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Applying the ProdRisk- SHOP simulator for investment decisions

NTNU SINTEF NINA

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ProdRisk-SHOP simulator

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Abstract

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The report describes status for the ProdRisk-SHOP simulator developed in HydroCen WP 3.3. Development of the simulator was motivated by the need for a tool that can calculate future production revenue for different investment alternatives for very detailed physical models. The ProdRisk-SHOP simulator is designed for this purpose and is implemented combining existing commercial models (ProdRisk and SHOP. The report describes more thoroughly the motivation for the development, how the simulator is implemented and experiences from application of the model to a real investment case in Sira-Kvina hydropower system.

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Content

1 Introduction

WP 3.3 in HydroCen concerns R&D related to new or improved tools/methods that can support hydro producers making decisions about new investments and or refurbishment of existing plants.

Many of the Norwegian and Swedish hydro plants are old and need major maintenance the coming years. Also, a significant share of the producers concessions are up for revisions. Since some work has to be done, this is also the right time to evaluate whether it is profitable to upgrade the production system. Upgrading could involve investment in new larger turbines, converting to a pumped storage plant, increase the ability to participate in balancing markets etc. In the following we call the decision of what to do with the system; either maintain the system back to its original state or to upgrade the system, an investment decision.

Investment decisions has been done with help of models for many years. Historically, most of the producer's revenue have come from the spot market where short-term variation in prices has been relatively small. The electricity system is developing to a system with more new renewable production like wind and solar production giving more short-term variation in market prices and increased need for balancing from the hydro system. This will result in the hydro system more often operating at its limits and it will consequently be more important to include the physical properties of the hydro system in investment type analysis. This is the motivation for the development of the ProdRisk-SHOP simulator. The purpose is to improve calculation of revenue from different investment alternatives where physical detailed properties are important. Some examples of physical details are pressure couplings, time delays, unit description and commitment status, non-convex relations between head, production and discharge.

2 Investment analysis

2.1 Overview

This chapter describes the main principles of how a typically Norwegian producer is evaluating larger investment decisions. With investment decision we here think of all types of decisions that changes that affect future operation of the hydro system. A typical example would be that the producers need to replace/maintain existing turbine. If going for a new turbine, typical questions could be:

- What should be the specification for the new turbine, could it be larger?
- Is it economical to increase tunnel capacities?
- Do we need new intakes that increase inflows?
- Could it be developed to a pumped storage plant?

The investment decisions involve many different tasks, here we focus on those that involve use of optimization and simulation models. The profitability of an investment consists of the following main components:

Cost side:

- Investments costs (labour costs, new equipment etc)
- Costs of unavailability during construction/maintenance period

Revenue side

- Revenue from future production

If the value of the above components is known, the best investment alternative is found by comparing the net present value for the different investment alternatives. The alternative with the best net present value is chosen if it satisfies the companies risk premium (could be included in the discount rate). Of course, this is very simplified and assumes, e.g., that the different alternatives have the same future operation costs, maintenance costs, failure probabilities etc.

Simulation and optimization models are typically used to calculate costs of unavailability during construction/maintenance period and to calculate the expected revenue from future production for the different investment alternatives. Models are also used to calculate lost revenue caused by forced outages of production units which again is input to maintenance scheduling decisions.

Our focus here is calculation of future revenue for different investment alternatives but the same models with small modifications are also used for the other tasks.

The lifetime of many hydro investments is very long, but the relevant planning horizon is limited by the discount rate use for the net present value calculations, for example 25- 30 years. Ideally, the expected production revenue should be calculated for every year in the planning horizon. The expectation is with regard to the uncertainty caused by weather on variation in inflows and market prices. Other uncertainties, e.g., price uncertainty caused by future market development of carbon taxes or gas/oil prices are handled using different development scenarios for the future electricity markets. Here we assume we follow one such future market scenario. Because of long calculation times and difficulties of making precise forecast for individual years in the planning period, revenue calculations are typically done for one or more stadiums/year that represent an average of the whole or parts of the planning period. Seen from now it does not make much sense to differentiate between 2033 and 2034. The chosen stadiums represent the average of market development in the chosen part of the planning period for the chosen future development scenario. Revenue from production for a chosen future production system (including a given investment) is calculated using what we call serial simulation.

In serial simulation the production system is simulated hour by hour with all weather years ordered sequentially. The reservoir fillings by the end of weather year 1962 is the start filling for simulation with weather year 1963 and so on. The average revenue over all weather years represent the expected production revenue.

3 Existing tools for system operation and simulation

SINTEF develops and delivers two tools that are used for this type of calculations Vansimtap and ProdRisk [1]. Both models consist of an optimization (strategy) part and a simulation part. The strategy part calculates the future value of the water in the reservoirs which is used as the cost of water in the simulation part. The simulation is done week by week sequentially with reservoir storages by the end of one week as input to the next week.

Inputs to Vansimtap and ProdRisk are identical and includes a detailed model of the production system and a description of future market prices. With detailed we mean that each individual reservoir and plant in a cascaded river system is modelled. Individual production units are aggregated to one plant.

Hydro module data include:

- Storage size
- Inflow statistics
- Topology information (discharge, bypass and overflow destination)
- Constraint information (discharge, bypass, storage)
- Plant description (P (MW) as function of Q m3/sec)
- Storage size as function of head

The market price input consists of one price for each time period for each weather year that is going to be simulated. Market price input is typically generated using fundamental based market models [2] and [3] but might be post processed to include properties (e.g. variation) that is not captured by the fundamental model approach.

The models give identical type results including production, discharges reservoir storage, overflow, bypass for each plant storage in the system for each time period of the year for all weather years. The time resolution is flexible and might be from hourly to a few accumulated time periods within the week depending on analysis and system.

3.1 Vansimtap

Vansimtap calculates the strategy for an aggregate description of the hydro system using a variant of Stochastic Dynamic Programming (SDP) called the so called "*water value method"*. Because the water value (dual) is calculated directly in the backward recursion instead of future profit as in SDP. In the simulation part of Vansimtap detailed system operation is found combining the water value for the aggregate system with a heuristics that accounts for the detailed properties of the system. The heuristics seek to minimize overflow risk and the risk of running empty for individual plants to find a near optimal operation of the system.

Vansimtap is used is used by many utilities for maintenance planning and estimation of revenue losses caused by outages. The model is also used for medium and-long-term scheduling, production and reservoir forecasting and investment analyses. Vansimtap is often used to supplement ProdRisk and solve tasks where short calculation time is crucial.

For standard ProdRisk use, aggregate water values from Vansimtap are also used to set the value of water by the end of planning horizon in ProdRisk.

3.2 ProdRisk

The ProdRisk strategy is calculated for the detailed description of the hydro system using the SDDP (Stochastic Dual Dynamic Programming) methodology. The method requires linear relations and a convex problem formulation. The core weekly decision problem is assumed deterministic (inflow and prices are known) and formulated as a Linear Programming (LP) problem. Uncertainties in inflow and market price are assumed to be resolved in the transition from one week to the next.

ProdRisk calculates the strategy for a detailed system description and is therefore more optimal than Vansimtap, especially for complicated cascaded systems. The downside is the calculation time which is much longer than Vansimtap. Computation time is an issue for some type of analysis, e.g. optimal timing of given maintenances because many runs are needed.

ProdRisk is used by almost all larger hydro producers in the Norway, Sweden and Finland for long-and medium-term hydro scheduling, maintenance scheduling, production and reservoir forecasting and for investment analysis.

The requirements of the SDDP solution methodology limits the type of physical details and non-linearities that can be modelled, especially for the strategy part of the model. The simulation part might include non-linearities modelled for example using Mixed Integer Programming (MIP) and/or iterative approaches. However, if the simulation part includes properties that has not been handled in the strategy part, there is no guarantee that the simulated results are optimal. The existing ProdRisk model include the possibility to model a few nonlinear effects in the final forward simulation, for example non-convex PQcurve handled by MIP modelling and production referred to actual head by the beginning of each week.

As mentioned in the introduction we believe it becomes more important to handle more of these non-linear physical properties of system when calculating future revenue for alternative investments. A possible development could be to include more and more non-linear effects in the simulation part of ProdRisk, for example using the MIP formulation and Successive Linear Programming, exemplified in [2] and [3]. Instead we have chosen a different development path where we will try to utilize a commercial short-term operation planning model (SHOP) in the final forward simulation. The SHOP model has been developed for many years, are used extensively, and include enough physical details that results can almost be used directly in scheduling. More about this in the next chapters.

