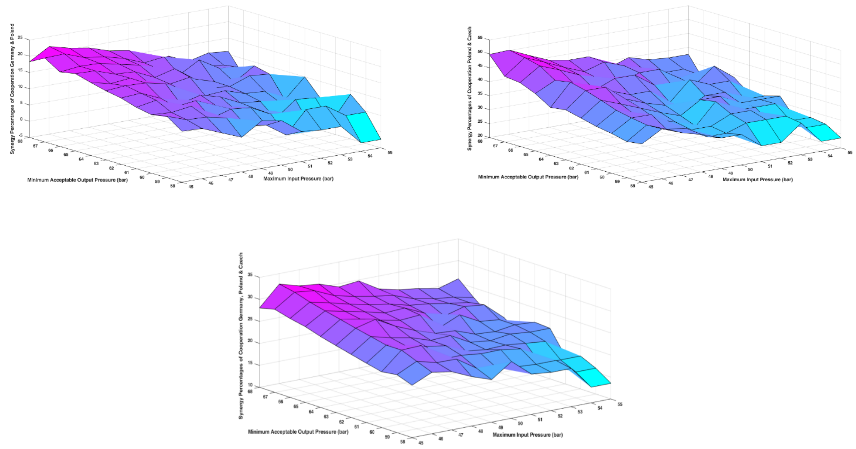
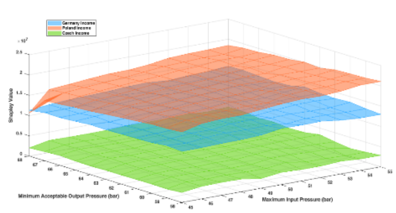
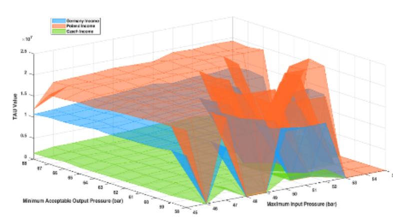


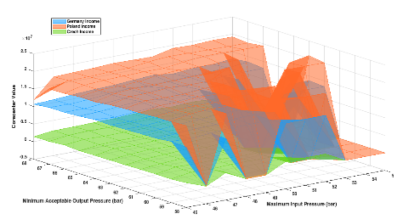
Figure 13: Allowable input and acceptable output gas pressure sensitivity analysis–synergy spectrum of each coalition



(a) Shapley value



(b) τ-value



(c) Core-Center

Figure 14: Allowable input and acceptable output gas pressure sensitivity analysis–income of each gas pipeline network using three methods

5. Managerial insights

Based on an examination of NGTN in the three EU countries, this study presents the following managerial insights and observations:

- The comprehensive functionality of MIMO network nodes and edges must be considered: Incorporating operational functions in nodes and edges and enhancing the accuracy and precision of previously simple models will increase the satisfaction and motivation of companies and nations to cooperate. This strategy is accomplished by redefining the CMFP and considering the various attributes of the transferable material that can be used in MIMO structures. This modeling structure is not unique to gas transmission networks; however, any other trans-network can be modeled using the same method.

- All the quality factors of the material to be transferred must be considered: The matrix approach stated in the modeling of mathematical relationships can be used to calculate the values of several quality factors related to the material to be transferred at the inputs and outputs of each node and link. Therefore, it is possible to model and calculate other qualitative parameters such as reliability and security in transmission with high accuracy in the context of cooperation between networks;, the compiled model is a comprehensive and general model for CMFP-TrNs.

- The CGT must be leveraged to form coalitions and share revenue: Generally, cooperation between networks leads to synergy, but in some cases, cooperation does not occur. From Table 5 and Figs. 9 and 12, it can be deduced that cooperation between networks results in synergy for equitable benefits to companies or countries. The stability of an alliance can be enhanced by accurately evaluating and equitably allocating the synergy generated through network cooperation among the participants. As depicted in Fig. 14, not all collaborations and circumstances increase income; therefore, it is necessary to design, solve, and analyze pertinent mathematical models to determine the optimal conditions and mode of cooperation. To foster active participation and rational decision-making among companies, it is imperative to establish precise definitions of the requirements and parameters pertaining to collaborative arrangements.

- Impact of the model on sustainability: Goal 7 of the Sustainable Development Goals states, “Ensure universal access to affordable, reliable, sustainable, and modern energy” [42]. According to numerous studies, NG has the lowest greenhouse gas (GHG) emissions among fossil fuels [21, 39]. In the context of regional conflicts and natural disasters, a sustainable energy supply requires an artistic approach and the adoption of external and internal border policies. By leveraging the cooperation between networks and establishing fair and accurate models, more gas can be transferred, reducing the consumption of other fossil fuels, and consequently, greenhouse gas emissions.

Transnetworks and industries encompassing a wide range of products and services can explore avenues for collaboration and engage in relevant contractual arrangements and agreements, leading to environmental sustainability and economic resilience. The adoption of realistic cooperative models provides stronger motivation and incentives for businesses to sustain collaborative efforts. Cooperative analysts, consultants, and technical specialists play crucial roles in facilitating this process.

6. Conclusions and Future Research

This study presents a pioneering approach aimed at optimizing the income of individual owners within the context of CMFP-TrN, considering the functionalities of both nodes and edges. A comprehensive model that allows for the modeling of cooperation between any network type was presented. The transferable material in the presented model may have numerous attributes that change during transfer from the nodes and edges; however, it must provide acceptable limits in terms of principles and goals. The proposed model structure is easily applicable to MIMO networks, a modeling framework that can generate favorable outcomes and advantages in terms of promoting environmental sustainability. This framework and model can accommodate both mathematical and non-mathematical functions and operations.

In this study, a SISO-structured numerical examples in the fields of signal transmission and NGTN were designed and solved. In addition, a real-world example of a portion of the European Union's gas network was selected, modeled, and solved for portions of the gas transmission networks in Germany, Poland, and the Czech Republic. To assess their influence on the financial performance of the network, a thorough sensitivity analysis was conducted, encompassing two scenarios based on the market and technical parameters. In certain situations and conditions, cooperation between networks does not produce significant results, and decision makers must find suitable spaces through detailed analyses and make optimal choices. A more precise examination of contracts is required to attain a fair distribution of income sharing. In this study, we established a collaborative game instance utilizing the Shapley value, τ-value, and core-center methods to enhance the analysis.

For future research, we suggest the following recommendations. Besides the primary characteristics analyzed in this study, the transfer time, speed, and chemical and security quality factors should be considered as well. This modeling methodology is also applicable to human operators and task networks. Moreover, this type of modeling can be examined in multidirectional networks with multiple materials transferred simultaneously. Ultimately, a systematic exploration of network collaboration requires the inclusion of participatory models in processes, construction, and engineering economics.

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