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DISCUSSION

Rejoinder on: A comparative study of time aggregation techniques in relation to power capacity-expansion modeling

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We are grateful to Trine Boomsma, Ken McKinnon, Silvano Martello, Kris Poncelet and Erik Delarue for their insightful and valuable comments on our overview paper. As all reviewers write, most previous papers on time aggregation techniques lack an accurate and systematic validation of the proposed approaches, and we therefore hope that we can help filling this gap. As mentioned by Trine Boomsma, a uniform comprehensive comparison of different aggregation techniques is not to be found in the literature.

Trine Boomsma starts out by giving a valuable motivation for the relevance of our contribution. Both she and Ken McKinnon emphasize on the fact that capacity expansion models typically benefit from being modeled in a stochastic framework due to the mentioned variability and uncertainty of renewable energy. As wisely proposed by Trine Boomsma, the current work could be extended by considering the variability as uncertainty regarding the realization of future renewable production or considering uncertainty as the ability to forecast future renewable production. Although this is not studied in the current work, we agree on the importance of handling uncertainty. We see a potential relevance of this work in a stochastic framework, in the sense that aggregation could be applied to problems representing different scenario realizations, to achieve speed up when solving these. Nonetheless, the ideas proposed by Trine

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Boomsma would indeed constitute new interesting research paths for the current work, and we thank her for pointing to relevant literature motivating these research questions. Especially her proposal of using scenario generation and scenario reduction literature to inspire the aggregation techniques development, is of great value to us, since this has been one of our considerations as well.

Trine Boomsma suggests some thoughtful improvements to the current work, which we find highly relevant. First, she proposes a sensitivity analysis of the applied input data to study the correlation between model sensitivity and importance of choice of aggregation. Aligned with this, she also points to the fact that an out-of-sample test would have brought insightful conclusions to the current work. Lastly, she proposes to perform a comparison between the current work and a similar analysis covering problem instances based on alternative countries with different regional characteristics. All suggestions would indeed bring value to the current work, and since similar suggestions are made by Ken McKinnon, will investigate this in further research.

Trine Boomsma further proposes a number of interesting extensions, that the current work creates a foundation for studying. This includes:

→ *Improving suggestions for the proposed aggregation techniques.* As the conclusions of the current work exactly indicate that cross-correlation might be an important measure in the aggregation technique development, Trine Boomsma suggests to use the auto-correlation, as this has importance capturing flexibility needs. We agree on this being an interesting measure for possibly improving the suggested aggregation techniques even further.

→ *A comparison like in the current work but made within the framework of spatial-domain aggregation.* In addition, to expand the current work by not only looking into short-term dynamics, but also looking into long-term dynamics which this being for example demand growth and different policies. Both suggestions are interesting research paths, which we hope will be followed in the future.

Ken McKinnon starts by giving an insightful introduction to the problem setting. In this, he does not only agree with the need for simplifications methods, with time aggregation being one of these, but also suggests a thoughtful list of alternative ways to handle the computational difficulty. Especially, the rolling horizon is suggested to have operational practice benefits over deterministic long-term models. We definitely see the potential in a future study, comparing a rolling horizon approach as simplification method against the aggregation methodology. Aligned with this, he also emphasizes on the importance of evaluating multiple years as the aim is to reach optimal capacity expansions. Although, the current work only covers a single year, a benefit of the aggregation methodology is, that due to the scalability of the methods, the study could as well have covered a larger horizon. One could have aggregated a 10-year period as a whole, or alternatively, each year could have been aggregated separately and selected elements from each would then constitute the aggregated time series. In addition, however, only briefly, he mentions relaxations as a simplification method. Although we have not made a systematic analysis on this, experimental results showed that the solutions achieved through simple relaxations are much more inaccurate compared to the aggregated solutions achieved in the current paper. As linear relaxations are used in Danish companies to simplify the computational difficulty, a study investigating

the consequences of such relaxations more systematically could bring value to this research field.

We are happy to see Ken McKinnon pointing out that although our analysis did not find a correlation between the studied features of the data and the performance of the aggregated problem, our study opens up for a further research of whether other features could be correlated. This is exactly our hope, and the reason for including these, unfortunately, negative conclusions. We are also very thankful to his observation of the current work providing some guidelines in the selection of an aggregation technique, as this is one of our goals of the paper. However, as he asks for a quantification of the sub-optimality of the true optimal in each aggregate case, we might have failed making it clear in the paper, that the analyzed values exactly cover such a quantification. The aggregated problem solution is found by fixing the aggregated investment plan in the originally scaled model and this solution is then compared to a solution of the same model but with non-fixed investments.

In the section on the paper's contribution, a number of interesting questions are raised:

→ *Alternative plausible investment plans:* Ken McKinnon highlights the fact that despite the aggregated solution being similar to the full-scale solution in objective value, it does not ensure similarity in investment and operational decisions, which also is seen in the results of the analyses. Moreover, he points out that small changes in the model assumption might influence the investments and operational decisions significantly more than it influences the objective value. Consequently, as he also mentions himself, with investors typically looking for alternative investment plans, the solutions achieved from the aggregated problems might be valuable in serving this purpose. To further follow-up on his argumentation, the aggregated methodology might as well serve a purpose in providing a high-level sensitivity analysis to different model assumptions and by that helping in identifying cases worth studying in further detail.

