Skoltech
Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Andrey Churkin

PhD Program: Engineering Systems

Title of Thesis: Game-theoretical approach to cooperation stability analysis in cross-border power interconnection planning

Supervisor: Professor Janusz Bialek, Skoltech

Co-advisor: Assistant Professor David Pozo, Skoltech

Name of the Reviewer: Benjamin F. Hobbs, Johns Hopkins University

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:**  **Date: 20 October 2020**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications

The summary of issues to be addressed before/during the thesis defense

Brief evaluation of the thesis quality and overall structure of the dissertation

Overall, thesis is excellent. It pushes the state of the art of the use of cooperative games in transmission expansion planning forward significantly by considering optimal modification of plans to constrain distributions of benefits in ways that might promote negotiation agreement ("stability of the grand coalition"). This seems to be a new model formulation in cooperative games in general, not just in power systems, and as such, I believe it deserves being published in a more general economic journal as well (such as the Journal of Regulatory Economics). The contribution of this thesis is consistent with the expectations for dissertations at internationally prominent research universities.

Further, although there were significant practical problems in implementing and applying the model to the case study, the candidate is to be congratulated for having largely overcome these. Also, the literature survey is thorough compared to most dissertations, and the network citation analysis is a highly insightful and complete way to structure a literature survey. I do note some omissions in the literature review. The writing is of excellent quality.

In terms of the thesis' practical contribution, in my experience, the cooperative game framework is very useful to the World Bank and other international funding agencies. This thesis points out some very important ways in which the solutions could be made more relevant to real situations and more informative to negotiations.

I do note some ways in which the thesis would be more complete, and suggestion some enhancements that would be desirable prior to a defense if practicable. Notably inclusion of Gately's seminal contribution in the literature network analysis; discussion of equilibrium manipulation strategies in the context of the simple Chapter 4 examples; and careful introduction and justification of the models of Chapter 5 (especially the assumption that the same line investments must apply to all subcoalitions – this feels restrictive). These suggestions are discussed in detail below. These are not fundamental objections to the thesis, but the thesis would be enhanced if they were addressed.

Other issues that could be addressed prior to or during the defense include the empirical and normative arguments in favor or against alternative cooperative game concepts; and the properties of Chapter 5's models (see detailed comments about, e.g., the properties of the solution that uses (5.19) as the objective).

The quality of publications is sufficient, and I anticipate that based on the importance of the thesis' contributions that additional very high quality journal articles will be provided.

OTHER DETAILED COMMENTS APPENDED

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense.*

NOTE: I recommend that the candidate consider making some of the changes suggested, which are relatively minor in scope but would improve the readability and completeness of the thesis. I believe these would take a week or so and can be completed prior to the scheduled defense.

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*
☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*

APPENDIX: DETAILED COMMENTS:

General Contribution Comments

"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?

The cluster/networking method for summarizing the literature is a very interesting tool for providing a more objective way to summarize and assess what problems and methods the literature has covered. It could be useful for identifying gaps and relatively neglected problems.

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)? Or is there a perverse outcome where the line is not built, even though in truth it is beneficial?) Because the line is free (per the assumptions of Table 2.1), this issue doesn't come up, but this would be a good place to explicitly re-state that assumption, and then consider what happens if the line has a positive cost and is not built if the apparent equilibrium benefits are less than the cost?
- The relationship between manipulability and the extensive literature on supply function equilibrium (SFE) models needs to be mentioned. There's a huge literature on supply functions both in general (Green and Newbery, JPE) and in the specific case where supply and demand functions are linear

(related to this example; here's an early transmission constrained case Berry et al. https://www.sciencedirect.com/science/article/pii/S0957178799000168 ; Baldick has several such papers). These models fail to consider how transmission cost allocation might be affected by deviations from true cost/benefit bidding, and so the thesis' model can be viewed as a generalization.

- 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.

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).