Ideally, the strategy part should include the same properties as are included in the simulation part to ensure optimality. However, we believe that there are possible advantages of having the possibility to simulate a system with more physical details than what can be included in the strategy part. Such detailed simulations resemble the operational planning done by hydropower producers in the Nordic market. This does not mean we think it is less important to improve the strategy part of the model, but we realise that this is much more complicated and that many of the details are not possible to include in the strategy part due to the extreme computational effort needed. Project 3.4 in HydroCen is working to improve the strategy part of ProdRisk and especially focusing on handling of state (reservoir/inflow) dependent environmental constraints and head dependent discharge constraints [3], [4].

3.3 SHOP – Short-term Hydro Operation

SINTEF maintains and develops a data program, called SHOP, that is used for short-term operation planning [5], [6]. The program is used daily for several bidding and scheduling tasks: bidding to the spot market, scheduling the obligation received from the spot market and decision support for bidding to intraday and balancing markets. The model is used by almost all producers in the Nordics and several in central Europe.

The model uses a combination of MIP and successive linear programming to solve an optimization problem. The objective of the optimization is to maximize revenue from production while fulfilling all judicial and physical constraints. The planning period is typically from 7 to 14 days, time resolution is flexible, but typically 15 minutes or hourly. The short-term operation problem is usually formulated as a deterministic problem, but it is also possible to use a stochastic formulation [7].

An important input to the SHOP model is the end point description for the reservoir storages. This description may take several forms, here we will mention the two most principally different:

- End storage levels are fixed (target volume).
- End storage levels have a marginal value (water value).

For operation planning, the end storage description is almost always given by marginal values in some form, from independent and constant values for each reservoir to described by cuts (i.e. coupled and dependent on reservoir storage) [8]. Individual water values are usually calculated using the ProdRisk model or from a separate medium-term model included in the Vansimtap program system.

Because SHOP is used for operational decisions and scheduling much more physical details than what is included in the long and medium-term models can be included. Among others the model includes modelling of each individual unit in a plant, pressure couplings, correct handling of head dependencies throughout the planning period, startup costs.

3.4 ProdRisk-SHOP simulator

The new tool that we develop for calculation of production revenue for different investment alternative is based on the following main principles.

- The operation strategy for the hydro are calculated using the SDDP methodology implemented in ProdRisk. The strategy is described by what is called cuts. Cuts are linear constraints that describe the relation between expected future profit and the state variables for each week in the planning period. State variables are storage levels, inflows, and market price.

- A new final simulation of the hydro system is done using the SHOP model. The simulation is performed week by week in sequence where end storage level from the previous week is input to the next week. Cuts are used to model end of week reservoir value.

A similar simulator setup was developed some years ago and tested in [9], combining the tools Vansimtap and SHOP for benchmarking the historical operation of a power producer in Norway.

We are not aware that this approach has been tried before for investment planning purposes, but we know of at least one producer who have developed a tool with similarities. The idea is in the producer case also that SHOP is used in the final simulation, but each week's end storage level is assumed given from the long-term model (in this case Vansimtap). Our proposed approach using cuts gives more flexibility to the final simulation but also increase the probability of larger deviation from the operation that was assumed optimal when the cuts were calculated. If the deviations become too large there is at least two possible ways to remedy the problem.

- Combine the cut approach with a trust interval for reservoirs. Cuts are used if the reservoirs are within the trusted interval.

- Feedback to the log-term model. New cuts are calculated in ProdRisk for the new storage levels.

The point of using the SHOP model in a final simulation is of course to include more physical details but it is important that everything that can be equal in ProdRisk and SHOP is equal, e.g. plant efficiencies for reference head.

4 Simulator implementation

The ProdRisk-SHOP simulator is implemented in the Python programming language using API versions of SHOP and ProdRisk. The API version of ProdRisk is relatively new and has been developed in parallel with the HydroCen work. The simulator is largely an exercise in wrapping and passing data between the two scheduling models in a consistent way. This requires knowledge of the core SHOP and ProdRisk models as well as their Python interfaces. For information about function calls, objects and attributes that are exposed by the APIs, please consult their respective documentation.

4.1 Input and output handling

The API versions of the models allows the simulator users to do input and output handling of the models in their own preferred way, e.g., reading and writing data to their own database. The simulator does however come with a standard format for input and output handling via HDF5 files, with data structure matching the data structure of the model APIs. The ProdRisk and SHOP datasets are specified individually. Note that the user must ensure consistency, as there is no check in the simulator.

A simple pre-process script may be run to convert the standard model input files (LTM input files for Prodrisk, and ASCII-files for SHOP) to the simulator HDF5 input format. Similarly, a post-process script may be used to convert the simulator results to standard ProdRisk results files, enabling use of Vansimtap/ProdRisk result applications. Note that these pre- and post-process scripts are limited, i.e., not all input and results are converted to and from the standard model input and output files. For instance is it not possible to represent all SHOP results on the ProdRisk results files due to different details in the description of the physical system.

4.2 The simulator framework

The framework of the simulator Python program is illustrated in Figure 1. A static system description (ProdRisk and SHOP inputs) is provided by the user. Information from the long-term model (LTM) is passed to the short-term model (KTM) in the form of cuts or water values. The figure indicates weekly runs of the LTM model with new forecasts and other types of updates each week. We emphasize that the LTM model can be run once for the whole planning horizon without such updates.

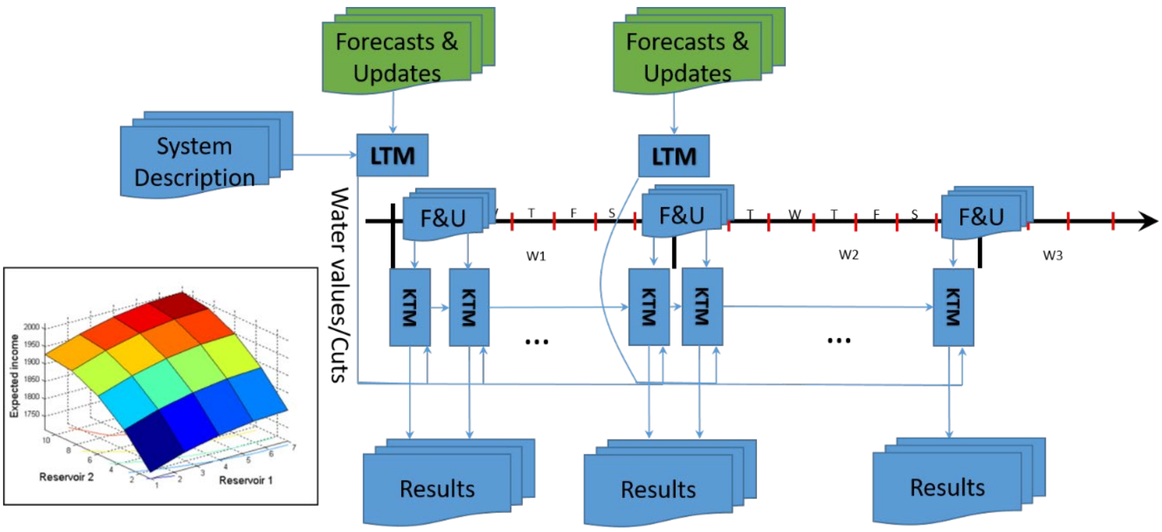


Figure 1 Simulator framework.

5 Case studies

5.1 Testing of cut handling

The cuts calculated by ProdRisk represent expected future profit as function of reservoir fillings, inflow and market price for a given point in time. For a given market price and point in time the cuts have the following form:

$$\alpha + \pi^T{}_i(v - v^*{}_i) + \mu^T{}_i(z - z^*{}_i) \leq \alpha^*{}_i \qquad \mathrm{i} = 1 \ldots \mathrm{N} \tag{1}$$

where:

α	- Future profit (also included as a variable in the objective function of the short-term optimization problem.
π^T	- Cut coefficients (water values)
v	- Vector of storage variables
μ^T	- Cut coefficients for inflow (future profit sensitivity to current inflows, due to auto correlation in inflow).
v^*	- Reference volumes for cut
z	- Vector of inflows
v^*	- Reference states for inflows
i	- Cut number
N	- Number of cuts

When the cuts for the first one or two weeks are used as end of horizon value of water in SHOP for the daily operation decisions, the inflow dimensions and market price dimension of the cuts are usually disregarded. The possible variation of inflows and price for the short-term planning period (first week) is small and/or knowing the values of these variables is assumed to give little information about what comes afterwards (zero autocorrelation). This simplification also makes it easier to understand the cuts which is important for the model operators that often have less theoretical background. Referring to equation (1), it means that the inflow part if the cut is not included.

