Improving operation of a complex headworks system for municipal use and hydropower production by mathematical programming

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Abstract: The paper presents a Mixed Integer Non Linear Programming (MINLP) model of the water resources system supplying Genoa, in northern Italy. The system presently features five reservoirs, three main river intakes, and two well fields. The hydrological regime is typically Mediterranean; water availability is however relatively abundant, so that drought issues are limited, especially now that water demand from the supply sources has decreased due to reduced population, deindustrialization and to improvement in the operation and maintenance of the water distribution network. In this context, it is worthwhile considering the possibility to relax an over-conservative management of resources, justified by the experience of previous drought events, and to explore the viability of exploiting resources from reservoirs for hydropower production. The MINLP model expresses cost minimization over a 40 year time period on a monthly basis, subject to physical constraints. Costs include scarcity costs (the economic value of possible water deficits) and extraction costs from wells, minus hydropower production. The model has been written in GAMS and solved through the SBB (Simple Branch and Bound) solver.

Results show that the system is able to meet demand over the 40 year hydrologic scenario with negligible water deficits and that hydropower production may be enhanced compared to present by increasing releases from reservoirs, which ultimately implies accepting keeping reservoirs emptier than presently done.

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Key words: Hydropower production; Mathematical Programming; Optimization; Water Resources Systems management.

Introduction

Probably never as today has the quest for efficiency become imperative for water utilities: increasing operating costs and constraints on tariffs tend to make water service financially unsustainable. Hence, even marginal improvements in the financial budget of the utility are regarded as highly desirable by water managers.

Many water resources systems supplying municipal demand are endowed with hydropower plants exploiting significant head differences between the supply source and city tanks or treatment plants, where hydropower production takes place. Although the first step to increase production, and hence benefit from incremental gains, is to provide all possible sites with production capacities consistent with the expected flows, a second important step is to adjust operation of the whole system to the objective of increasing hydropower production, albeit with the constraints deriving from the need to meet municipal demand as much as hydrological variability permits.

Optimizing operation of a complex headworks system with multiple reservoirs and conjunctive use of surface and groundwater resources unavoidably requires some modelling. Mathematical programming provides well-established methods for developing models of water resources system operation (e.g. Loucks *et al.*, 1981, Loucks and Van Beek, 2005). These models express net benefit maximization while accounting for the physical structure of the system. For a number of well – known reasons, first of all the assumption of perfect foresight that is inherent to the mathematical programming approach to water resources system modelling in the presence of hydrological variability, mathematical programming is not the ultimate tool to define detailed operation rules for the system: simulation is necessary to refine rules and to make them realistically applicable to the system (e.g. Perera and Codner, 1996, Lund and Ferreira, 1996). However, optimization techniques, and mathematical programming among them, are essential to reveal undisclosed capabilities of the system and operation modes, which simulation alone would be incapable to provide.

In the paper, a Mixed Integer Non Linear Programming (MINLP) model of the water resources system supplying Genoa, in northern Italy, is presented. The system presently features five reservoirs, three main river intakes, and two well fields. The hydrological regime is to a good extent typically Mediterranean, with rainy winters and dry summers; water availability is however abundant, so that reservoirs are designed for seasonal storage and have little, if any, over-year carryover capacity. Drought issues are limited, especially now that water demand from the supply sources has decreased due to reduced population, deindustrialization, and to an improvement in the operation and maintenance of the water distribution network, with subsequent reduction of withdrawals from the sources. In this context, it is maybe worthwhile considering the possibility to relax an over-conservative management of resources, justified by the experience of previous drought events, and to explore the viability of exploiting resources from reservoirs for hydropower production.

In the following, the model is presented, input data are discussed and finally results are commented.