In game theory, Nash cooperative equilibria (nonexchangeable utility) are accorded a place in the pantheon nearly as important as cooperative equilibria with exchangeable utility. This could be stated clearly, and then the thesis should make a strong statement on why the exchangeable paradigm is used. Brief reference is made at the top of p. 7 to investments in cross-border power interconnections as a Nash bargaining game between regions. What view does the author of the thesis have of the usefulness of this work and approach?

p. 52 bottom. Which works are the closest attempts? Where does Gately fit in (manipulability)? This work seems very seminal, but is not nearly as stressed as some Generation 0 papers.

There are some relevant older power papers that are not cited. I'm not suggesting redoing the literature analysis, but perhaps the impact of older literature could be mentioned. These papers precede "Generation 0" p. 10, are they not considered in the analysis because they are not optimization-based planning (expansion) models?

- The foundational paper is Gately, with hundreds of citations, which was published in 1974, long before Generation 0. A nod is given to it in the thesis. But I think it would be desirable to include it in the network analysis.
- 1992 Kelly and Hobbs on transmission allocation. https://www.sciencedirect.com/science/article/abs/pii/037722179290219Y

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.

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. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/WR018i003p00463 ; recent review in https://escholarship.org/uc/item/7tt7880f and https://link.springer.com/content/pdf/10.1007/BF00133625.pdf . Dinar, A., Dinar, S., Mckinney, D. C., & Mccaffrey, S. C. (2013). Bridges over water: Understanding transboundary water conflict, negotiation and cooperation (Vol. 11). World Scientific Publishing Company. 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?

p. 72. Not clear why just one application is highlighted ("A relevant work was done by Lozano et al. [133], ...") What is distinctive about that? Is it just one example among dozens, or somehow exceptional?

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 a 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: https://www.researchgate.net/profile/Vernon_Smith4/publication/283463764_Game_Theory_and_Experimental_Economics/links/5639330008aed5314d221d08.pdf . Later papers: https://idp.springer.com/authorize/casa?redirect_uri=https://link.springer.com/content/pdf/10.1007/BF00133460.pdf and https://onlinelibrary.wiley.com/doi/pdf/10.1002/bs.3830330306); AN EMPIRICAL TEST OF COOPERATIVE GAME SOLUTION CONCEPTS by Michael A. Williams "This article reports the largest empirical test to date of cooperative game solution concepts with observations taken from naturally occurring markets. In contrast to some previous empirical tests of cooperative game solution concepts with observations taken from classrooms, the empirical results support the theory of the core in general and the "equal propensity to disrupt" solution concept in particular. The Shapley value and the nucleolus receive weaker empirical support". Given this "weaker support", this suggests that the thesis should warn the reader that although the Shapley and nuceolus solutions are emphasized in the thesis, this does not

mean to imply that they are strongly descriptive of actual behavior. (They might be appealed to on normative/fairness grounds, see previous comments).

p. 100 "However, to the best of the author's knowledge, no work has been done to implement manipulability analysis and Algorithmic Mechanism Design in powersystems research and transmission expansion planning". How about in other fields such as transportation, water, or other infrastructure planning?

There is no mention of FERC Order 1000 or other rules (in the EU, for instance) designed to encourage interregional cooperation (which have largely, but not completely failed). There's quite a bit of literature on these institutional aspects that could be cited.

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).

- 1.2.2 -- a 43 page section needs to have an introduction and scope section (road map) before getting into the analysis itself. What questions are addressed? For instance, there's no anticipation of the analyses at the end of the section (which journals are most dominant, which authors make the most contributions, etc.).
- An example where the present ordering is a bit awkward is where the contribution of 1.2.2.2 is highlighted later (rather than before), in the last paragraph of Section 1.2.3, whereas alal the other contributions occur after Section 1.2.3.

Comments on Chapter 5 Model 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.
- 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.) The subproblem is the TEP problem based upon the expressed (not truthful?) cost functions of the suppliers? Or is CG the actual cost? (So we are not explicitly calculating an equilibrium in a manipulation game, which the previous chapter hints at; instead CG is assumed?) It seems the F is a variable (5.3 is its first order condition) in the lower level. If that's so, what is the role of the upper level if not to choose F? (This can be contrasted to Sauma's framework, where the upper level chooses F subject to the spot market outcome.)
- 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?