When SHOP is used in the simulator to simulate operation for the whole year covering a wide variation in inflow and prices, correct handling of the price and inflows dimensions of the cuts in SHOP becomes very important. Because this functionality, as mentioned, is typically not part of the operational use of the model we made an initial test to verify that these additional dimension of the cuts are handled correctly in SHOP.

The simulator is applied to a cascaded hydro system consisting of two reservoirs and plants. The SHOP model is in this case made to be as identical as the ProdRisk model as possible, i.e. we only model physical details/properties that are also handled similarly in the ProdRisk simulation.

The inflow and price dimensions of the cuts are handled correctly if the simulations results from ProdRisk and ProdRisk-SHOP simulator give the same results because we know they are handled correctly in ProdRisk.

We are aware of some minor differences that makes it impossible to get identical results. For instance, the price dimension of the cuts is handled differently. In SHOP interpolation is used to pre-process a set of cuts referring to the actual price while in ProdRisk the sets of cuts for the price node above and below the actual price are weighted in the objective function according to price distance.

Figures 2 and 3 show percentiles (0,25,50, 75 and 100) for simulated reservoir level (Mm3) for a three year long planning period (156 weeks) using ProdRisk and the ProdRisk-SHOP simulator. Simulated operation is very similar and we conclude that the cuts are handled correctly in the SHOP model.

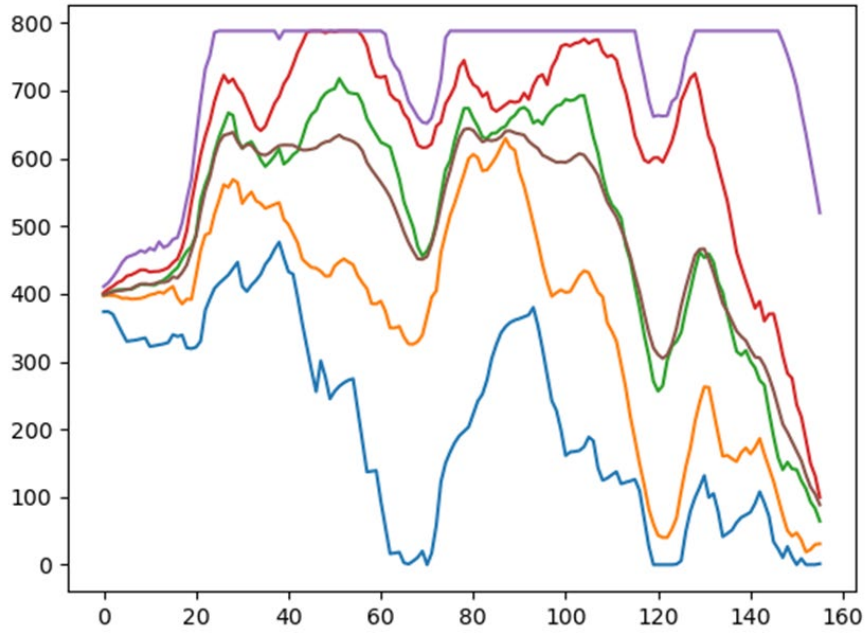


Figure 2. Simulated reservoir operation from ProdRisk

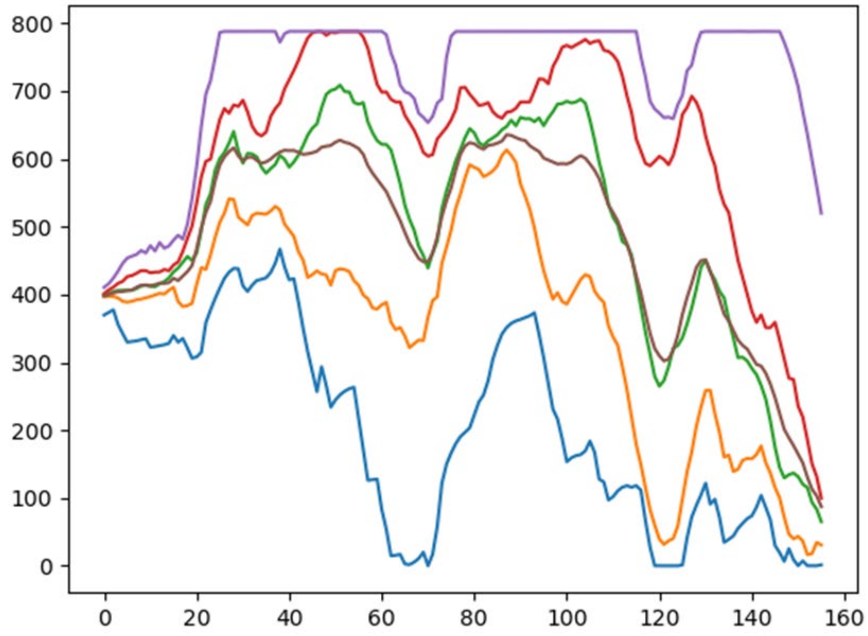


Figure 3. Simulated reservoir operation with the ProdRisk-SHOP simulator.

5.2 Sira-Kvina investment project

The ProdRisk-SHOP simulator has been applied to a real investment problem in the Sira-Kvina hydropower system. This system is owned and operated by the Sira-Kvina kraftselskap. The company is owned by four Norwegian producers.

Sira-Kvina's investment problem is whether to upgrade the turbines in the Duge pumped storage plant. A sketch of SINTEFs model of the whole water course is shown in Figure 4. The reservoir Svartevann is the upper reservoir of the Duge plant located upstream in one of the two parallel watercourses that are both discharging into the large Tonstad power station downstream.

SINTEF and the HydroCen project were asked to contribute to the simulations of the different investment alternatives using the new ProdRIsk-Shop simulator. Additional analyses were done by each of the four owners of Sira-Kvina using separate assumptions about future market prices and inflows and using their own optimisation/simulation models. The project constitutes a real test of the type of decision problem the new simulator is intended to contribute to.

The project consisted of three main phases as explained in the following sections.

- Model backtesting;
- Assumptions about the future;
- Simulation of investment alternatives.

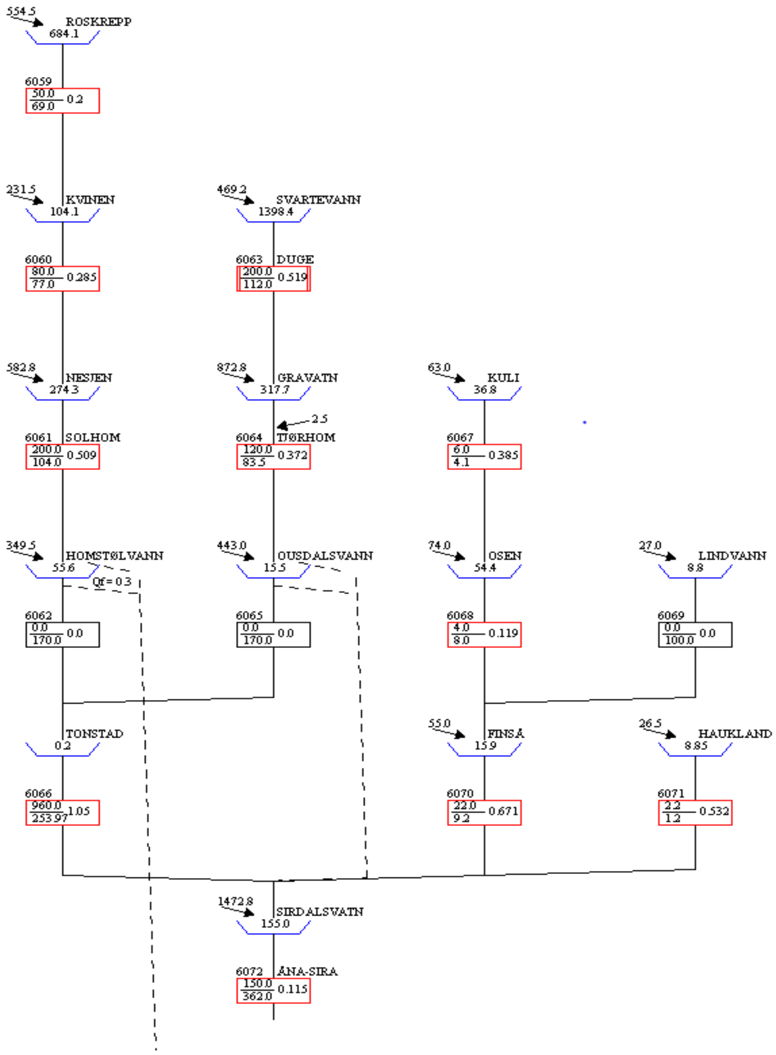


Figure 4 Sira-Kvina water course

5.2.1 Backtesting

The purpose of the backtesting is to verify that the physical model of the existing hydro system is satisfactory. Especially, the inflows to the different modules are difficult to estimate. The inflow series should refer to a long historical period and possibly be corrected for climate change. In the simulations we have used the historical period 1958-2018 to represent the natural inflow variation. This period is chosen because it is the historical period for which NVE provide official inflow series for a number of locations throughout Norway. The official NVE series located "closest" to a particular reservoir series are scaled to give physical inflows to the individual reservoirs in the system. Initial scaling is based on the size of the drainage area but calibrated with observations. To verify that the model for Sira-Kvina was good enough we did a backtesting where model simulations results were compared with observed production and reservoir operation data. Market prices for the 1958-2018 period was initially calculated by a fundamental model market model [12] and [13], but simulated prices for the backtesting period 2006 -2018 where replaced by observed prices while keeping the average for whole 1958-2018 period unchanged.

