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Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Andrey Churkin

PhD Program: Engineering Systems

Title of Thesis:
Stability Analysis in Coalitional Games for Cross-Border Power Interconnection Planning

Supervisor: Prof. Janusz Bialek

Co-advisor: Prof. David Pozo

The thesis document includes the following changes in answer to the external review process.

I want to express my gratitude to both internal and external reviewers, who put much effort into reading the thesis scrupulously and making useful comments and suggestions. Many of the comments aim to improve the clarity in the presentation of results, open interesting discussions, and highlight future research directions. Thanks to the reviewers' suggestions, during the last few weeks, I improved the thesis significantly through text editing, additional discussions, explanations, and simulations. I hope that the committee will be satisfied with the latest improvements in the work.

The purpose of this document is to specify the changes in the thesis and directly reply to reviewers' comments and questions. I group the modifications by reviewers who requested them. The reviewers are listed in alphabetical order (as they appear in the Skoltech system): **Ross Baldick, Javier Contreras, Clement Fortin, Elena Gryazina, Benjamin Hobbs, Henni Ouerdane.**

For the sake of clarity, I use the following notations while responding to the comments. Citations from the reviewers' reports are displayed in *italics*. Then, my response is given using the regular font. Finally, the modifications in the thesis are provided in blue color. All page and reference numbers in the response are based on the revised thesis unless otherwise stated.

I hope to address the remaining questions during the upcoming defense.

Sincerely,

Andrey Churkin.

Response to Prof. **Ross Baldick**

Prof. **Ross Baldick** left multiple useful suggestions and questions throughout the thesis draft, which I highly appreciate. All of the comments were incorporated into the final version of the work. Below I address some of the main points.

Comment:

"stability is commonly used in power systems to refer to stability of dynamical systems modeling electromechanical transients. I appreciate that you added "cooperation" here, but perhaps there is another way to phrase this, eg analyzing stability of coalitions"

Response:

I agree with the comment. After several discussions with my advisors, we decided to use the following title:

STABILITY ANALYSIS IN COALITIONAL GAMES FOR CROSS-BORDER POWER INTERCONNECTION PLANNING

Comment:

"What about economies of scale in transmission construction?"

Response:

Thank you for the comment. The economies of scale have been mentioned in Section 1.2. Please, find the modifications below.

Additional benefits of cooperation may be reaped due to the economies of scale in transmission construction [53], [54]. A large-scale transmission expansion project can lead to a lower per MW cost than a series of smaller transmission constructions. This effect should also be reflected in cost allocation mechanisms. In this regard, in [50], *Stamtsis and Erlich* stated, "The allocation of embedded costs is a typical case where the cooperation between some agents produces economies of scale. Consequently, the resulting benefits have to be shared among the participating agents. The Cooperative Game Theory concepts, taking into account the economies of scale, suggest reasonable allocations that may be economically efficient."

Comment:

"definition of transit flow and loop flow?"

Response:

I fully agree with the comment. The following footnote has been added at the beginning of Section 1.2.1 to clarify the discussion.

The transit flows, loop flows, and counterflows are the well-known phenomena in transmission systems. The point is that the power purchased does no flow according to a contract. Instead, it follows the laws of physics and flows through available parallel paths, leading to unintended outcomes. Transit flow is the share of power that is transmitted through a third party's network. Such flows cause an additional load of equipment and power losses. In some cases, a share of export power can flow back to the exporting power system. This effect is called a loop flow. An increase in generators' output power at the importing system creates a counterflow that can decrease the amount of inflow power purchased. We refer to [29], [30] for the detailed discussion of unintended flows in transmission systems.

Comment:

"all of these items: cost reduction, CO_2 reduction, and losses are commensurable (at least given a carbon price), so I do not think they are a fundamental problem. A more fundamental problem would be presented by attributes that are incommensurable. Do you have an example of incommensurable attributes?"

Response:

Thank you for the comment. The discussion of transferable utility game assumptions in Section 2.5 has been expanded. Please, find below the modified part where I discuss the incommensurable attributes of cooperation.

Some authors mentioned the transferable utility assumption as a crucial one. The point is that in practice, it may not be possible to fully represent the worth of cooperation in transferable units, say monetarily. The values such as fuel cost, generation cost, and transmission investment cost can be represented monetary and serve as a basis for transferable utility games. However, other attributes of cooperation cannot be easily measured. For example, the cost of CO_2 emissions depends on current carbon pricing mechanisms, which could significantly differ from country to country [124]. Other incommensurable attributes include: number of jobs appearing due to the project; the overall impact on countries' economies; environmental impacts of transmission lines; future opportunities related to the transmission project; shifts in political power, political or economic dependence, and mutual trust. Moreover, the outcome of cooperation could be multi-valued. For example, electricity trade could lead to cost reduction, CO_2 emissions reduction, an increase in power losses, etc. Considering the above values and their possible combinations, it might not be always practically possible to apply the TUG formulation in cross-border TEP projects.

Comment:

"a good topical example of this is Nordstream"

Response:

I agree. The discussion in Section 2.5 has been extended. Please find the modified part below.

However, it is worth addressing the dynamic nature of cooperation. In the first stage, players may cooperate in planning and building assets. Then, several stages of operation follow. During the operation, some players may change their initially declared strategy or refuse cooperation at all. An example of multistage cooperation can be found in the European gas transmission system. In 2012, the Nord Stream project was completed, which allowed natural gas export from Russia to Germany through offshore gas pipelines. Despite the economic benefits, the project affected multiple countries' interests and raised questions of energy security [125], [126]. As a result, the expansion of the project (named Nord Stream 2) was halted due to international sanctions and imposed European gas import regulations. This case clearly indicates the need for accounting externalities and dynamic changes in international projects.

Comment:

"I am not sure I agree with this. In the US, for example, RTOs seem to have taken over the role of transmission planning from their constituent transmission owners. This means that classical approaches are possibly now more applicable in deregulated power systems because there is a single planner. Of course, individual owners might choose to not cooperate!"

Response:

Indeed, RTOs in the US and ENTSO-E in Europe have regional planning roles and can implement centralized TEP approaches. However, such regional planning still requires cost and benefit allocation mechanisms among independent system operators and market participants. Moreover, in many regions, there are no coordinating entities to develop and promote cross-border power interconnection plans. Therefore, decentralized and game-theoretic planning approaches are of great interest.

The discussion in Section 2.6 has been modified to give more details about the problem. I also included the quotes from three papers that justify why Cooperative Game Theory becomes a promising tool in TEP cost allocation. Please, see the modifications below.

While being useful for finding optimal (for example, least-cost) decisions, classical expansion planning approaches are not able to fully address the modern issues of deregulated power systems. There is a need for novel methods applicable to the multi-agent environment that include allocation mechanisms and can provide effective economic incentives to independent participants. Even in the presence of the planning and coordinating entities such as Regional Transmission Organizations (RTO) in the US [127] and the ENTSO-E in Europe [128], it is still necessary to develop rational cost and benefit allocation rules and inter-PSO compensation mechanisms. In [49], *Evans et al*. stated, "A network expansion can generate multiple effects, such as load flow changes, relief of congested lines, etc., as well as a variation of the benefit of the connected agents, depending on existing expansion plans. Game theory, and Cooperative Game Theory in particular, arises as an appealing tool to deal with the matter, with advantages over other cost assignment methods, given it considers interaction by the agents and their rationality in decision making." In [50], *Stamtsis and Erlich* mentioned, "In the modern deregulated electricity markets the issue of network fixed-cost allocation is of great significance. The reason for this is that the fixed-costs are the largest part of transmission charges. Therefore, it becomes obvious that there is a big demand for a fair and effective allocation of the costs among the market participants. Discrimination policies, by assigning unreasonably high use-of-network charges, could be applied in order to prevent some market participants accessing a part or even the whole network. Several methods have been proposed for a proper allocation of fixed-costs. Although these methods are well established from an engineering point of view, some of them may fail to send the right economical signals." The authors then concluded that Cooperative Game Theory could be a good basis for reasonable and economically efficient allocations. In [51], *Ruiz and Contreras* also referred to the restructured market environment. They justified the need for using Cooperative Game Theory in the following way, "In this multi-player setting, the lack of appropriate incentives has resulted in investments in transmission not keeping pace with load growth and investments in generation. As a result, the network is being frequently used at its maximum limits, leading to economic inefficiencies and reduced reliability. Hence, new, effective incentive schemes are needed for transmission network expansion. The incentives have to take into account both the prospective investors and the prospective users of the new assets." To solve the above cooperation and cost allocation issues, more scientists turn attention to Cooperative Game Theory and other multidisciplinary approaches. We hereby conclude that our work contributes to the highly relevant and developing research direction.

Comment:

"Could you indicate which chapters involve which contributions? From my reading, most of chapters 2 to 4 is background and stylized examples, and it is only in chapter 5 that you begin to make a seriously original theoretical contribution. It would be helpful to point the read to what is background and what is fundamentally new."

Response:

I agree with the comment. The Original Contributions section has been modified. It is now mentioned which chapters involve the contributions.

Comments on the two-system case in Section 3.1:

"unless there is some compensation for them [consumers]."

"I know that this is a first introductory example, but it would be useful to also explore a two-period model where the direction of flow is different in each period. This represents eg seasonal diversity and can result in net benefits to consumers in both places."