The model

Although the model has been developed specifically for the Genoa water resources system, it can be easily generalized to other similar systems. In the following, reference is made to a system featuring reservoirs, connected in series and in parallel, as well as river intakes and groundwater extraction, as depicted in Figure 1. It is a network flow model, following an ISO (implicit stochastic optimization) approach (e.g. Labadie, 2004), in that variability of the input (hydrologic variability) is not embedded explicitly in the model, as for instance in stochastic dynamic programming, but it is represented through a time series with a given time step (one month, in this application). The objective is to find the optimal allocation schedule at the different demand centres. The objective function, minimization of the expected value of annual variable costs E[C], is hence expressed as the sum of variable costs over the length of the time series. The objective function may be written as follows:

$$\text{Min } E[C] = 1/N_{years} * \sum_{i=1, Nyears} \sum_{j=1,12} [SC_{ij} + Extr_{ij} + Spill_{ij} - HP_{ij} - 100EF_{ij}] \qquad (1)$$

Where N_{years} is the number of years over which optimization is performed; in the spirit of stochastic optimization they represent a set of equally-likely water years (Guzman and Lund, 1999). SC_{ij} represents the scarcity cost, i.e. the cost of a water deficit, in month j of year i. Scarcity costs are directly related to the demand – price relationship for domestic water, as benefits associated to water consumption are measured by the area below it (Griffin 2006, Harou *et al*. 2009). Scarcity costs measure the benefit foregone for not consuming target water quantities and are hence associated to deficits (Jenkins et al, 2003), and as such they are a suitable way to measure the impact of water deficits and make them comparable to financial costs/revenues such as extraction costs and hydropower production. In this work, the scarcity cost – deficit relationship has been derived from a log-linear demand function estimated with a panel of 6 yr. data from 57 municipalities in the Genoa area (Moisello and Di Novi, 2012). The elasticity of water demand to price is -0.45, a value that is totally consistent with elasticity estimates found in other studies worldwide (Espey and Espey, 1997 Dalhuisen *et al*., 2003). In (1), $Extr_{ij}$ are costs for extracting groundwater, $spill_{ij}$ are total spills from reservoir and HP_{ij} is the revenue from selling hydropower produced in the j-th month of the i-th at the different plants of the system. Finally, EF_{ij} is the total release for environmental flow downstream reservoirs and large water intakes; the large multiplicative coefficient for environmental flows should ensure the fulfilment of environmental water demand in