The backtesting method used here is relatively simple.

- The long-term operation strategy is fixed for the whole historical period, i.e. cuts (water values) are calculated for a given input price and inflow statistics (1958-2018) and not updated in the simulations. No updating based on price forecasts, inflow forecast or maintenance plans. In practice, Sira-Kvina and its owners would have seen many very different futures throughout this period.
- Weekly decisions are optimized assuming observed prices and inflows for the whole week.
- Actual unavailability of units is not included in the simulations.

Even with these simplifications, major results should be very similar, such as the simulated total production (GWh) for the whole observations period. Figures 5 and 6 compare simulated operation with observed operation for two of the reservoirs in the system. As expected, with the given the simplifications, simulated reservoir operation is not equal for every time period, but the overall evaluation is that it is close enough. Sum production for two selected plants is compared with observed data in Table 1. Production data is not corrected for differences in storage levels by the end of the observation period. The two selected plants are chosen because we ended up to model only those two plants in the ProdRisk-SHOP simulator. More about this simplification in the next chapters.

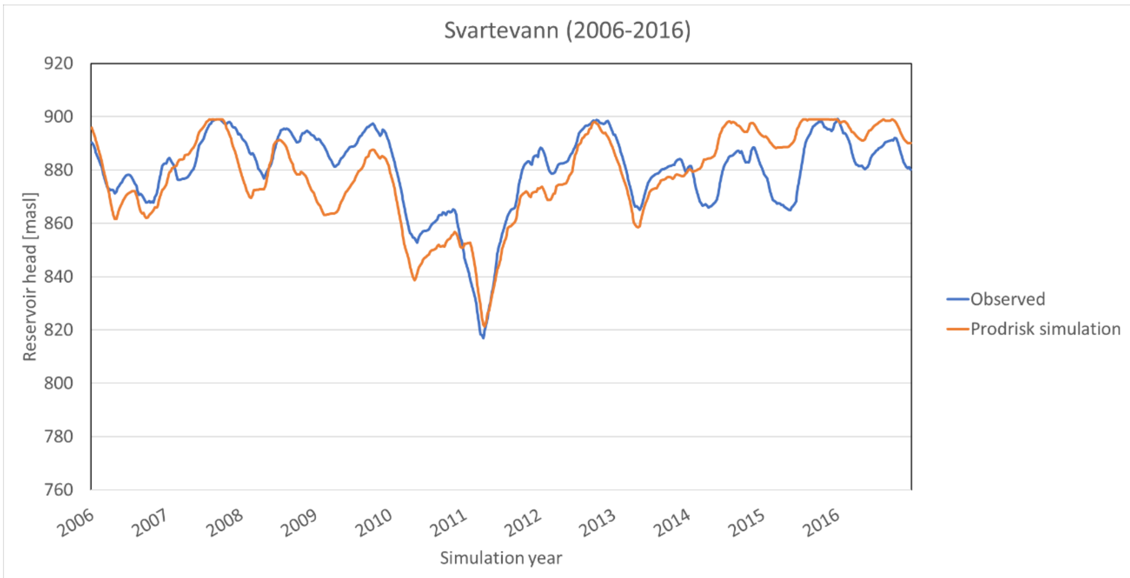


Figure 5: Simulated and observed operation of Svartevann for the backtesting period.

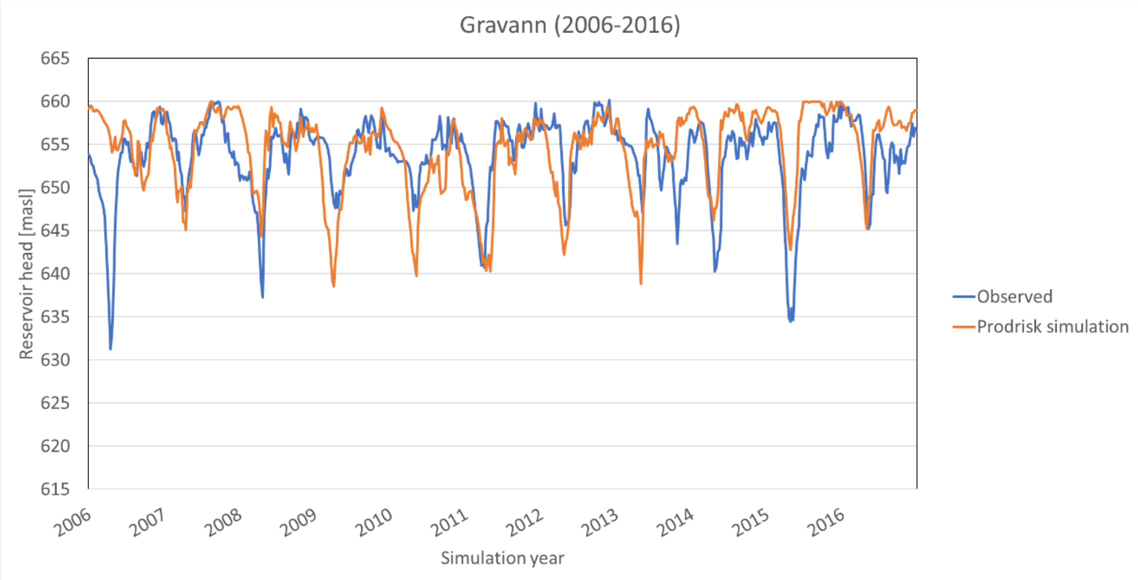


Figure 6: Simulated and observed operation of Gravann for the backtesting period.

Table 1. Yearly averages for selected plants for the backtesting period

	Observed	**Simulation**
Duge gross production (GWh)	378	351
Duge pumping (GWh)	132	101
Duge net production (GWh)	247	251
Tjørhom production (GWh)	**610**	612

5.2.2 Assumptions

Backtesting is used to verify that inflows and physical modelling for the existing system are satisfactory. Investments are for the future system and requires additional assumptions about future inflows and future market prices.

Future inflows are as mentioned based on the historical period 1958-2018 but assuming 5% increase in inflows, due to climate change, from 1975 to 2030 which is the reference stadium for our investment analysis. The climate change correction is SINTEFs rough estimate based on participation in several Nordic climate change projects [10] and [11].

Future spot market prices referred to stadium 2030 are taken from the work done in HydroCen [12]. In this work a fundamental based market model is used to simulated the balance between supply and demand in the whole of Northern Europe. Figure shows hourly market spot market prices for three weather years. The weather years couples all weather related variation that affects supply and demand for electricity in time and space, i.e. precipitation, wind speed, solar radiation and temperature.

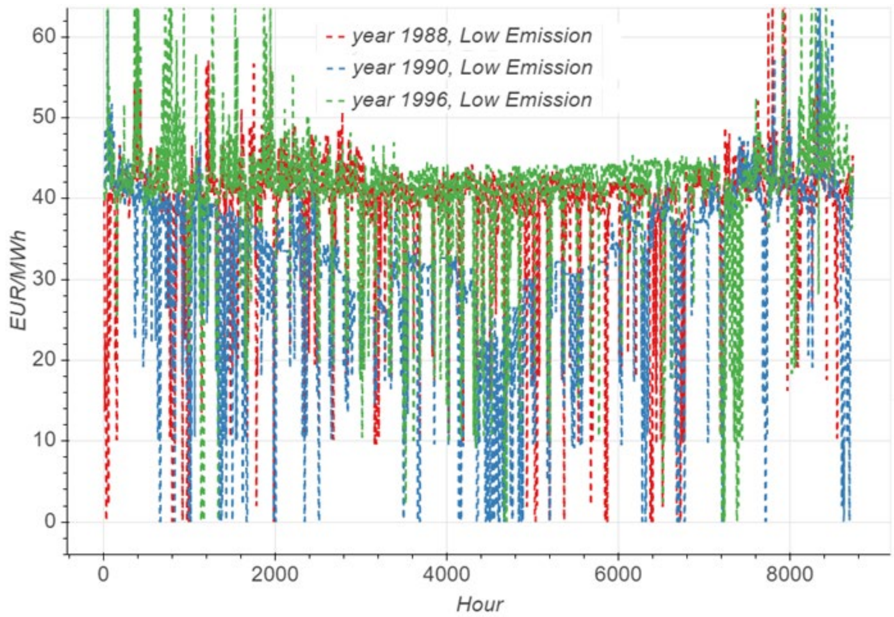


Figure 7. Power prices in South of Norway referred to stadium 2030 for a wet (1990), normal (1988) and dry inflow year (1996).