Response:

Thank you for the comment. I agree that multi-period models can give more insights. However, I do not want the reader to be distracted by additional cases. The allocation of benefits among producers, consumers, and transmission investors is an important issue. But, it is not the main focus of the work. I decided to avoid additional simulations and extended the discussion instead. Please, see the modifications below.

But, the consumers in System A have to pay more after the interconnection and, therefore, should be against the market integration unless there is reasonable compensation for them. It is worth mentioning that trading in pool-based electricity markets can be far more complicated than illustrated in our two-system case study. For example, the operation of real-world electricity markets implies repeating market clearing procedures. In this regard, studies as [138] suggest formulating multi-period market equilibrium problem. It might happen that the power flow between the systems will reverse its direction due to the seasonal changes. In such cases, the power systems can export and import electricity in turn, which will result in net benefits for consumers in both systems. For the sake of clarity, in this chapter, we consider a single-period model where System A acts as an exporter and System B as an importer.

Comment (on the model in Section 3.2):

"Why no binary decision variables for build/not build?

Why no economies of scale in transmission construction?

Why no admittances?

Why no contingency cases?

I realize that there is some discussion of this below, but the simplifications should at least be briefly acknowledged up front."

Response:

Thank you for the comment. We used the mentioned assumptions to keep the TEP model simple and linear. This allowed us to focus on game-theoretic aspects of cooperation, perform the manipulability analysis, and develop the bilevel TEP model.

I mentioned at the beginning of Chapter 3, "However, our interest lies in Cooperative Game Theory applications in TEP cost allocation. Thus, we avoid using complex expansion models to provide clear insights into possible allocation solutions. We consider TEP as a static, deterministic, centralized, linear programming model. The exact mathematical formulation is given in the following sections." And then, in Section 3.2, "To provide clear insights into Cooperative Game Theory applications, we avoid using complex models and rely on the classical cost-based transmission planning..."

The following modification has been added right before the introduction of the TEP model.

Before introducing the model, we briefly mention the main assumptions. We do not consider admittances of power lines, reactive power, voltage magnitudes and angles. By doing this, we formulate a linearized OPF model with fully controllable power flows. We omit the constant part of transmission investment and, therefore, do not introduce binary decision variables of lines' construction decisions. Transmission capacity is treated as a continuous variable. The cost of transmission investment linearly depends on the capacity. Thus, economies of scale in transmission construction are not considered in our formulation. We also do not perform the contingency analysis. These assumptions allow us to keep the TEP model simple and focus on the game-theoretic aspects of cooperation. The resulting optimization problem is formulated as the following linear programming model.

Comments on the characteristic function formulation in Section 4.1:

"this section is very confusing. I think you have cost and value muddled in the definitions. Please fix this!"

"so, to be clear, v represents value and bigger v is better, right?....but this seems to contradict much of the discussion below."

"....but this says that the merger is less desirable than the sum of the individual utilities. Did you intend \geq rather than \leq ?"

"Unitil here, discussion was about value; here you discuss minimizing costs. So, is cost equal to minus v? Please clarify."

"Here talking about cost. Is cost equal to v or minus v?"

"on page 91/211, you referred to v(N) as the value of the grand coalition, not the cost. Please fix these inconsistencies!!!"

"is x a vector or a set? I do not understand what you mean by x(N;v)"

"Comment: you have not explicitly defined value versus cost games! This is part of the reason why your section 3.1 is so confusing!!!"

Response:

Thank you for pointing this out. There was the following comment at the beginning of Section 4.1 (definition and properties of cooperative games).

"At this point, it is important to highlight the interpretation of the characteristic function. If a value $v(S)$ associated with a coalition S represents some profit or gain that players obtain together, then a cooperative game is called a profit (or value) game. However, in this work, we are interested in cost games, where players act together to decrease the costs that their coalitions should pay. Therefore, in the following definitions, we imply that the characteristic function is formulated in terms of costs."

However, I have realized that the section could be confusing. Modifications have been added throughout the section to avoid ambiguity.

Comment:

"How does this relate to a traditional 'split savings' rule in inter-utility trade?"

Response:

Electricity trade between two utilities can be achieved via a bilateral agreement with a specified price and amount of energy. In this case, the savings of cooperation will be split in a ratio that depends on the contract price and cost functions of the utilities. Multiple allocation solutions are possible. This is the point that we address in the thesis. We try to justify the allocation of savings (or any value of cooperation) and then estimate the payment needed and the contract price.

One simple mechanism used to support transmission interconnections is the equal share principle. Under this paradigm, each country hosting a new (bilateral) transmission project is responsible for financing 50%

of the capital costs of the transmission project and gets a 50% share of the congestion rents. In [58], *Kristiansen et al*. studied the cost allocation of the North Sea offshore grid and compared the equal share principle with Cooperative Game Theory solution concepts. It was shown that the Shapley value leads to more reasonable allocation solutions and, therefore, can be used as the basis for defining power purchase agreements.

Comment (on the bilevel TEP model in Section 6.1):

"Indeed, but any actual TEP problem is non-convex because of binaries to represent build or not build decisions."

Response:

I agree with the comment. The additional discussion has been added in Section 6.1 to highlight the issues of nonconvexities. Please, see the text below.

This is the reason why we keep the TEP model (3.1)-(3.5) linear. KKT conditions can be applied only to models with continuously differentiable convex functions. In the case of nonconvexities such as binary variables representing investment decisions, the bilevel model reformulation based on KKT conditions does not guarantee that the global optimum will be found. Similar issues appear in electricity market pricing with unit commitment and economic dispatch, where integer decision variables make the problem nonconvex. Multiple studies relied on the convex hull formulation to overcome the issues of pricing under nonconvexity [183]–[185]. Solving bilevel optimization programs with nonconvex lower levels is also a challenging task that requires using constraint smoothing algorithms and heuristics [186]–[188].

Comment (Section 7.2.3):

"this needs more explanation!" [on the money flows and bilateral contracts]

Response:

Thank you for the comment. The point of the money flows example is to demonstrate that arranging bilateral contracts and payments can be a challenging task. Cost allocation solutions based on Cooperative Game Theory can lead to economically counter-intuitive results, for example, where exporters sell a share of power at a price lower than their marginal costs. This effect depends on the topology of interconnections. In the case study, a share of power from Russia to Japan went through Mongolia, China, the DPRK, and the ROK. It would be impossible to arrange bilateral contracts and payments that do not contradict nodal pricing, as we visualized in Figure 7.9.

The discussion in Section 7.2.3 has been modified to explain better the possible contradictions between Cooperative Game Theory and locational marginal pricing.

Comment (on Section 7.2.4):

"How about sensitivity to transmission capital costs? Eg, initial estimates for CREZ transmission in Texas came in at around $5 billion and cost-benefit studies were based on this number and partly used to justify construction. However, actual transmission construction costs were around $7 billion, ie 40% more than estimated. Using the actual transmission cost, and everything else equal, the cost-benefit studies would have indicated that CREZ was not economic from the perspective of avoiding gas generation costs. (The cost-benefit study ignored carbon benefits of renewables, but used much higher gas prices than turned out because increased fracking meant that gas generation prices were much lower than assumed in the cost-benefit studies.)"

Response:

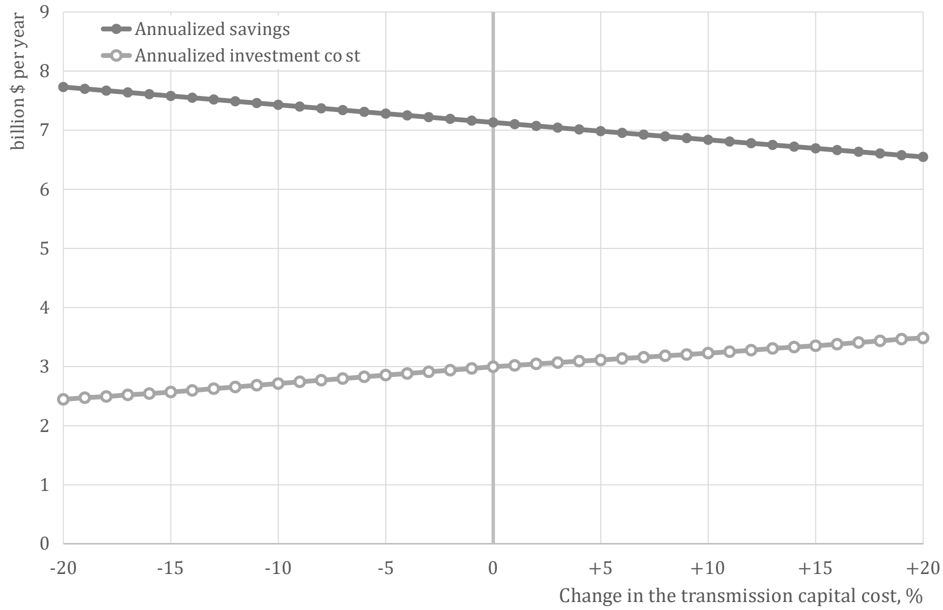
Thank you for the comment. This is indeed an important aspect that I missed in the sensitivity analysis. Section 7.2.4 has been modified. I performed additional simulations and included the discussion of the sensitivity to transmission capital costs. Please, find the modified parts below.