→ *Impact of using residual load in aggregation:* Ken McKinnon sharply notices one of the big challenges of the aggregation approach being the choice of data to base the selection upon. In the current work, the selection of elements is based on RLDCs originating from the assumption that all renewable capacities are produced whenever available. A very good suggestion from Ken McKinnon is a backtracking analysis comparing the actual hourly production of renewable energy against the assumed production. Such an analysis could provide valuable learning in the further research of appropriate data to aggregation. However, in the current work, we force low prices on the renewables, to make sure that these are installed and used, which enables us to reflect on the consequences of the variability of the renewables. Therefore, the solutions achieved in this work might not give a realistic insights in the suggested analysis. Furthermore, he raises the question whether better selections could be achieved by basing the selection on the different profiles separately, and this is indeed a research question that we would like to approach in the future. In addition, we also consider the effect of possible model extensions, such as import/export which would introduce new time-dependent data such as prices. The question is then whether these new time series are worth including in

the aggregation or what the consequences would be, if they are omitted. Ideally, as also pointed out by Ken McKinnon, a model selecting the aggregated time series endogenously would be particularly valuable, also in relation to the raised questions.

→ *Data similarity:* As pointed out by Ken McKinnon, a summary of the characteristics and costs of the equipment considered in the test system would have been helpful in understanding and clarifying the different conclusions. Especially with respect to similarity in solutions of the different years, as well as similarity in aggregated solutions. We agree on this, and realize that we could have put much more focus on the actual solutions. As mentioned in the paper, small adjustments are made to the costs securing a diversified investment selection in the full-scale optimal solution. Due to this, we did not consider the input characteristics important to include in the paper, as it might give an inaccurate picture of the Danish energy system. However, we will make the data publicly available on the net.

Kris Poncelet and Erik Delarue start by giving an insightful introduction to the problem, in which they agree on the challenges identified in the paper. In contrast to the other reviews, Kris Poncelet and Erik Delarue focus their review on the validation part of our contributions, which is very valuable feedback.

With respect to data validation, Kris Poncelet and Erik Delarue point out that, although the RLDC captures some features well, there are other important features that are not captured, wherefore a more suitable basis for a validation metric would be of great value. However, they emphasize that such a metric is hard to define, which we fully agree on. Moreover, Kris Poncelet and Erik Delarue point out that, since renewable capacities are optimized in our model, the assumption of having perfect knowledge of the RLDC constructing the aggregated problem might give a wrong basis. We definitely agree on this, and while some of the tested aggregation techniques are not affected, others are potentially, and it would be valuable to investigate further what impact the assumed renewable capacity has on the aggregation technique performances.

With respect to model validation, Kris Poncelet and Erik Delarue start out by providing a valuable overview of the potential challenges. Based on this they point out a disadvantage of the method used in the paper being the potential influence of multiple solutions with same objective values. This is a very good observation, which we highly agree on. Kris Poncelet and Erik Delarue suggest instead to evaluate the aggregation techniques by their ability to accurately approximate the total system costs of the non-aggregated problem, which not only avoids the multiple solution challenges, but also overcomes the tractability challenges often faced in model validation. Furthermore, a validation as suggested by Kris Poncelet and Erik Delarue would also limit the influence on certain parameter values, as it covers some built-in sensitivity analysis. This also leads to a broader performance evaluation of the different aggregation techniques. We think that the suggested model validation is very valuable and we will aim at using it in the future and highly encourage other to investigate this approach. Using this methodology would, as pointed out by Kris Poncelet and Erik Delarue, also help gaining insight into a possible relation between type of system and aggregation per-

formances, which can be a help both in the future aggregation technique development as well as in the development of a more suitable data validation metric.

As noticed in the paper, and as pointed out by most of the other reviewers, Kris Poncelet and Erik Delarue also emphasize on the fact that the choice of model features included in the model potentially impacts the performance of the aggregation technique. Further analysis studying this relation would be valuable. Also related to the actual model used in the paper, Kris Poncelet and Erik Delarue notice that the use of a small scale test instance might cause some disadvantages which can be avoided using their suggested model validation instead. We agree, that a test instance as close as possible to the real life case would provide more valuable insight. Lastly, Kris Poncelet and Erik Delarue mention the potential importance of how selected elements are put together which for example decides the ramping values of the aggregated problem. We think that this is a very important observation, potentially having high impact on the aggregation technique performance. Although, we did not analyze such choices in the current paper, we agree that this is an interesting future research question. Aligned with this, Kris Poncelet and Erik Delarue end their review by providing several other interesting research questions to be studied in future work. One of these ideas is to combine different aggregation techniques, which we believe has great potential, as well as the question of how to handle multi-region problems. This also relates to one of our own future research questions asking whether the RLDC is the most suitable basis for the aggregation techniques, or whether another selection criteria, taking the individual profiles (demand, wind, PV) into account, is a better basis.

Lastly, Silvano Martello comments on the fact that terminology in the studied field is huge and not always intuitive. We, therefore, hope that our list of nomenclature can help standardize terminology. Moreover, he suggests to use the term *computational difficulty* rather than *computational complexity*, which we indeed agree on could be a more clear terminology. This has, therefore, been changed in the final version of the paper. Silvano Martello also mentions that a future, systematic and comprehensive survey on this subject will be appreciated by the Operations Research community. We hope that our test methodology can help compare aggregation techniques in such a survey. All our data and solutions will be made publicly available, hence providing some standard benchmarks for comparison.

In general, we hope that our paper can serve as a guide to aggregation methods, helping to standardize assessment criteria as well as notation, and in this way pave the way for future research on this exciting topic.