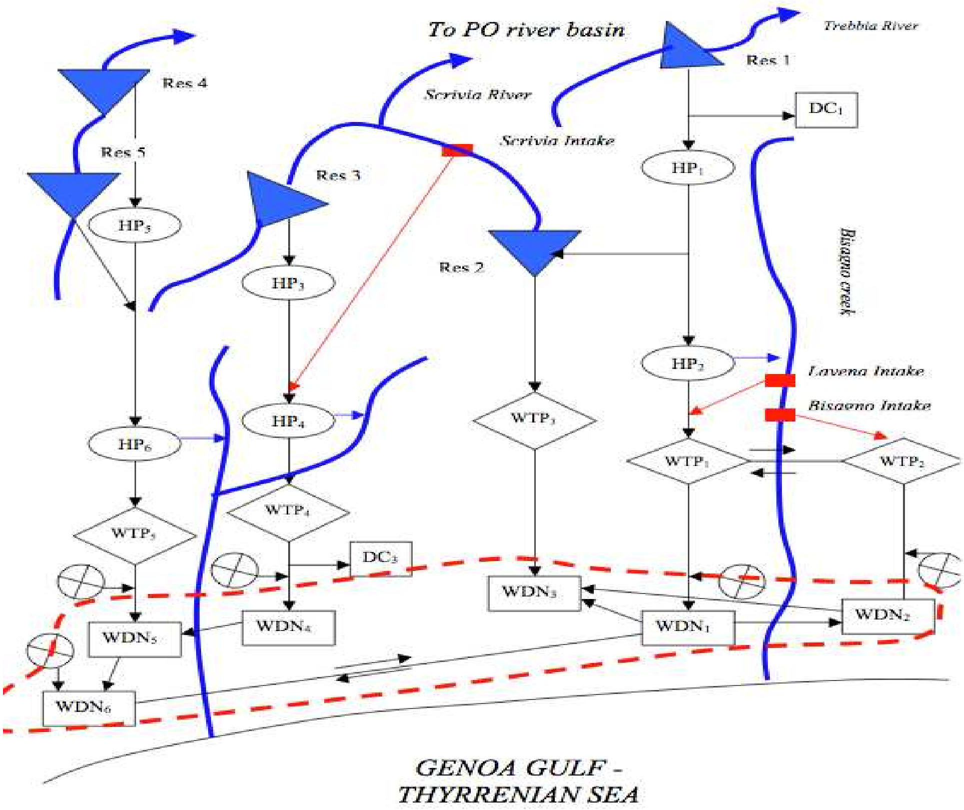

Figure 1 A schematic of the Genoa Water Resources System – HP stands for hydropower plant, WTP for water treatment plant, WDN for water distribution network, DC for demand centres along aqueducts, off Genoa city. The city of Genoa, encompassing several WDNs, is represented by the dashed red line. Red rectangles are water intakes, blue arrows spills from hydropower stations. Crossed circles represent wells.

almost all years. Computation of each term of (1) will be discussed in more detail in the subsequent subsection.

Minimization of (1) is constrained by a number of physical/technological limitations that will be reviewed in the following section.

Model constraints

Continuity constraints at nodes

As in any network flow model, physical connection between system's elements is represented through a network, where *nodes* (supply sources, demand centres, treatment plants, etc.) are connected through *arcs*. Now denote with q_{ijk} the flow (in

Mm^3/month) in the k-th arc of the system. For nodes with no capacity, continuity constraints at each node imply that at a given time step the sum of flows entering the node must equal the sum of flows exiting:

$$\sum_{k=1}^{Nin\_s} q_{ijk}^{(in)} = \sum_{k=1}^{Nout\_s} q_{ijk}^{(out)} \tag{2}$$

Where Nin_s and N_out_s denote the number of arcs entering and exiting node s.

In formulating the model, equations (2) have been aggregated along the four aqueducts stemming from each reservoir, thus obtaining a single equation expressing reservoir release to the system as a function of all flows exiting and entering the aqueduct.

Continuity constraints at reservoirs

To ensure continuity between subsequent time steps, mass balances of reservoirs must be included among the constraints for the r-th reservoir of the system:

$$S_{i,j+1}^{(r)} = S_{ij}^{(r)} + I_{ij}^{(r)} - Rel_{ij}^{(r)} - EF_{ij}^{(r)} - Ev_{ij}^{(r)} - Spill_{ij}^{(r)} \tag{3}$$

Where $S_{i,j+1}$ and S_{ij} are reservoir storage in month j+1 and j, I_{ij} is the inflow to the reservoir, including transfers from other sources and spills from upstream reservoirs, Rel_{ij} is the release from the reservoir, Ev_{ij} are evaporation losses and $Spill_{ij}$ are spills from the reservoir, occurring when the right-hand side of (3) could exceed reservoir's active capacity. To ensure that this actually occurs, and that spills are not used by the model as a free-standing variable to close balance (3), a condition like the following must be included in the model:

$$Spill_{ij}^{(r)} * (S_{ij}^{(r)} - K^{(r)}) = 0 \tag{4}$$

In (3), EFij are releases for environmental purposes. Although evaporation losses are not particularly relevant in the case of the Genoa system, they have been added to make the model more general, as they can be an important part of the water budget in some context. Their evaluation requires storage – area relationships for each reservoir. Average unit evaporation for each month is then multiplied for the area of the reservoir's surface to obtain the volume lost for evaporation in month j of year i. As area – storage relationships are not linear they have been piecewise linearized using the techniques described in Loucks and Van Beek (2005, chap. 4, pp. 129-132).