Finally, we analyzed the sensitivity to transmission capital costs. Our initial transmission cost assumptions (given in Table 7.3) were varied for every line in the range of -20% to +20%. The analysis is shown in Figure 7.12. The dependence of the total cost savings on the transmission capital costs is rather obvious: higher investment costs decrease the savings of cooperation (Figure 7.12 (a)). The resulting curves resemble a linear dependence with an average correlation factor of -1.15, which means that a 1% increase in transmission capital costs leads to a 1.15% decrease in the total cost savings.

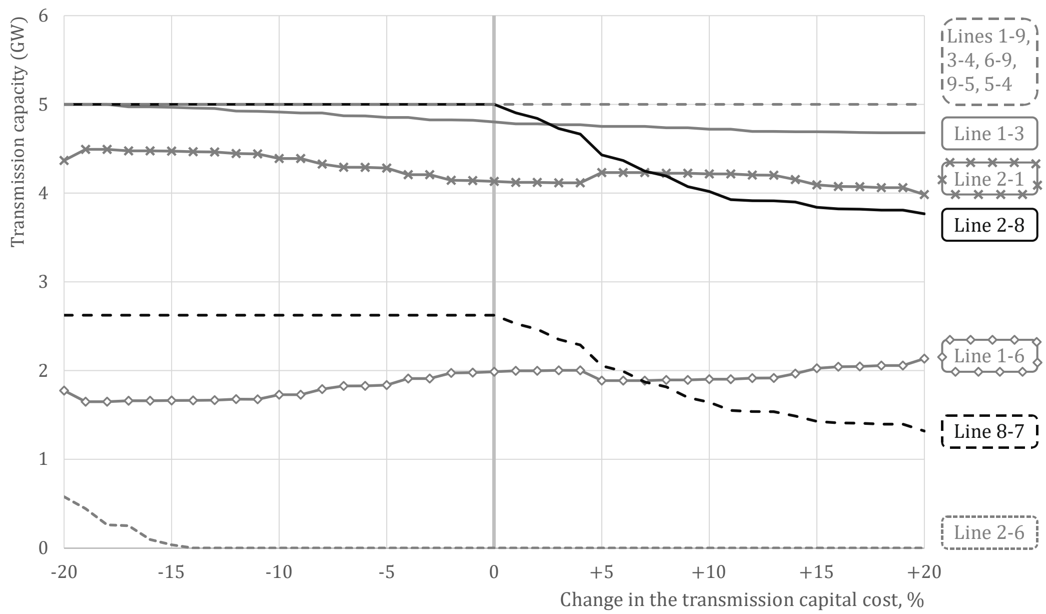
To give more details on the project's possible outcomes, we visualized the dependence of optimal transmission capacities on the capital costs in Figure 7.12 (b). Several lines close to the ROK and Japan, namely lines 1-9, 3-4, 6-9, 9-5, 5-4, are not sensitive to moderate changes in transmission capital costs. Those lines are always built up to the maximum capacity of 5 GW, which tells us that the interconnections are highly effective and bring significant cost reduction to the systems. Other lines, such as 2-8 and 8-7, turned out to be sensitive to the cost assumptions. These lines correspond to the Russia-Mongolia-China power export corridor. The conclusion could be drawn that this power export route is less effective than other interconnections. Lines 2-8 and 8-7 could be built with less capacity or even be abandoned in the project due to changes in the transmission capital costs.

Accurate estimation of transmission capital costs is an acute issue for many expansion projects. For example, in 2008, the Public Utility Commission of Texas started the Competitive Renewable Energy Zone (CREZ) program, which aimed to connect distant regions with cheap wind energy to the main grid and accommodate more than 18 GW of wind power. The program was essentially completed in 2013. However, the transmission cost grew from the estimated 4.9 to 6.8 billion dollars [207]. Such an increase made power from new wind plants more expensive than from conventional power plants. Even though some studies praise the cost and CO_2 reduction achieved by CREZ [208], there exist disputes over the program's rationality [209], [210]. Some critics state that the government rushed to promote wind power, which was not yet competitive. As a result, Texas consumers should pay for electricity more.

Summarizing the sensitivity analysis, we could say that higher power demand of the systems, lower shares of renewable generation, and lower transmission capital costs are favorable factors for the Asian Super Grid project that increase the effectiveness of the proposed interconnections. The possible risks of the project include the decrease in power demands, higher renewables integration, and underestimation of the actual transmission construction costs.



a)



b)

Figure 7.12: Sensitivity analysis for transmission capital costs: dependence of the annualized savings and investment cost (a); dependence of the transmission capacities (b).

Response to Prof. **Javier Contreras**

I thank Prof. **Javier Contreras** for the very positive review of the thesis. There are no particular questions or modification requirements in the reviewer's report. I hope to address any remaining questions during the thesis defense.

Response to Prof. **Clement Fortin**

Prof. **Clement Fortin** appreciated the quality of the thesis and the results presented. I am grateful for such a review. There are several comments in the reviewer's report, which I address below.

Comment:

"The Citation Network Analysis methodology used for the literature review is very well presented and the diagrams and the corresponding text provide a very clear perspective on the field. I suggest to add a few references for the method and tool used for the literature review."

Response:

Thank you for the comment. I briefly mentioned the literature review tools at the beginning of Chapter 2:

"We used the Scopus citation database and Gephi software [60] to collect and visualize the references."

"To further analyze the citation network, we exploited graph layout algorithms that allow spatial mapping of interconnected groups of nodes, namely "ForceAtlas2" [61] and "Yifan Hu Proportional" [62]. The community structure was retrieved by the modularity algorithm [63]."

However, I have now realized that more details should be given about the algorithms used. The following explanations have been added to Section 2.1.

We visualized the main stages of the citation network exploration in Figure 2.1. First, information on the three generations of references was collected from the Scopus database. Each reference has been assigned an ID number, which corresponds to a certain node in the network. Similarly, every citing was recorded as a link between two papers (nodes). Thus, tables of nodes and edges were created, which could be directly exported to Gephi software. The initial collection of references is shown in Figure 2.1 (a). It is practically impossible to analyze such a disordered network. We, therefore, applied graph layout algorithms to reach a decent visualization of the network's structure. The first graph layout algorithm selected was ForceAtlas2 [61], which is a powerful tool of force-directed graph drawing. Force-directed graph layout algorithms provide intuitive results since they simulate a physical nature to spatialize a network. As the authors state in [61], "Nodes repulse each other like charged particles, while edges attract their nodes, like springs. These forces create a movement that converges to a balanced state." Thus, the algorithm stretches out the network depending on the topology, initial positions of nodes, parameters as the attraction force, the repulsion force, gravity, etc. The resulting layout is displayed in Figure 2.1 (b). The visual densities of the graph denote structural densities, which represent communities and groups with stronger relations. However, the layout is yet too tight. Groups of nodes form bunches with significant overlapping. To further improve the network visualization, we exploited another force-directed algorithm developed by *Yifan Hu* [62]. The algorithm combines a multilevel approach based on the global energy model. The movement of nodes has an adaptive speed with ''heating'' and ''cooling'' phases. This creates a layout resembling an explosion snapshot, as shown in Figure 2.1 (c). Such a layout clearly reveals the network's structure. But, it lacks community identification. To analyze the community structure of the network we launched the modularity optimization algorithm [63]. The algorithm iteratively regroups nodes until a high quality of partitioning is achieved. The identified communities can be highlighted using different color schemes, as shown in Figure 2.1 (d). Finally, the nodes' sizes can be set proportional to the number of citations.