The physical system is defined by the existing system plus the properties of given investment alternative. The principle differences between investment alternatives are shown in Figure 8. The grey curve (1b) represents the current turbine efficiency as function of discharge and the three other alternatives represent the investment alternatives. The figure shows the curve for one turbine, but the plant consists of two equal turbines.

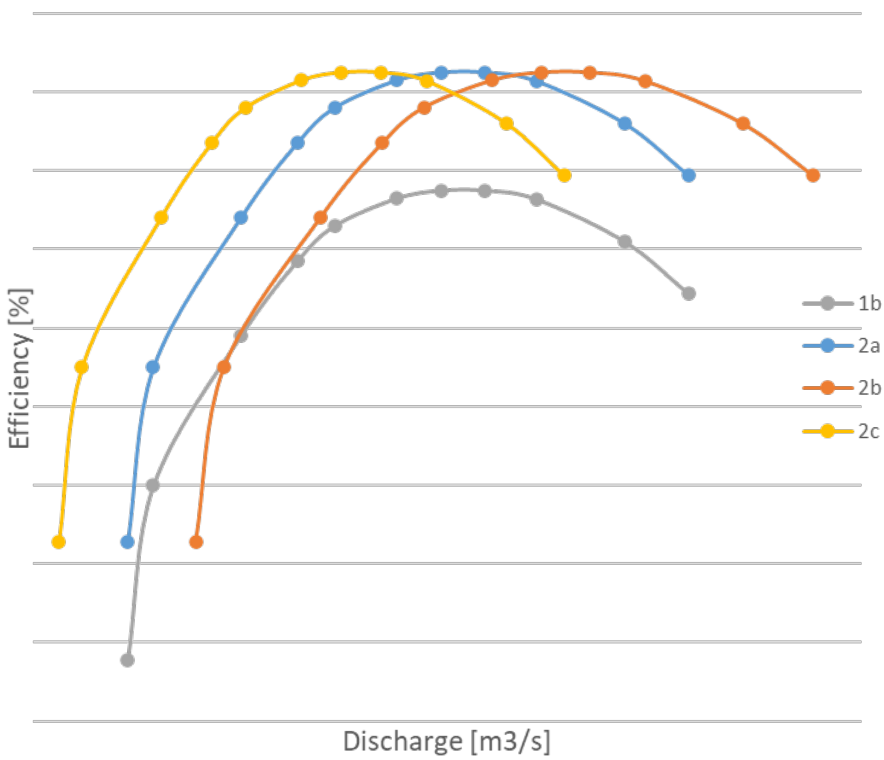
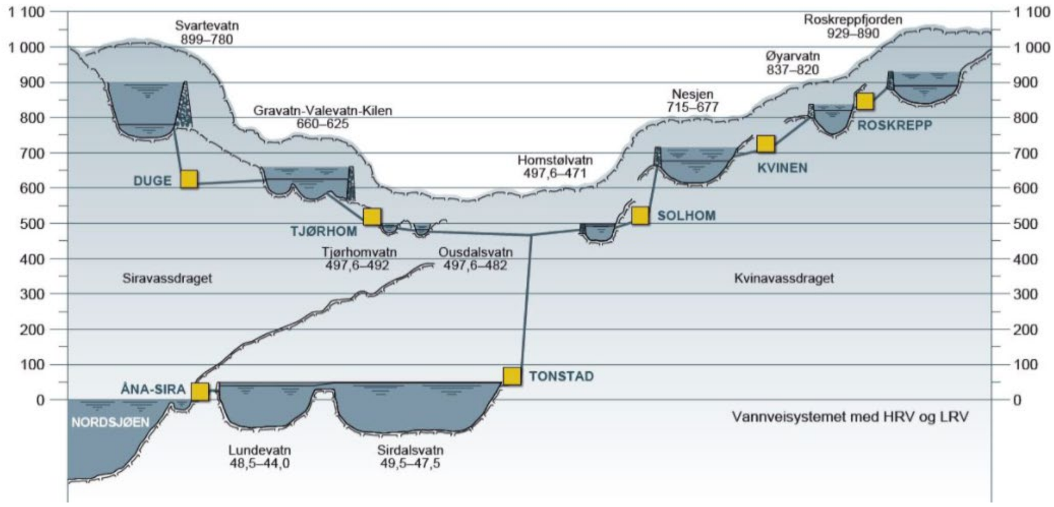


Figure 8. Anonymized turbine efficiencies for the different investment alternatives

5.2.3 Simulation of different investment alternatives

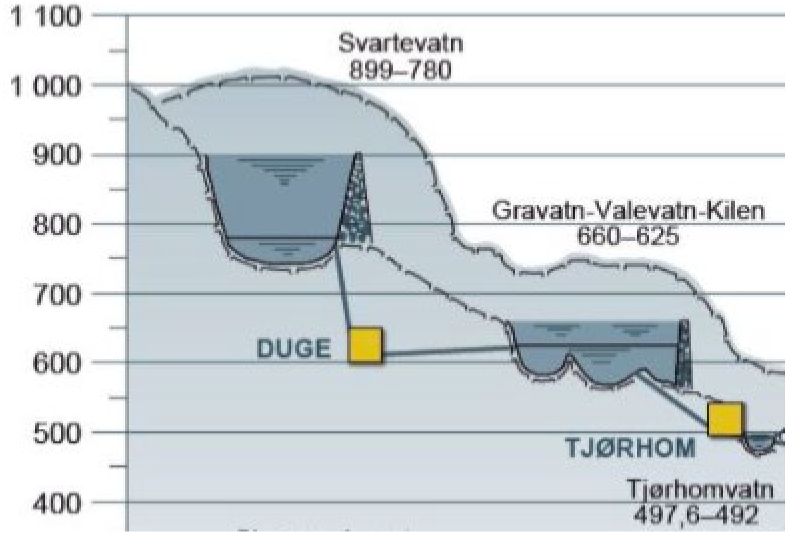
It became clear very early in the project that it was not possible, at that time (beginning of 2020), to do the analysis with the existing ProdRisk-SHOP simulator for the whole physical system. This was to some extent caused by calculation time, but the main reason had to do with stability issues. The SHOP model did not find a solution for all problems. Some of the other project participants which used a SHOP-based simulator with fixed end storages instead of cuts had the same experience.

The ProdRisk-SHOP simulator was therefore run for reduced system that consisted of only the two upper reservoirs that is directly affected by the investment, i.e., the reservoirs Svartevann and Gravann with the Duge and Tjørhom plants. The whole system is shown in Figure 9 and the reduced system in Figure 10. The Y axis shows meter above sea level and therefore also illustrates the importance of modelling head dependency correctly. The Duge plant consists of two units and Tjørhom of one unit.



Source: Sira-Kvina (2020)

Figure 9 The Sira-Kvina system



Source: Sira-Kvina (2020)

Figure 10 The reduced Sira-Kvina system.

Because these two reservoirs are the first two in the water course this separation from the rest is simpler to do, but it still represents a simplification of the real problem.

SHOP use Mixed Integer Programming (MIP) and successive linearization to solve the weekly optimization problem. ProdRisk solve a Linear Programming (LP) problem. This gives differences to e.g. to how head dependencies are handled throughout the week.

The modelled main difference between the SHOP and ProdRisk model in these analysis are the following.

1) The Hill diagram is almost fully represented in SHOP. In ProdRisk production is proportional to head but with a fixed maximum discharge.
2) Individual unit representation in SHOP with minimum generation and startup costs. Plant description in ProdRisk.
3) "Gravann" in ProdRisk actually consists of two physical coupled reservoir (see figures 10 and 11 . Pumping from and discharge to Kilen and discharge from Gravann. Flow in the channel between depend on head differences. This relation is modelled in SHOP but is represented with one reservoir in ProdRisk
4) The pump description is much more detailed in SHOP, e.g. individual turbines are represented. I ProdRisk, constant energy used for pumping, amount of water pumped proportional to head.