- Or does the upper level indeed choose F by choosing F'_max? (This is not clear in the beginning of this section) Is that what is meant by "In such cases, our formulation allows changing the characteristic function solely by tuning the limits of the capacity investment decisions". If so, please state that explicitly.

p. 111 "Specifically, we consider the optimization of planning decisions constrained by the maximum surpluses among the players" That vague statement is of course made more precise mathematically later, but I think it would be a more useful introduction if elaborated on more here. What type of constraint? Upper bound on the maximum surplus? Lower bound? What solution concept or other idea from an earlier chapter is being applied?

"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 A-B, 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.

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.

p. 118: "The resulting game has a nonempty Core" Can the thesis give some intuition as to why a nonconvexity arises? Is it due to the quadratic (but convex) supply cost functions, or? Some intuition would be nice.

"(3.9% cost decrease from 255 975 to 246 045.2 $/h)." Would be helpful if a footnote or the title in Tables 5.2 and 5.3 highlight the cost of optimal plan, and the savings (rather than just burying it in the text).

Are there other parameterizations or other profit constraints for the four region model that result in no solution for 5.3? (Maybe it is impossible in some cases for all parties to benefit equally). Please discuss these economic questions.

I'm missing something: Table 5.2 has an equal sharing solution. So why does the imposition of an equal sharing constraint result in a lower benefit for the grand coalition (Table 5.3) and a lower equal share result? Is it because the model in 5.2 assumes a Shapley value , and the equal sharing solution is just calculated ex post, but wouldn't be a feasible solution somehow? (I.e., because one would need side payments that are somehow infeasible?) Or is it because equal sharing in Table 5.2 is not imposed within all subcoalitions, but is imposed in Table 5.3's solution? This is not clear.

At any rate there is money left on the table if the equal share solution from Table 5.3 is implemented instead of Table 5.2's solution. Can't side payments be arranged such that Table 5.2's solution would be acceptable?

Section 5.3. One might summarize the conclusion of this section as: if you build a suboptimal system, there are fewer benefits, as well as fewer costs to allocate. With a smaller pie to fight over, the incentive to lie is less. This is not surprising, and stated this way seems trivial. Can the thesis explain why this is not trivial?

For instance, is the scope for manipulation reduced much more (proportionally) than the reduction in net benefits (about 1/3, from 4800 to ~3200)? If the scope for manipulation is reduced roughly in proportion to the net benefits, this is not surprising. Then why not argue that we could eliminate all scope for manipulation by imposing constraints that ensure that nothing is built (zero benefits, zero scope for manipulation). In future work, it would be interesting to show a graph of some index of manipulability vs net benefits for a variety of solutions that might be generated by the imposition of the type of constraints imposed. Is this graph concave, linear, or?

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.

Some English/typographic issues: p. 4"The development of TEP algorithms remains an actual research direction for several decades."... refers to past or future? p. 8 "also highlighted the value of cooperation of transmission planners" would be better phrasing. p. 9: “The issues of transmission lines investors incentivization were further discussed in [50]” (awkward). Fig. 1.5, the y axis mislabelled as "per year" -- should just be cumulative number of publications. p. 48 insert "and" before A.J. Conejo, and before "S. Lehnhoff". p 50. "most contributed authors." Correct English is "most published authors.” Reference [163]: Capitalize "Ministry". Not clear why some references italicized, and others not (p. 7) (Contreras and Wu). Before (5.13), "use the maximum surpluses among players" -- more precise would be "the maximum individual player surplus among players" Footnotes should follow punctuation (.4, not 4., p. 115). p. 114. Sometimes an extra line of space appears between paragraphs (after "...-(3.31)", top of page). These should be taken out for consistency. p. 120 "that there exists a severe imbalance in player’s positions in the cooperation." Should be "the players' positions"

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.

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.

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.)

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.

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.

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.

"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.