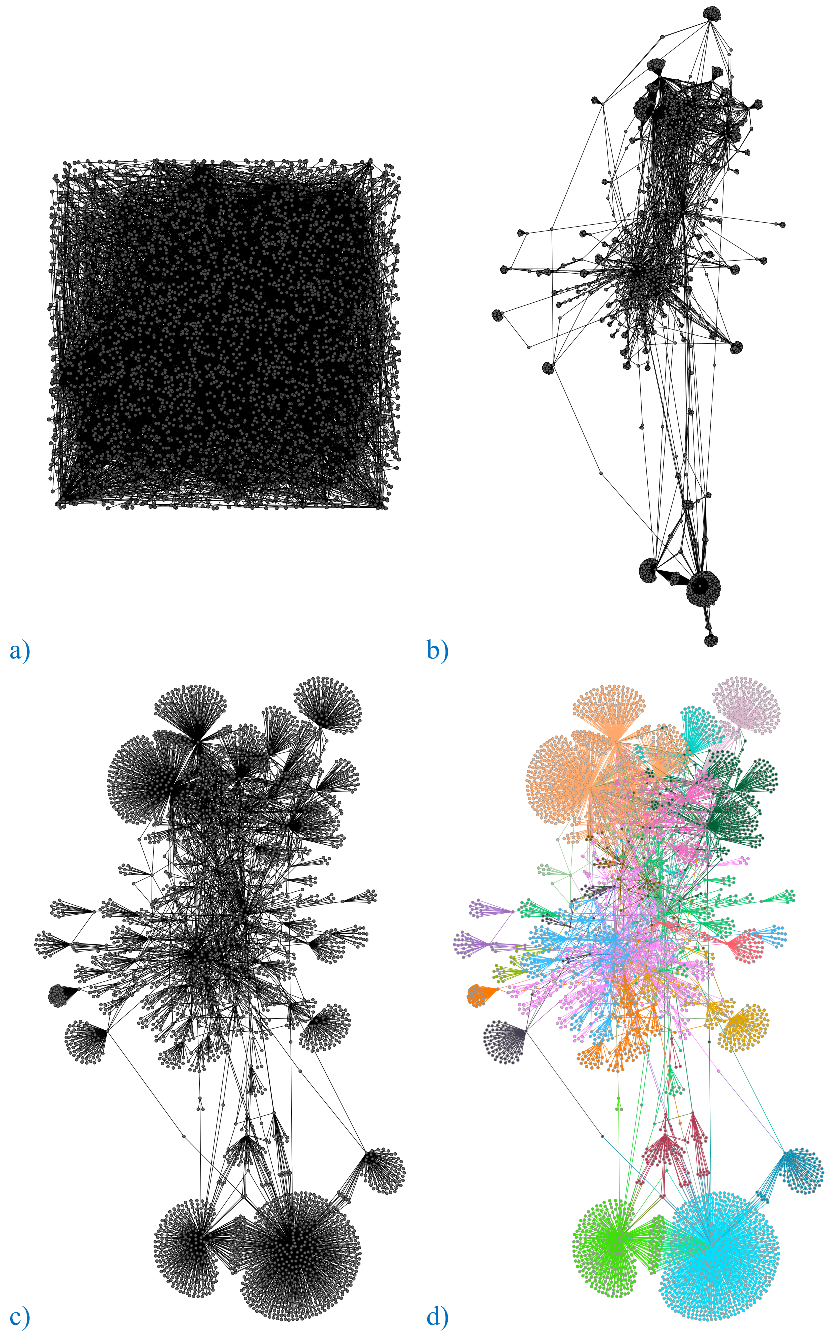


Figure 2.1: Citation network exploration: a) initial collection of the references from Scopus database; b) application of ForceAtlas2 layout algorithm; c) subsequent application of Yifan Hu Proportional layout algorithm; d) extraction of the community structure via the modularity algorithm.

Comment:

> *"I was surprised to see that the analysis of chapter 3 is based on Costs as the main parameter rather than Value. I think that business partners are looking much more at value than strictly costs in any of their negotiation strategies. The mathematics are certainly correct, but it is more a question of the philosophy of approach."*

Response:

Thank you for the comment. Cooperation on a power interconnection project can be viewed from different perspectives. Indeed, the value of cooperation in terms of profit can be more appealing for investors. However, the main benefits of electricity trading come from cost savings and possible CO_2 emissions reduction. Therefore, it makes sense to formulate cooperative cost games, where a synergy of cooperation comes in cost savings. Many of the preceding works focused on TEP cost allocation issues and formulated optimization models for investment and operating costs minimization. The corresponding cooperation was usually formulated as cost games. However, it is worth mentioning that several studies considered value games based on the social welfare and surpluses of players. For example, in [106], *Banez-Chicharro et al*. aimed to estimate the impact of transmission expansion projects on the social welfare using the Aumann-Shapley approach. In [119], *Hasan et al*. considered the cost allocation of renewable power integration projects based on the net market benefit. The formulation of benefits included producer surplus, consumer surplus, merchandizing surplus, carbon emission tax, and additional payments. *Kristiansen et al*. [58] considered the allocation of both benefits and costs that result from the development of international transmission interconnections. The authors stated that "trading of electricity between regions as a result of new transmission capacity in congested lines always results in nonnegative changes of welfare and net welfare in aggregate terms." The welfare was formulated as the sum of consumer and producer surpluses and congestion rents.

I did not change the cooperative game formulation and the subsequent allocation results in the thesis. Instead, a discussion has been added to Section 4.3.1 to clarify possible formulations.

Response to Prof. **Elena Gryazina**

I thank Prof. **Elena Gryazina** for the positive feedback on the thesis. There is one question in the reviewer's report that requires additional discussion. Please, find my response below.

Comment:

> *"Taking into account the decentralization trend (in particular, microgrids development) I'm just curious if the approach proposed in the Thesis could be used to analyze cost and benefits of turning to autonomous mode significant part of the grid with developed distributed generation. Although in the Thesis the transmission grids were analyzed, the proposed mathematical framework seems to work regardless the voltage level."*

Response:

Thank you for the question. Game Theory in general, and Cooperative Game Theory in particular, has a wide range of potential applications in power systems. The game-theoretic framework developed in the thesis can be used not only in cross-border interconnections analysis but in every planning task that concerns the interests of several independent players. As you rightly noted, it works regardless of the voltage level.

As found in the citation network analysis (Section 2.4), multiple studies focused on the Cooperative Game Theory applications for microgrids. It has been demonstrated that microgrids can bring significant savings if cooperating in energy exchange and demand-side management. Such cooperation can potentially increase the overall stability, monitoring, and control of microgrids. I found an encouraging review of game-theoretic methods for smart grids in [102].

The methods mentioned can be used not just in microgrids planning or ex-post analysis of cooperation. It is expected that Game Theory will help to create autonomous grids with decentralized operation and control. In such a case, the role of Cooperative Game Theory would be to provide allocation rules with effective economic incentives for autonomous players. The authors of [102] concluded, "Clearly, cooperative games could become a foundation for introducing local energy exchange between microgrids in future smart grid systems. This local energy exchange could constitute one of the main steps towards the vision of an autonomous microgrid network." Possible benefits of microgrids coordination based on Cooperative Game Theory were also thoroughly studied in [103], [121].

I hope to address the remaining questions during the defense.

Response to Prof. **Benjamin Hobbs**

Prof. **Benjamin Hobbs** wrote eight pages of detailed comments and suggestions. I am grateful for such a thorough review of the thesis. Most of the comments have been incorporated into the final version of the work. I do not include the entire list of comments in the changes log file. Instead, I group my response in a way that Prof. **Benjamin Hobbs** did in his report: comments on **general contribution**; comments on **coverage of literature**; comments on **thesis structure**; comments on **Chapter 6 model (Chapter 5 in the previous numbering) and simple examples**; **other comments**.

General contribution comment:

"'The question arises, what is the possible implementation and justification of the bilevel TEP approach for real-world projects?' This is a very interesting question. It would be interesting to discuss the role of the World Bank and other funding agencies in steering negotiations, and what preferences they might have. They could refuse to fund a project if too many benefits are given up. The thesis does not consider the roles of such third parties (in addition to the participating countries), does the author have any suggestions/ideas to offer?"

Response:

Indeed, this could be a possible application of the bilevel planning approach. I added the following point to Section 6.2.3.

Second, the bilevel planning approach can be used by the World Bank and other funding institutions and agencies in the assessment of projects and negotiations. A preference could be given to projects with an acceptable level of coalitional stability. In other projects, a compromise between stability and economic efficiency could be found. A project that requires giving up many benefits to be coalitionally stable would be refused.

General contribution comment:

Several comments mention the incompleteness of manipulations analysis in Chapter 5 (Chapter 4 in the previous numbering).

"Perhaps the problem is too difficult, but the discussion of manipulation in Chapter 4 feels incomplete. Section 4.2: This section shows the effect of unilateral manipulation, given truthtelling by the other side (Figs. 4.1a,b), and coordinated manipulation (each matches the action of the other, Fig. 4.1c). The discussion seems incomplete to me. The question is asked " what happens if one of the systems (or both of them) behave strategically and declare its supply cost function untruthfully?" The answer is incomplete, though, without an equilibrium analysis. What is the equilibrium? If we assume that players are either Nash in manipulation strategies, or believe that the other side is telling the truth when it is actually lying, an equilibrium level of manipulation for each player should be obtainable. (An assumption has to be made about whether the interconnection is itself a decision variable, and how the costs are allocated between the two players. Does the player recognize that if the benefits from the market are too low, the line won't get built? In that case, is the equilibrium perhaps at a level at which there seem to be zero apparent netbenefits (zero apparent value to the coalition, net of the line cost)? …"

"The relationship between manipulability and the extensive literature on supply function equilibrium (SFE) models needs to be mentioned."

"So a more general equilibrium should consider both the effect on short-term spot market profits (a la Berry, Baldick etc.) and on the allocation of network costs, yes? This should be explicitly stated to be a

generalization of the SFE literature. And how the equilibrium feeds back to the network design decision should be discussed. Has anyone pointed this out before, either in an electricity context, or in SFE-type models for other markets?"

"Section 4.3 (3 region case) seems incomplete in the same way."

Response:

Thank you for pointing this out. Indeed, a thorough analysis of equilibria in manipulation games is needed. It could take another thesis to examine possible players' strategies under different allocation rules and assumptions. Therefore, I decided to focus on the two-system case and perform an equilibria analysis for it. Section 5.4 "Equilibrium Analysis of Manipulation Games" has been added to the thesis, where I discuss existing equilibrium approaches and visualize the manipulation game in the two-system case study.

Please, find the figure for the equilibrium analysis below. As you correctly mentioned in the report, the equilibria happened at the level with zero apparent benefits. Here is a part of the discussion that I give in Section 5.4:

Interestingly, the equilibria are located near the strategies that cause a slight decrease in the overall efficiency of the project. We repeated the simulation for 6,400 strategies in the same range of cost deviations and found that, indeed, the equilibria are right on the brink of the optimal transmission investment. These strategies correspond to cooperative games with almost zero savings revealed. Further cost deviations will result in suboptimal planning solutions with less transmission capacity. The equilibrium analysis shows that, under the current manipulation game formulation and TEP assumptions, players would not have incentives to harm the overall efficiency of the transmission project while manipulating their cost functions. The resulting expansion plan would remain optimal or near-optimal. However, the main problem of such manipulations lies in the fact that very few savings of cooperation will be revealed. Transmission projects with low profitability can be considered economically or politically unacceptable.