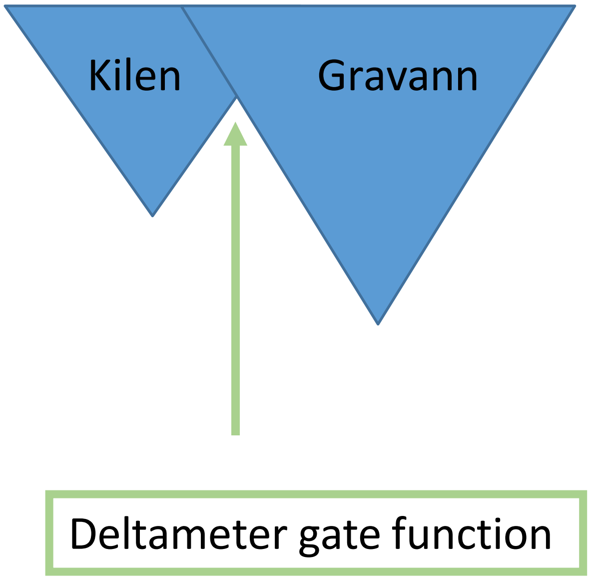


Figure 11 Illustration of a physical constraint in Gravann reservoirs.

Figure 12 shows simulated reservoir operation for Svartevann from only ProdRisk and from the new ProdRisk-SHOP simulator. The ripple differences are because reservoir data are stored with different time resolution in the two models. The seasonal operation and variation between weather years are very similar. Meaning that including more physical details in the final simulation does not affect in this case the long-term operation of this large reservoir. A tactical limit was used in the SHOP model to limit the maximum reservoirs in Svartevann to 1387 Mm^3 , a bit below the physical maximum of 1398 Mm^3 used in ProdRisk.

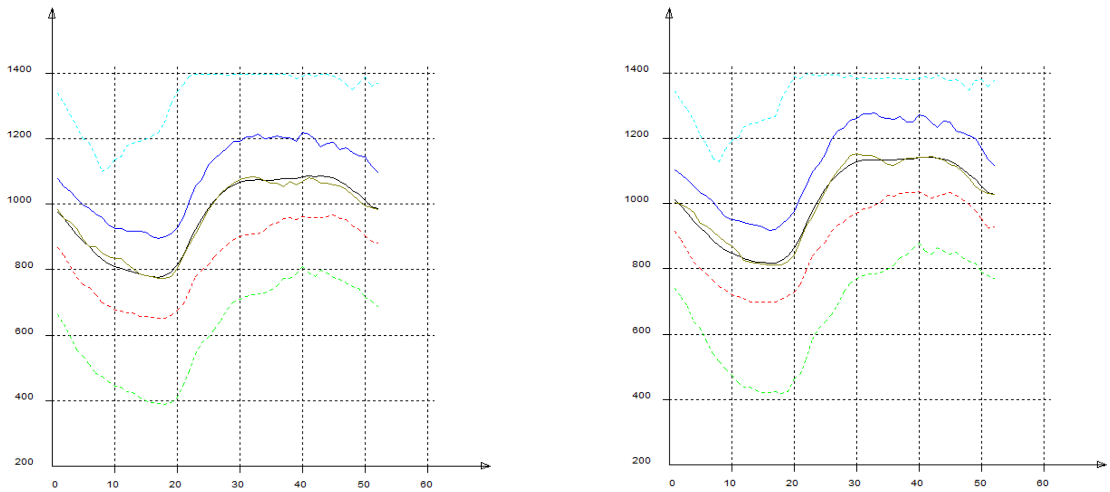
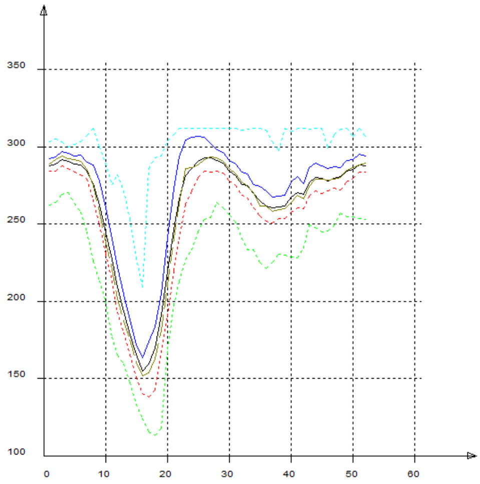


Figure 12. Simulated reservoir operation of Svartevann, ProdRisk (left) and ProdRisk-SHOP simulator (right), percentiles (0, 25, 50 75 100) and average. Y axis (Mm^3), X axis (week of the year).



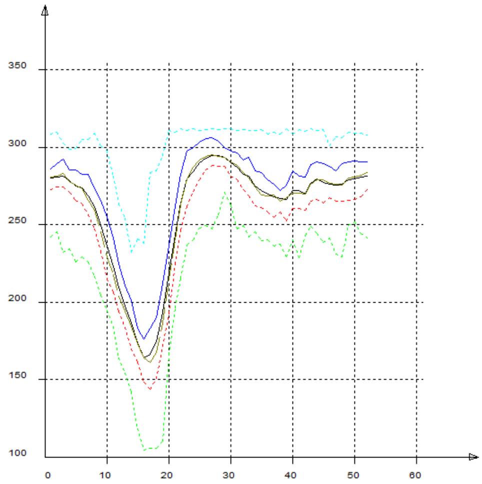


Figure 13. Simulated reservoir operation of Gravann, ProdRisk (left) and ProdRisk-SHOP simulator (right), percentiles (0, 25, 50 75 100) and average. Y axis (Mm^3), X axis (week of the year).

Figure 14 shows the simulated average number of hours per year with pumping at different powers for the Duge pumped storage plant. This figure illustrates some of the more detailed information the simulator provides and take into account. Pumping is split between the two turbines, even though most of the time both turbines are used also in the simulator. Furthermore, we also see that the pumping power used for pumping depends on the head, while in ProdRisk pumping power is assumed constant and the amount of water pumped is scaled based on head.

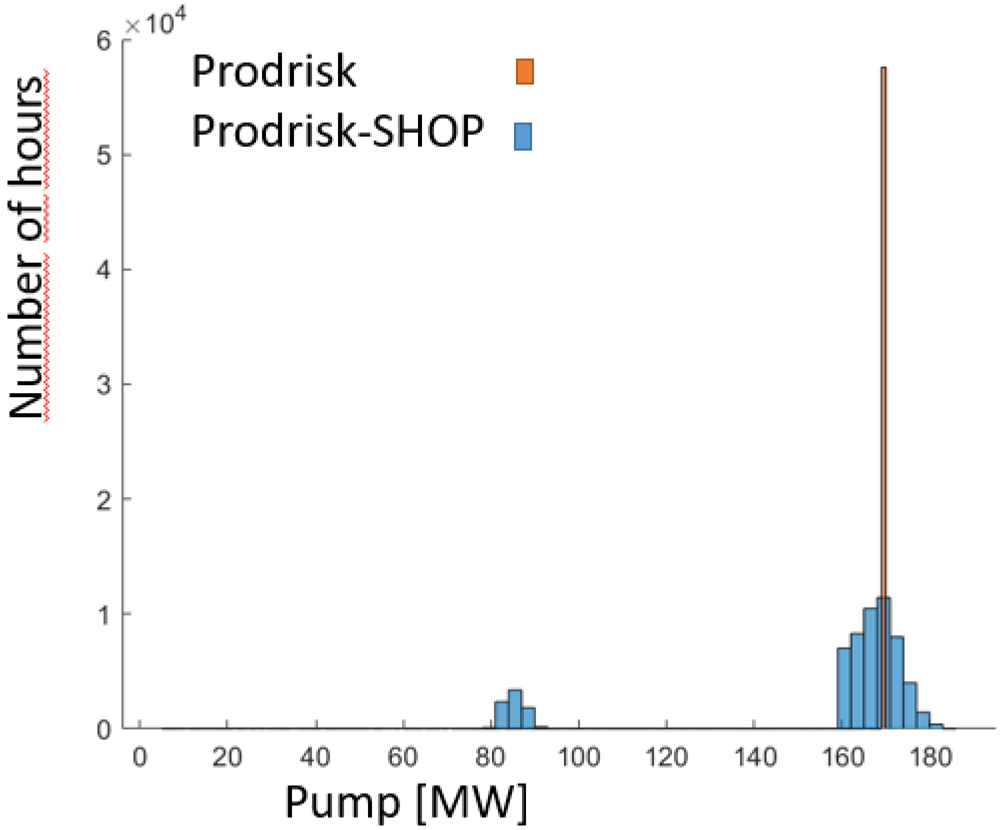


Figure 14 Diagram showing average number of hours per year with pumping (MW)

Figures 15 and 16 show simulated revenue for the different investment alternatives. Results are shown as relative numbers with revenue for the existing system simulated with ProdRisk scaled to 100 %. The ProdRisk-SHOP simulator gives a total production revenue that is about 3 % lower than the ProdRisk only simulation. It is reasonable since including more constraints would always lead to lower revenue, assuming everything else was equal. Our simulator includes more constraints but there are also other modelling and solution differences as discussed above.