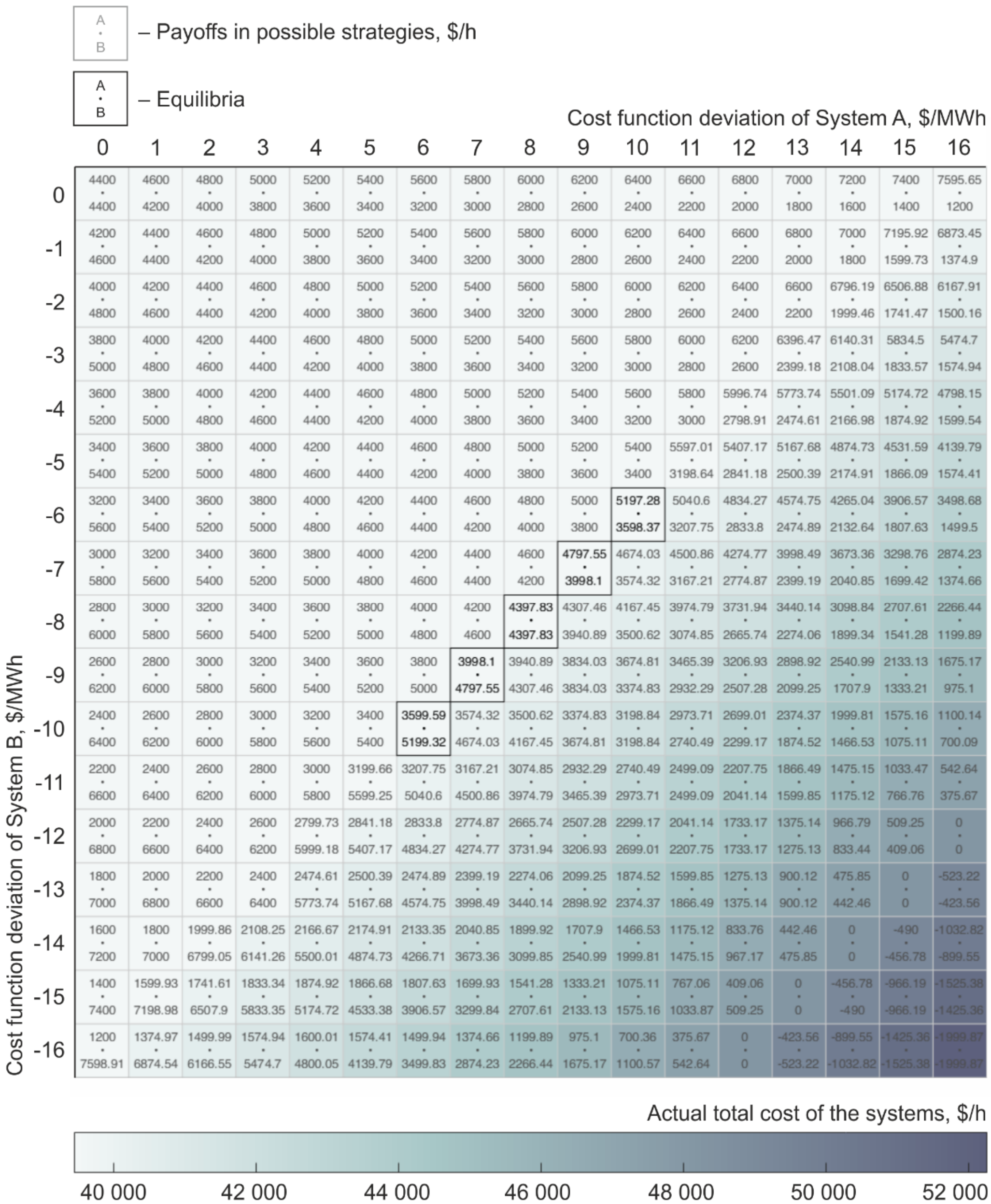


Figure 5.4: Equilibrium analysis of manipulations in the two-system case study.

Comment on **coverage of literature**:

"One of the earliest studies on mathematical programming applications in power systems planning was done by Massê and Gibrat [118]," Who first proposed having transmission capacity as a decision variable? p. 62. Pipes and bubbles formulation of the TEP--When did this first appear in the literature? (See Turvey and Anderson's survey in the Bell Journal, or their book for a survey)."

Response:

Thank you for suggesting the references. The introduction of Chapter 3 has been complemented with the discussion of the early TEP models. Please, find the modified part below.

One of the earliest studies on mathematical programming applications in power systems planning was done by Massé and Gibrat [130], who formulated a linear programming model for optimizing decisions of investment in power plants. Bessière [131] discussed methods of optimal electrical equipment investment in France. In the following years, Bessière and Massé demonstrated the practical value of linear and nonlinear programming in expansion planning and marginal cost pricing. The early models neglected Kirchhoff's voltage law and used the transshipment formulation of load flows (also known as the transportation problem, or "pipes and bubbles" formulation). These models were later documented by Turvey and Anderson in their classic book on electricity economics [132] and the preceding reviews [133]. Since then, the optimization models substantially complexified to account features of modern power systems.

Comment on **coverage of literature**:

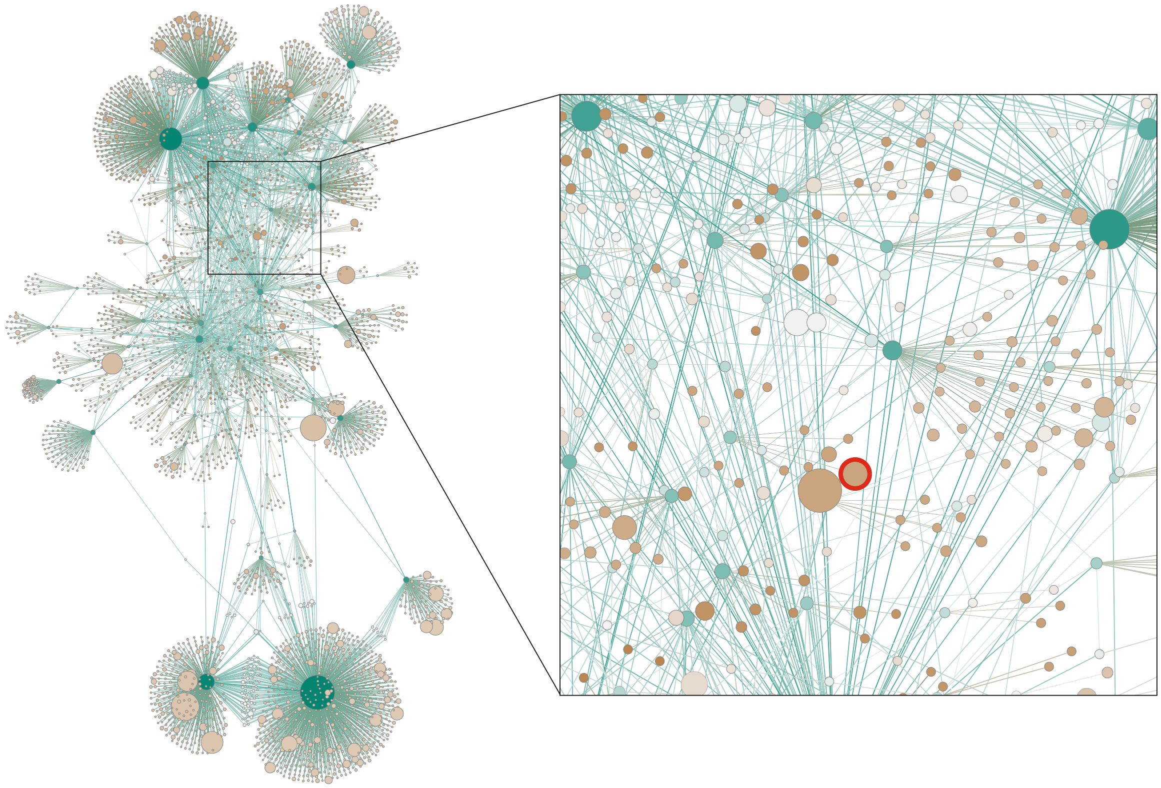
"Is the network analysis supposed to be exhaustive (include all significant and well cited work), or just examples of work of each type? I notice for instance that van der Weijde's well-cited work with me is not cited under stochastic methods on p. 17; this work was the foundation for my group's work (which is cited) later in the decade. https://www.sciencedirect.com/science/article/pii/S0140988312000436 (170 cites)

Might this indicate that there is an important issue with the citation method – that its Achilles heel is the discovery of what papers to include in the first place, and its results might depend a lot on how thorough the user is in finding those papers."

Response:

Thank you for raising this important issue. First, I need to admit that regardless of the algorithms used, the quality of the citation network analysis depends on the effort one puts into the review. It usually takes hours to analyze each group of papers thoroughly. Some references could be overlooked.

Definitely, there is room for further improvement of the review methodology. Additional algorithms can be used to identify the most important nodes in a graph. For example, nodes with the highest degrees (number of connections) can be explored first. To visualize possible outcomes of nodes ranking, I selected the PageRank algorithm, a powerful tool developed by Google to rank web pages. The resulting ranking is shown in the figure below. Nodes with low rank are colored brown. More important nodes are highlighted in green.



Example: Nodes ranking based on the PageRank algorithm.

The results are rather intuitive. The most important nodes are the ones that have more interconnections in the network. Note that there are clouds of brown nodes. Those are the second-generation papers that have only one link to other papers. Such nodes are indistinguishable from the algorithmic point of view. The van der Weijde's work you mentioned is included in the network. I highlight it with red color. This is a second-generation paper that does not cite the zero-generation nodes directly. Moreover, it has only one link to a first-generation paper "A game-theoretic approach to study strategic interaction between transmission and generation expansion planning" by Ng et al. Therefore, giving the current selection of papers, van der Weijde's study is rated as a less important node, which is easy to overlook.

This example illustrates the limitation of the citation network analysis. Namely, it is hard to estimate the true importance of references due to the limited selection of papers. Better estimations could be achieved if three or four generations of citations are included in the network. Unfortunately, it is impossible to properly display and analyze networks with tens of thousands of citations. Therefore, there is a need for compromise between coverage of literature and focused analysis of the topic.

Comment on **coverage of literature**:

"p. 71. There's a lot of water resources-related cooperative game work. Cite Peyton Young's pioneering work in using cooperative game concepts in water resources planning. …"

"… The thesis would be improved with a discussion of whether the stability/ manipulatability concepts in the thesis have been applied in other fields. Do the applications in other fields predate power systems? Is there a literature in which cooperative game theory concepts have been embedded in infrastructure or other system planning models that use optimization outside power systems?"

Response:

Indeed, Cooperative Game Theory applications in water resource management appeared earlier than in power systems research. I include the following discussion in the introduction of Chapter 4.

Cooperative Game theory was found especially appropriate for solving water resource management problems. For example, in [155], *Young et al*. examined different methods, including the Core, the Shapley value, and the Nucleolus, for allocating the cost of water supply projects. The authors mentioned high dependence on detailed cost information as one of the main drawbacks of the game-theoretic methods. Multiple other studies applied Cooperative Game Theory to address water resources issues such as urban water supply and sanitation, irrigation, hydropower generation, reservoir operation, water pollution control, international/transboundary water conflicts, etc. An exhaustive review of Cooperative Game Theory developments in water resources was done by *Dinar and Hogarth* [156].

However, I did not see a study that claims to address the allocation rules manipulations or embeds the Cooperative Game Theory concepts into planning mechanisms. Some authors mention that game-theoretic concepts highly depend on the accuracy of the information, which obviously could be corrupted.

In this regard, the most relevant studies are the mentioned works by W. Thomson, who analyzed the manipulability of resource allocation mechanisms. However, his works seem fundamental research in Game Theory. I did not find practical applications of these results in the subsequent studies.

Comment on **coverage of literature**:

Several comments suggest modifying and extending the discussion of Cooperative Game Theory solution concepts.

“Who first formalized cooperative games with exchangeable utility? Who invented the idea of the core of the game? (Wiki Core: "The idea of the core already appeared in the writings of Edgeworth (1881), at the time referred to as the contract curve.[1] Even if von Neumann and Morgenstern considered it an interesting concept, they only worked with zero-sum games where the core is always empty. The modern definition of the core is due to Gillies.[2]") A paragraph should point the reader to the intellectual origins of the basic ideas upon which the thesis is built.”

“p. 81 Some folks argue that the Shapley value is somehow a more desirable solution than other points in the core (in a convex game). It would be desirable if the thesis summarizes quickly the arguments for and against using the Shapley value (or other solution concept, such as the Nucleolus) as a normative concept?”

“p. 109 “unfair distribution of savings and efficiency” Economists do not like the use of the term “unfair” unless it is very precisely defined, and even then they are squemish because it is a question of income distribution, not efficiency. Its use in this context should be avoided unless the thesis states explicitly that it defines a particular solution concept (e.g. Shapley) as “fair”, and whenever something is said to be fair or unfair, the thesis should qualify the statement with something like “(using the Shapley value as a standard for fairness)”. The thesis should then also somewhere argue why it should be used as a fairness metric, and why some other solution (nucleolus) shouldn't be.”

“Is there an empirical literature that tries to argue that the Shapley value is better at predicting the outcomes of negotiation than other concepts? E.g., see the early paper by Nobel prize winner V. Smith …”

Response:

Thank you for sharing such useful references. I did not know about the empirical tests of the allocation mechanisms. These results are definitely worth including in the thesis. The following discussion has been added to Section 4.4.

An essential question to be asked at the end of the chapter is: what is the best solution concept to choose for cost allocation? Yet, there is no simple answer. The solution concepts such as the Shapley value and the Nucleolus are different types of the axiomatic approach: the concepts satisfy several axiomatic properties. This means that one has to judge to what extent certain properties reflect the original goals and choose the solution concept accordingly. As discussed in Section 4.2.3, the Nucleolus could be given a slight preference since it is guaranteed to be a part of the Core when the latter is not empty. However, the Shapley value is widely recognized as a useful concept for its ability to capture players' marginal contributions. The selection of the solution concept can be considered from the experimental economics point of view. Several studies performed empirical tests of the allocation mechanisms to analyze their acceptability and stability. For example, in [166], *Michener et al*. compared the predictive efficiency of Cooperative Game Theory solution concepts for side-payment games with nonempty Core. The Euclidean distance between an observed payoff distribution and all distributions predicted by a theory was used as the comparison metric. It was reported that the Core solution is significantly less accurate than the Shapley value and the Nucleolus. Furthermore, the authors mentioned, "The bright side of this finding is that one of the competing solution concepts - the Shapley value - consistently shows a comparatively high level of predictive accuracy. Across the many games studied, the Shapley value performs at least as well as, and frequently better than, all the other solutions tested. The performance of the Shapley value has been noted in earlier research reports, and the present analyses underscore its superiority relative to the Core." In [167], *Williams* presented a large empirical test of Cooperative Game Theory solution concepts based on the observations of markets occurring in multi-purpose river developments. It was reported that the empirical results support the theory of the Core (in contrast to the previous results of Michener). *Williams* made the following ranking of the concepts, "the Cooperative Game solution concepts can be ranked in descending order of accuracy as the equal propensity to disrupt method, the just payoff vector, the Shapley value, and the Nucleolus. The equal propensity to disrupt method generally performs best. However, the just payoff vector performs nearly as well in all cases. The Shapley value performs well in predicting the actual cost allocations; however, it lies outside of the Core in several instances. The Nucleolus performs worst among the cooperative game solution concepts." Similar tests were performed by *Dinar and Howitt* [168], who analyzed acceptability and stability of allocation mechanisms in environmental control. The Shapley value was confirmed to be a more acceptable solution concept than the Nucleolus. The above results show that Cooperative Game Theory solution concepts do not describe the actual behavior of players accurately. However, they can be applied as the normative ground for cooperation.

The origins of Cooperative Game Theory have been mentioned at the beginning of Chapter 4.

We focus on cooperative games with transferable utilities, where benefits generated by cooperation may be easily distributed and shared among the players. The origins of such games come from the famous book "Theory of Games and Economic Behavior" by *Neumann and Morgenstern* [151]. However, even earlier studies existed. For example, the concept of the Core was first proposed by *Edgeworth* [152] in 1881 and later reinvented and defined in game-theoretic terms by *Gillies* [153].

As you advised, I avoid using terms "fair" and "unfair" in the thesis.

Comment on **thesis structure**:

"Personally, I prefer an Introduction that is on the order of 10-20 pages, briefly introducing the problem and research questions, their importance, and summarizing the contributions and scope of the thesis (road map). The citation network analysis is 43 pages, and is a lot to go through before the reader learns about the contributions. My preference would be to have the citation network analysis be a separate chapter 2 (Chapter 1 could refer to it when describing the contributions)."

Response:

I agree with the comment. The thesis structure has been modified. Chapter 1 has been divided into two chapters: Introduction and Citation Network Analysis. The corresponding changes have been made throughout the sections.

Comment on **Chapter 6 model (Chapter 5 in the previous numbering) and simple examples**:

“Chapter 5 could be structured to be easier to read.”

“I found that Section 5.2, which is very long, needed subsections and a structure to its discussion, especially of the results (figure 5.7 and afterwards). A road map/scope paragraph at the start to inform the reader what the section is about and what results will be discussed would be helpful.”

Response:

Thank you for the suggestion. The structure of Chapter 6 has been modified. I added the following paragraph before the discussion of the results.

In this section, we present and discuss the results of the bilevel TEP. First, we design a case study with interconnections between four power systems. The case is developed in a way that the cooperative game is highly nonconvex, and players’ positions in cooperation differ significantly. Using this case, we illustrate that optimal expansion plans can lead to coalitional stability issues. We then implement the developed bilevel approach and find a suboptimal transmission expansion plan with the enhanced stability of cooperation. By varying game-theoretic constraints, we identify a range of possible suboptimal solutions. The impact of the constraints on the coalitional stability and efficiency of expansion plans is analyzed. Finally, we discuss possible applications of the developed approach.

Comment on **Chapter 6 model (Chapter 5 in the previous numbering) and simple examples**:

“Section 5.1 would be clearer with a statement of the economic structure of the problem. Right now the section launches into the math without explaining the economic set up of the multilevel / Stackelberg game. (Figure 5.1 would help if presented earlier and clearly explained earlier. Figure 5.1 should show that the upper level controls just F'max, right? That could be shown by the arrow to the lower level, whose decision variables are really just the spot market generations and flows, right? This could be indicated in the figure as well for clarity. Right now 5.1 doesn't show which variables are controlled by which entities.)”