The investment decision is based on the revenue difference between the reference and the different alternatives. Even if the two models give different revenues the calculated difference is the same for alternatives 2a and 2b, just above 1% increase in revenue. For alternative 2c the simulator gives a bit less increase in profit compared to ProdRisk simulations.

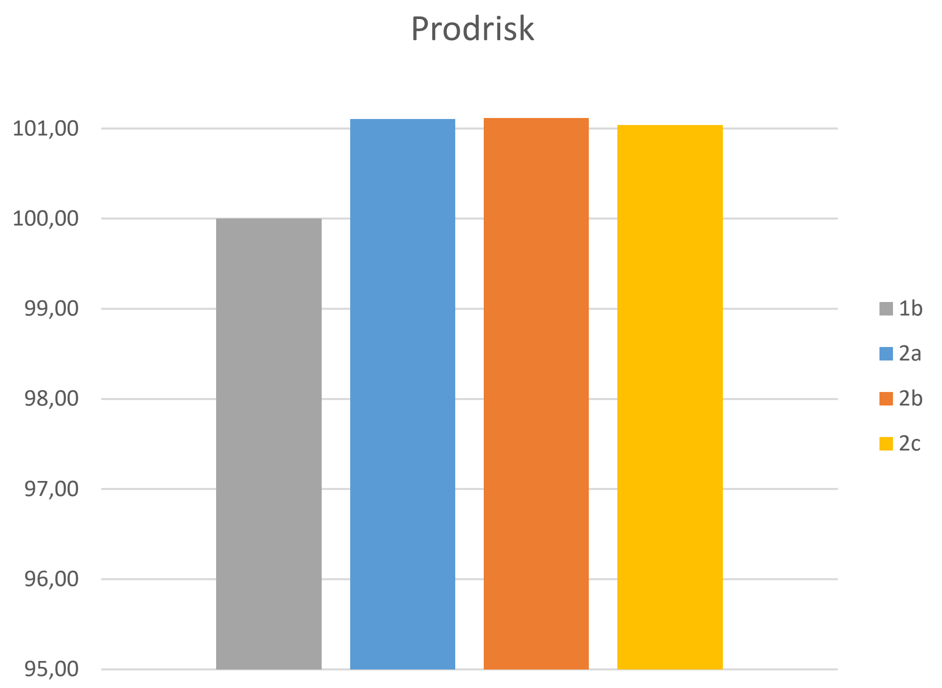


Figure 15 Simulated production revenue for the different investment and the reference with the standard ProdRisk model.

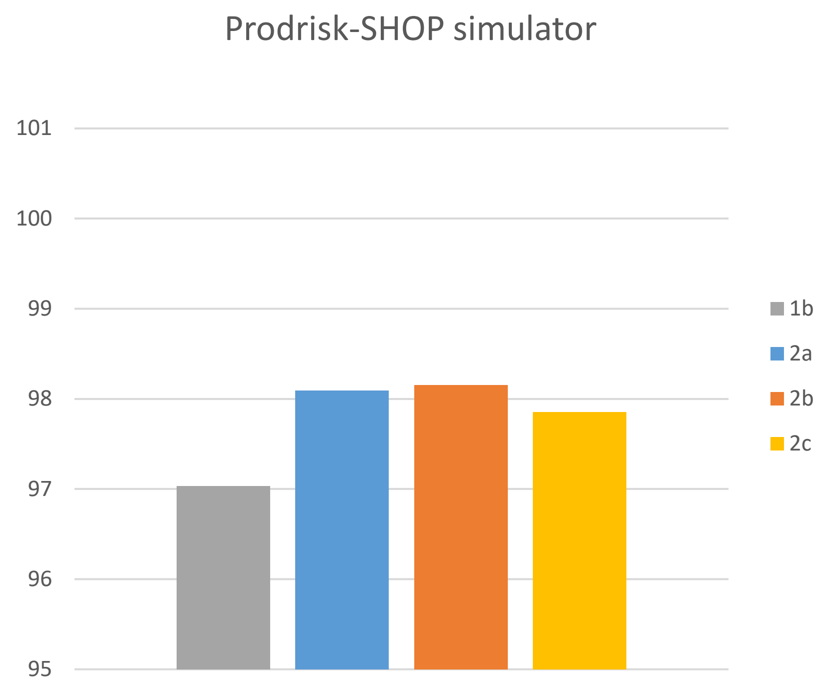


Figure 16 Simulated production revenue for the different investment and the reference with the new ProdRisk-SHOP model.

Sira-Kvina's recommended investment decision are based on the results shown above, but also including similar type of results from the four owners. The decision also includes qualitative based evaluations of the additional value of ancillary services. The different owners used (as mentioned earlier) other tools and assumptions, especially the assumptions about future market prices were different.

The recommendation from Sira-Kvina, considering investment costs and the results from different revenue simulations, is to invest in alternative 2a.

Even if the new tool gave the same increase in revenue for the different alternatives as standard ProdRisk, the simulator results are useful because they give more certainty about the robustness of the result. A more difficult interpretation problem would occur if the two optimization/simulation tools gave very diverging results. The question would then be whether this is because of the more physical real-world details included in the simulator or because the long-term strategy is far from optimal given the detailed physical description used in the simulation. If it is because of the first explanation, then the simulator has provided important decision support information which is the whole point of developing the simulator. Updating the long-term strategy based on the simulator results may reduce how often diverging results is caused by poor long-term strategy. This will be of further investigated in the project. There is no general answer for how to identify what is the reason for diverging results, but a thorough investigation of the simulation results may explain why and thereby point to which of two model results to trust.

Projects participants that had used a simulator based on SHOP before experienced that it was not possible to apply the simulator to large systems, because they too often run into unsolvable problems. Therefore, they always applied this type of simulator only to the part of system directly affected by the investment. This experience is based on an application of the SHOP model in a simulator where end of week storages are given from a long-term model. It is reasonable to believe that such an approach increases the possibility of giving the SHOP model "unsolvable" problems because "hard" constraints are coming from another model. However, this approach also makes it easier to apply the simulator to a reduced part of the system, that can even be in the middle of cascaded system.

Our simulator approach is more flexible because we are using cuts. However, we were not able to run the whole system in the actual investment project which had a given deadline. More about the work we have done applying the simulator to the whole water course in the next chapter. This is work that was done after the investment project was finished.

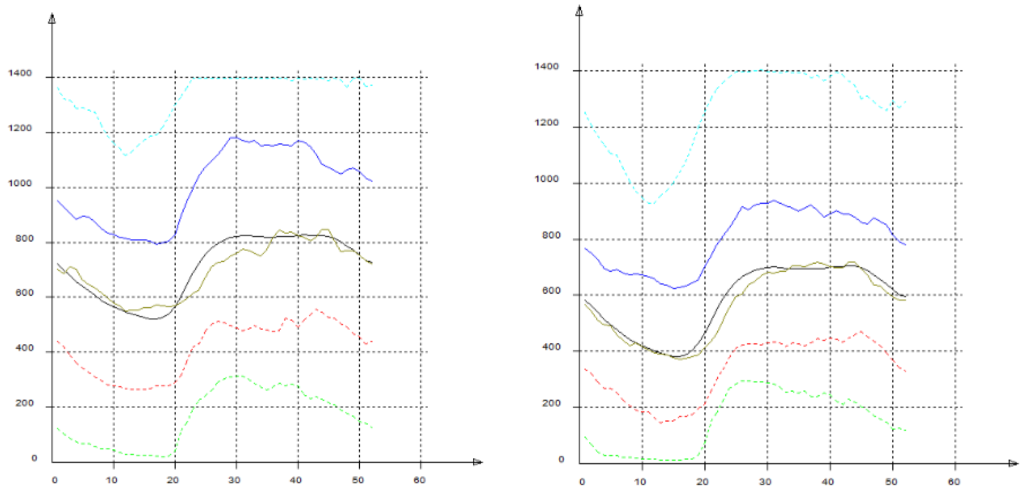
5.3 Experience from testing on larger systems

After the Sira-Kvina investment project was finished, we have kept working on testing the simulator on the full Sira-Kvina system. The daily operation of the Sira-Kvina system (and other large systems) is scheduled based on the state of the whole system, using a long-term strategy prepared based on the state of the whole system. The main objective of developing this new simulator has been to provide simulation results closer to how the system will be operated. To meet this objective, the simulator should be robust enough to also run on larger systems, and we have used this system to gain experience with this new tool and make necessary modifications.