Response:

I agree with the comment. The following paragraph has been added at the beginning of Section 6.1.

Before introducing the bilevel TEP formulation, it is important to state the economic structure of the problem that we are solving. Our main goal is to capture the effect of transmission planning decisions on the stability of cooperation over the project. This task can be broken into the following two stages. First, the TEP model is used to identify the optimal expansion plans for the grand coalition and all the subcoalitions. A cooperative game is formulated based on the optimized costs of coalitions. Second, a metric of coalitional stability is selected to evaluate the cooperative game. Then, a coordinating variable is introduced to modify the expansion decisions at the first stage, subject to the coalitional stability constraints at the second stage. In this study, we select maximum line capacity as the coordinating variable. Thus, we perform a topology control of interconnections to achieve a desired level of coalitional stability. More detailed explanations will be given in the following sections. We now proceed to the model formulation.

I also modified Figure 6.1 as you advised. Please see the new diagram below.

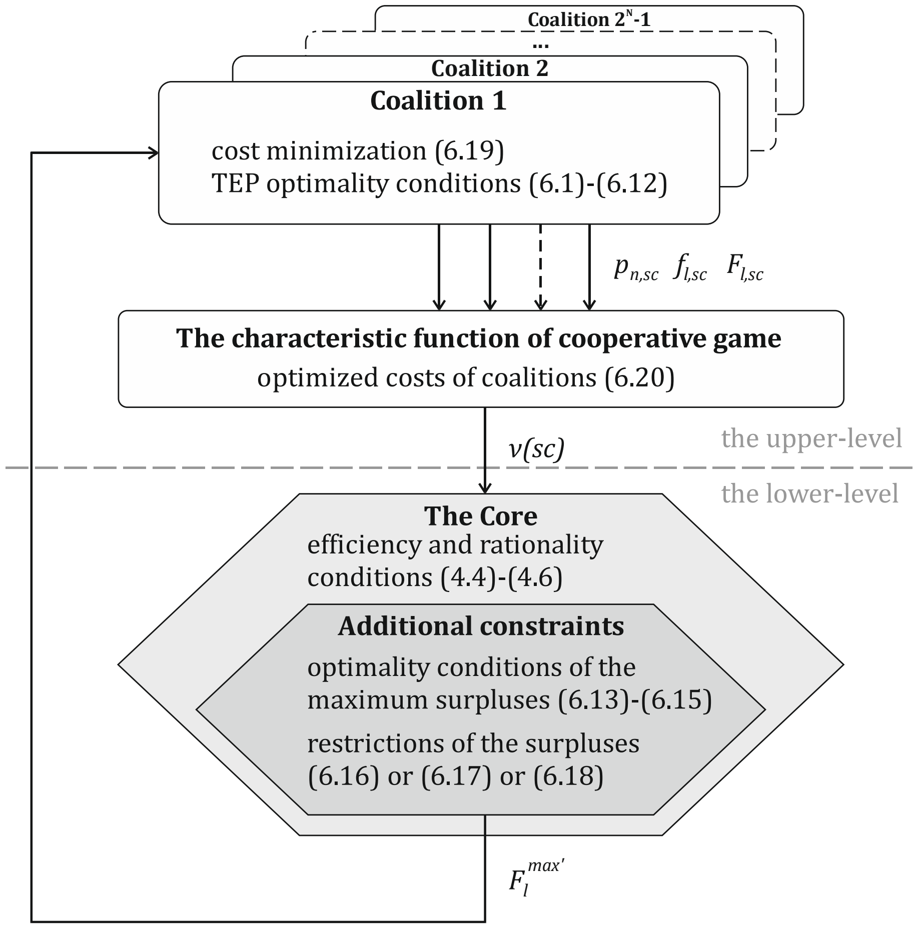


Figure 6.1: The bilevel TEP framework.

Comment on **Chapter 6 model (Chapter 5 in the previous numbering) and simple examples**:

> *"'Namely, it forbids changing lines capacity limits in one of the scenarios while not applying the same limits to other scenarios.' I don't understand why this is necessary. Let's say that there are three players A,B,C, and three possible lines A-B, B-C, A-C. For subcoalition {A,B}, wouldn't the only line that could be built be AB, and why should it be constrained to be the same capacity as in the grand coalition? B-C and A-C would be zero necessarily in that subcoalition, which might be different from grand coalition solution. Also, the more general case would have different manipulations of CG for different subcoalitions. This also does not seem to be considered."*

Response:

A footnote has been added in Section 6.1. Please, find my justification below.

This assumption may seem overly restrictive. We have the following explanations of why the same line investment limits must apply to all coalitions. First, in some cases of TEP coordination, it would make sense to restrict line capacity limits for subcoalitions (groups of players should not build more capacity than in the grand coalition). This would make cooperation in the grand coalition more appealing. Second, we want to avoid unreasonable bilevel planning solutions, where suboptimal investments would be suggested to reduce the bargaining power of some players. Suppose a game where players A and B have much more bargaining power than other players. Suppose this happens due to the fact that they can form a very beneficial coalition {A,B} by building a line A-B and obtaining significant cost savings. Suppose we want to find a suboptimal expansion plan via bilevel game-theoretic modeling where all the players would have equal bargaining power. Without the coordinating constraints, it might happen that the new plan would suggest overinvestment in line A-B since this makes the coalition {A,B} less profitable. We avoid such solutions by using the coordinating capacity variable $F_l^{max\prime}$. This assumption can be reconsidered in future research.

Comment on **Chapter 6 model (Chapter 5 in the previous numbering) and simple examples**:

> *"More economic discussion is needed when making statements like 'The model is able to identify expansion planning decisions in an anticipating manner,' Is this anticipative in the Sauma meaning of the word? What precisely is being anticipated? Not manipulation, just the spot market solutions for each subcoalition?"*

Response:

I agree. Please, see the following footnote added to Section 6.1.

We use the term anticipative in a similar way Sauma did in [77], [86]. Sauma suggested transmission planning that anticipates its effect on generation investment decisions and market clearing outcome. We propose transmission planning that anticipates the cooperative game over the expansion plan and evaluates its coalitional stability. Thus, an undesired outcome of cooperation can be discovered in advance and avoided by changing transmission investment decisions.

Comment on **Chapter 6 model (Chapter 5 in the previous numbering) and simple examples**:

> *"Does use of (5.19) guarantee the overall surplus maximizing solution if there are no profit constraints? I.e., choosing F'max to maximize the sum of surpluses across sc will also maximize the surplus in the grand coalition? I would like to see a proof of that."*

Response:

Thank you for raising this important question. As mentioned in Section 6.1, the formulation of the objective function (6.19) is similar to a multiobjective optimization problem, where the costs of possible scenarios are simultaneously minimized. In the thesis, we did not distinguish the scenarios by setting weighting coefficients or other parameters. However, it is important to study the effect of coalitions' importance (weights) on the bilevel TEP planning results, especially with additional game-theoretic constraints. Indeed, proof of optimality for the grand coalition is needed. To address your question, I experimented with the bilevel TEP models for the three-system and four-system case studies. I solved them with modified objective functions, where the costs of the grand coalitions were multiplied by 10^6. Thus, I stated that the grand coalitions are far more important than subcoalitions. I compared the total costs of the systems and capacity investment decisions for the modified function and the initial objective (6.19). I found no difference in the bilevel TEP planning results for the cases with lower bound constraints on players' maximum surpluses (6.16) and equality constraints (6.18). This could indirectly confirm that the current bilevel formulation can result in optimal or near-optimal expansion plans for the grand coalition. However, further research is needed here.

The related question is if treating coalitions differently in bilevel TEP planning, how to capture their true importance? Making the grand coalition too important could be a drastic solution.

Other comments:

"Section 2.1. "evaluate optimal power flows from systems with lower prices towards systems with higher prices, subject to transmission constraints." (Similar statement made on p. 64) See Wu and Oren https://oren.ieor.berkeley.edu/pubs/folk96.pdf; flows can be from high priced nodes to low priced nodes in linearized DC networks. This intuition only applies, strictly speaking, to "pipes and bubbles" models."

Response:

I agree. The following explanation has been added to Section 3.1.

We must note here that such an intuitive interpretation of power trading holds only for simple linear OPF models. Counterintuitive results can appear in linearized DC and AC models. For example, in an efficient allocation, power can flow from nodes with higher prices to nodes with lower prices. Moreover, strengthening transmission lines or building additional lines does not necessarily increase transmission capacity. These counterintuitive cases have been studied by *Wu et al*. in [137] and *Kirschen and Strbac* in [6]. We neglect such effects and assume that power flows can be directed according to economic signals.

"Some English/typographic issues: …"

Response:

Thank you for highlighting this. I have made the corrections.

"p. 63, Figure 2.3 is referred to, but the figure doesn't appear until p. 69. Good form puts the figure on the page that the first reference is made, or on the following page. Otherwise, the reader has to hunt."

Response:

I agree. Fixed.