Our investigations of why the simulator runs into infeasible weekly SHOP problems have led to certain modifications of the simulator, to make it more robust. These improvements involve changes to how the model inputs are read from files and set through the APIs, as well as changes of certain modelling details in SHOP (e.g. how the tunnel junction upstream Tonstad power station is modelled). After these modifications we have been able to run the simulator on the full system. Figure 15 shows simulated reservoir operation for Svartevann from only ProdRisk and from the new ProdRisk-SHOP simulator. By comparing Figure 12 and Figure 17 one sees that the difference between the simulated system operation is larger for the simulation of the full system (Figure 17) compared to the simulation of the reduced system (Figure 12). Such differences may have many explanations, e.g.

1. Different modelling in ProdRisk and SHOP which the simulator is meant to capture (e.g. non-convex relations between head, production, and discharge).
2. Inconsistent system descriptions in the ProdRisk and SHOP models (e.g. different minimum/maximum discharge or reservoir restrictions for the involved reservoirs).
3. Programming bugs not yet

We also observe that applying ProdRisk to the whole system (figure 17) gives on average lower simulated storage levels than what is simulated for the reduced system. This is reasonable since seeing more downstream constraints increase need for flexibility which is provided by Svartevann.



Figur 17: Simulated reservoir operation of Svartevann, ProdRisk (left) and ProdRisk-SHOP simulator (right), percentiles (0, 25, 50 75 100) and average. Y axis (Mm^3), X axis (week of the year).

In the simulation that the plots in Figure 17 are based upon we still ran into 11 infeasible weekly SHOP problems (out of the 52*60 = 3120 weeks in our simulation period), occurring in the transition from "full" to "incremental" iterations. These weekly problems were solved by skipping the incremental iterations. We consulted the SHOP experts at SINTEF, and according to them these crashes were caused by limited numerical precision in CPLEX. The tolerance for such deviations may be adjusted in CPLEX. Such crashes may be avoided if adjustment of this tolerance limit is made available through the SHOP API. The ProdRisk-SHOP simulator is a new way of using the SHOP model, and we expect running into similar issues as we move on to testing the tool on other systems. What to do when running into infeasible SHOP problems will be an important decision in our further work on improving and testing the simulator.

In the Sira Kvina investment project, the simplified simulation (reduced system) was acceptable since the plant of consideration (Duge) is located at the very top of one string in the watercourse. The two main advantages of such a simplification are

1. Reducing the computation time and
2. Reducing the probability of stability issues occurring (SHOP crashes).

For an investment decision which affects a station in the middle of a large system, such a simplified strategy calculation cannot be done, and the strategy for the system operation should be made by running ProdRisk for the full system. However, it may still be of interest to run a detailed SHOP-simulation for only a "local snip" of the system. In the next subsection we discuss whether and how this might be done for our simulator setup, where the strategy is described by cuts.

5.3.1 Snip part of physical system

Reference cut states not available

In this section we discuss how the cuts from a large system can be applied in a simulation of a snipped part of the total system. The presented inequalities for the reduced cuts are developed intuitively and we do not provide a formal proof. Ongoing testing will be part of further verification.

Consider two modules in cascade, where module 1 discharges into module 2. A sample cut will take the form:

$$\alpha + \pi_1(v_1 - v_1^*) + \pi_2(v_2 - v_2^*) + \mu_1(z_1 - z_1^*) + \mu_2(z_2 - z_2^*) \leq \alpha^* \qquad (2)$$

In ProdRisk the sample reservoir volumes and inflows are embedded in the right-hand side. Historically, this was done to reduce memory requirements and possibly computation time.

$$\alpha + \pi_1 v_1 + \pi_2 v_2 + \mu_1 z_1 + \mu_2 z_2 \leq \alpha^* + \pi_1 v_1^* + \pi_2 v_2^* + \mu_1 z_1^* + \mu_2 z_2^* \qquad (3)$$

$$\alpha + \pi_1 v_1 + \pi_2 v_2 + \mu_1 z_1 + \mu_2 z_2 \leq \beta \qquad (4)$$

If we "snip" the upper reservoir for SHOP simulation, we need to remove the part of the cuts that is connected to module 2 since this module will not be part of the SHOP model. "Sea" level is moved upstream module 2. The new cut for the snipped system is then given by.

$$\alpha + (\pi_1 - \pi_2)v_1 + \mu_1 \frac{(\pi_1 - \pi_2)}{\pi_1} z_1 \leq \beta - \pi_2 \overline{v_2} - \mu_2 \frac{(\pi_2)}{\pi_1} \bar{z}_1 - \mu_2 \bar{z}_2 \qquad (5)$$

The third part of the left side of the inequality represents future profit's dependence on the inflow (z1) to reservoir i. When model 2 is removed from the system, this dependence has to be scaled proportional to value of water for the module that is removed.

$\overline{v_2}$ and $\bar{z}_2$ is the simulated average values in ProdRisk.

Reference cut states available

If the actual cut reference states for reservoir 2 (v_2^*) is available, as it is in a prototype version of ProdRisk, the modified cut could be corrected based on the reference states, assuming v equal to v*and z equal to z* for modules not included. This should be an improvement because more information about the state of whole system is included when the cut is modified to the snipped system.

$$\alpha + (\pi_1 - \pi_2)(v_1 - v_1^*) + \mu_1 \frac{(\pi_1 - \pi_2)}{\pi_1}(z_1 - z_1^*) \le \alpha^* \tag{6}$$

In this case we refer the cuts for module 2 to the reference volume the cut is calculated for. With constants moved to the right hand side this becomes:

$$\alpha + (\pi_1 - \pi_2)v_1 + \mu_1 \frac{(\pi_1 - \pi_2)}{\pi_1} z_1 \le \alpha^* + (\pi_1 - \pi_2)v_1^* + \mu_1 \frac{(\pi_1 - \pi_2)}{\pi_1} z_1^* \tag{7}$$

The equation would be valid for any cascaded system where we want to snip the upper module and module 2 refer to the first module downstream module 1.

In the middle of a larger system

It will also be valid in cases where module 1 and 2 are in the middle of a larger cascaded systems and module 2 is the first downstream module that are not included. For this cases, simulated discharge, bypass and overflow in ProdRisk from upstream modules that are excluded are inflow to snipped system.

It can also be generalize to a snipped system consisting of I modules that all are upstream module D as in equation 8 where all modules i are part of the snipped system.

$$\alpha + \sum_{i}^{I} (\pi_\mathrm{i} - \pi_D)v_i + \mu_\mathrm{i} \frac{(\pi_\mathrm{i} - \pi_\mathrm{D})}{\pi_\mathrm{i}} z_\mathrm{i} \quad \le \alpha^* \sum^{I} + \ (\pi_\mathrm{i} - \pi_\mathrm{D})v_\mathrm{i}^* + \mu_\mathrm{i} \frac{(\pi_i - \pi_\mathrm{D})}{\pi_\mathrm{i}} z_\mathrm{i}^* \tag{8}$$

6 Summary and future development

The report describes the motivation for development of and status for the ProdRisk-SHOP simulator. We believe there is a need for such a tool and that some users already had developed tools with some similarities is a good testament to that.

The development is complicated because of the following:

- One needs competence and understanding of two different models and methods to identify possible problems;
- One needs a good understanding of the hydro production system components, especially for the SHOP model which is closer to the real world;
- The newly developed API for ProdRisk has had some technical challenges. Different models are programmed in different languages. Simulator (Python), ProdRisk (Fortran), SHOP (C++), API (C#);
- Models that are very different in many ways need well defined cross coupling for proper exchange of data.

As previously mentioned, there will never be any guarantee for how close to optimum the ProdRisk-SHOP simulation results will be. This is because of the methodology; strategy is calculated for a simpler system/model than what is used in the simulation. But as long as it not possible to optimize with all physical details it will always be useful to have model that can simulate the physical system with a reasonable god strategy.

The participation in the real investment project was very useful for the HydroCen researchers. It gave information about the whole investment decision process, where the new tool fit in the process and shows many of the practical considerations that are part of such a process. This experience is included in the future simulator work.

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