*"p. 61. With inelastic demand (perhaps with a VOLL), the total surplus (including consumer surplus) and the total cost metrics yield the same rank ordering of solutions for each player (the difference in their cost = -1*difference in their surplus). (I'm assuming price doesn't reach VOLL and that no rationing occurs.) As a result, surpluses can be calculated as a difference from a base (say no interconnectionn solution). Consumer surplus changes = -1*changes in payments. I think the statement "It is worth mentioning that we do not include consumer surplus in our analysis" is a bit misleading because it seems to imply that its omission will somehow change the analysis in this, the inelastic case. It doesn't."*

Response:

I agree. The point of the consumer surplus discussion was to mention possible welfare formulations. The following footnote has been added in Section 3.1.

As we discuss later in Section 4.3.1, welfare formulation as a generation surplus can lead to the allocation of negative values. Therefore, more welfare components could be considered. In [58], *Kristiansen et al*. formulated net welfare as the sum of consumer and producer surpluses and congestion rents. It was demonstrated that such formulation always results in nonnegative welfare changes caused by interregional electricity trading.

"The TEP problem - need to mention limitations in addition to omission of the voltage law. In particular, transmission capacity is treated as a continuous variable with a linear cost. In Chapter 5, the thesis should mention (in association with (5.1)-(5.5)) that this is necessary for use of the KKT conditions. The

limitations of this assumption (lines come in discrete voltages, there are fixed costs of acquiring the right-of-way, there are economies of scale- twice the capacity doesn't cost twice as much due both to voltage increases and the ability to have multicircuit towers, etc.)"

Response:

Thank you for the comment. Similar issues were mentioned by Prof. **Ross Baldick**. I added additional explanations to Chapter 3 and Chapter 6.

"p. 89 'The question arises, which criterion of cooperation is more appropriate than the others? We believe that for consistency with the TEP approach, allocation based on the costs is the preferable one. Moreover, we want to avoid situations where some players may be allocated negative values, as it happens for the generation surplus allocation in the twosystem case study. Thus, in the subsequent cases, we use generation cost for formulating characteristic function of cooperative games.' Proposition: As the power sector moves more towards market-based philosophy with an active demand side, this cost-orientation is likely to become outmoded, and allocation will be based on surpluses rather than costs. The thesis could discuss whether this is a plausible alternative view to the view of the candidate."

Response:

Thank you for the suggestion. A similar point was made by Prof. **Clement Fortin**. The following paragraph has been added to Section 4.3.1.

The main benefits of electricity trading come from cost savings and possible CO_2 emissions reduction. Therefore, it makes sense to formulate cooperative cost games, where a synergy of cooperation comes in cost savings. Many of the preceding works focused on TEP cost allocation issues and formulated optimization models for investment and operating costs minimization. The corresponding cooperation was usually formulated as cost games. However, it is worth mentioning that the value of cooperation in terms of profit can be more appealing for investors. As the power sector moves more towards market-based philosophy, the cost-orientation is likely to become outmoded. Several studies considered value games based on the social welfare and surpluses of players. For example, in [106], *Banez-Chicharro et al*. aimed to estimate the impact of transmission expansion projects on the social welfare using the Aumann-Shapley approach. In [119], *Hasan et al*. considered the cost allocation of renewable power integration projects based on the net market benefit. The formulation of benefits included producer surplus, consumer surplus, merchandizing surplus, carbon emission tax, and additional payments. *Kristiansen et al*. [58] considered the allocation of both benefits and costs that result from the development of international transmission interconnections. The authors stated that "trading of electricity between regions as a result of new transmission capacity in congested lines always results in nonnegative changes of welfare and net welfare in aggregate terms." The welfare was formulated as the sum of consumer and producer surpluses and congestion rents. In this work, we keep the classic cost-based formulation of cooperative games in TEP.

"Chapter 7 (former chapter 6). Some limitations should be discussed, perhaps in a separate subsection. E.g., no generation capacity expansion (so the "anticipative" nature of the model is limited. One would expect that if there are a lot of power imports and exports, then the optimal investment in each country would change.) Limited load slices (4 per year, average seasonal demand); a full load duration curve accounting for peaking, baseload, and cycling needs might result in very different solutions. These limitations suggest possible future research directions."

Response:

Thank you for the comment. The following paragraph has been added to Section 7.2.

Before introducing the results, it is important to summarize the main assumptions and limitations of our modeling approach. A share of the assumptions comes from the linear TEP model (3.1)-(3.5) formulated in Section 3.2. Namely, we: do not consider admittances of power lines, reactive power, voltage magnitudes and angles; omit the constant part of transmission investment and, therefore, do not introduce binary decision variables of lines' construction decisions; do not consider economies of scale and treat transmission capacity as a continuous variable with a linear cost; do not perform the contingency analysis. These assumptions allow us to formulate the TEP problem as an LP model. Other limitations are related to the case study description. For example, we do not consider generation capacity expansion. This limits the "anticipative" nature of the model, which is unable to capture the effect of power imports and exports on the optimal generation investment. We considered the limited number of representative loads (only four seasonal regimes per year). The inclusion of the full load duration curve could lead to different solutions (the detailed representation of load curves could also capture the time shifts in energy consumption between nodes). Generation cost bids are considered constant. Finally, we suppose that the resulting cooperative game is formulated in costs. The mentioned assumptions and limitations point out future research directions.

"Note that some models of DC line expansion (for the North Sea) actually have to use KVL (flows are not controllable in a DC grid); so not all DC interconnections can be modelled as "pipes and bubbles". See Torbaghan et al. https://ieeexplore.ieee.org/abstract/document/6851949 . Thus, it would be useful to point out in an extensive footnote or a short section how your approaches can be generalized."

Response:

Thank you for sharing the article. The following footnotes have been added in Sections 3.2 and 3.3.

Note that detailed modeling of some HVDC interconnections has to respect voltage constraints and Kirchhoff's laws. It can result in nonlinear nonconvex optimization problems [146].

Note that some HVDC interconnections have to respect voltage constraints and Kirchhoff's laws, which means that power flows are not fully controllable [146].

"'We, therefore, believe that it is reasonable to assume that future projects of cross-border power interconnections would be realized based on HVDC transmission.' This is offered without much support. Could inventory cross border proposals to support this statement. This statement is obviously true with connections of asynchronous systems."

Response:

I think that reference [142] provides a perfect justification of the HVDC technology in terms of the number of projects, market trends, etc. My statement was changed to:

Considering current trends [142], we believe that it is reasonable to assume that future projects of cross-border power interconnections would be realized based on HVDC transmission.

Response to Prof. **Henni Ouerdane**

I thank Prof. **Henni Ouerdane** for the interesting questions and useful suggestions included in the report. Please, find my response below.

Comment:

"Perhaps, a question to ponder over: Mr. Andrey Churkin mentions that a major challenge for the further development of his work would be the development of strategyproof mechanisms of cooperation. A collusion between two or more players, for instance, can affect the mechanism of global cooperation and the collective payoff; a naïve question then would be: could a hybrid cooperative game and non-cooperative game theories approach be developed, if it can make sense?"

Response:

Thank you for the question. I absolutely agree that a mechanism of competition over cooperation should be described using both cooperative and noncooperative game formulations. A similar question was raised by Prof. **Benjamin Hobbs**, who mentioned that our discussion of possible manipulations is incomplete without an equilibrium analysis.

As discussed in Chapter 5, one of the very first studies on the manipulability of allocation mechanisms were done by Thomson [170-172]. It was demonstrated that an allocation mechanism could be unilaterally manipulated by players. When multiple players jointly manipulate the allocation rule, the cooperation can be described as a manipulation game. Such games combine cooperative and noncooperative game formulations and can be studied based on equilibrium analysis. I consider the equilibrium analysis of allocation rules in TEP as an extension of the thesis. The goal of such an analysis would be to find allocation mechanisms that do not give players incentives to deviate much from their true information while submitting bids in a TEP project. I.e., possible equilibrium allocations should not lead to significant efficiency violations. The equilibrium analysis of cooperative games in TEP was mentioned in the concluding chapter as a direction for further research.

I also feel it important to mention that the idea of combining both cooperative and noncooperative game formulations is well known in other applications. For example, Brandenburger and Stuart [194] proposed a hybrid noncooperative-cooperative game model, which they called a biform game. The idea behind biform games is to describe possible business strategies in a competitive environment that precede cooperation among players. For example, a supplier can decide on which of cooperating companies to supply with a branded product. Such games can also be analyzed using equilibrium analysis and bilevel programming.

Comment:

"I also would like to point out that though non-cooperative game theory is mentioned several times in the manuscript, the framework remains fundamentally that of cooperative game theory. The title contains the notion of cooperation stability, but the generic "game-theoretic" formulation in the title may suggest that the work rests on a framework that goes beyond the cooperative game theory. Perhaps the title may be revised to make it more specific, i.e. aligned with the core content; but this is an optional point to consider."

Response:

I agree with the comment. After several discussions with my advisors, we decided to use the following title:

STABILITY ANALYSIS IN COALITIONAL GAMES FOR CROSS-BORDER POWER INTERCONNECTION PLANNING

Comment:

“The citation network analysis is one of the pillars of the doctoral dissertation presented by Mr. Andrey Churkin; instead of being embedded in the (hence lengthy) Introduction, it could have been the object of a dedicated, separate chapter.”

Response:

Thank you for the comment. The same issue was mentioned by Prof. **Benjamin Hobbs**. I have modified the thesis structure. Chapter 1 has been divided into two chapters: Introduction and Citation Network Analysis. The corresponding changes have been made throughout the sections.