Capacity constraints of pipelines, reservoirs and plants

$$0 \le S_{i,j}^{r} \le K^{r} \qquad \forall i, j, r \tag{5}$$

Where K^r is the active capacity of the r-th reservoir

$$0 \le q_{i,j,k} \le Cap_k \quad \forall i, j, k \tag{6}$$

Where Cap_k is the transport capacity of the k-th arc.

$$0 \le q_{ijk} \le P_p \ \forall i, j \quad k \ entering \ or \ exiting \ a \ plant \tag{7}$$

The flow entering (or exiting) the p-th plant (hydropower, water treatment, pumping, etc.) must be less than plant's capacity P

$$0 \le q_{ijk} \le P_p \ \forall i, j \quad k \ entering \ or \ exiting \ a \ plant \tag{8}$$

Allocation to demands must be less or equal target values:

$$\Sigma_{k=1, N_D} \pm q_{ijk} <= T_D \tag{9}$$

Where N_D is the number of arcs entering and exiting demand center D, and T_D is target demand for demand center D (in Mm^3/month).

Assessing costs and revenues

Pumping costs

Pumping costs in month j of year i from wells are evaluated as follows:

$$Extr_{ij} = \sum_{l=1}^{Nwells} UC_l \cdot q_{ij}^l \tag{10}$$

Where N_{wells} is the number of wells in the system, UC_l (in €/m^3) is the average unit pumping cost for the l-th well and q_{ij}^l(in Mm^3/month) is the volume extracted from the l-th well in month j of year i. $Extr_{ij}$ is hence expressed in M€.

Hydropower revenues

Revenue from hydropower production has been evaluated in two different ways, depending on where the hydropower plant are placed: some of them (type 1) are placed directly below the dam, so that head is given by the water level in the reservoir; in others (type2), head is provided by difference in elevation between the hydropower plant and some surge tank upstream.

In the first case, revenue was hydropower production was assessed as follows:

$$HP_{ij}^1 = \sum_{l=1}^{Nplants^1} UP_j^l \cdot \eta_l \cdot \frac{9.81 \cdot f(S_{ij}^l) \cdot q_{ij}^l}{3600} \cdot \tag{11}$$

Where $Nplants_1$ is the number of plants of type 1, UP^l_j is the average unit price of energy (in €/kWh) in month j for power plant l, η_l is the efficiency of the l-th plant (set to 0.8 for all plants), $f(S_{ij})$ is water elevation in the reservoir, as a function of storage, q_{ij} is the flow in month j of year i entering the power station. Once again, water level in the reservoir is a nonlinear function of storage; hence the need to piecewise linearize the elevation-storage relationship. For hydropower stations of type 2 revenue is given by:

$$HP_{ij}^{(2)} = \sum_{l = 1, Nplants2} UP_j^{(l)} * CF^{(l)} * q_{ij}^{(l)} \qquad (12)$$

Where CF_l is a plant-specific production factor, in kWh/m^3, and HP is expressed in M€.

Scarcity costs

The scale of aggregation for scarcity costs assessment is the water distribution network, as in figure 1. The system presently supplying Genoa is actually the result of a merging process among three different companies, each managing, up to year 2006, a part of the supply sources and of the water distribution networks. Although considerable work has been done since 2006 to increase the rate of interconnection among the various distribution networks, so that they may be now considered completely interconnected, it was deemed useful to model connections among the various sub-networks; this clearly also adds generality to the model and makes managers more trustful towards model results as different part of the cities may not be supplied by all the aqueducts, but only through some of them.

As previously mentioned, the relationship between scarcity costs and deficits was developed from a Cobb-Douglas demand function with elasticity $\eta = - 0.45$. Deficit is here the difference between target and actual network’s consumption. To assess target consumption at sub-network’s scale, volumes supplied to the various sub-networks and supplied totals to the whole system were analysed to detect trends both in time and in space. Analysis of the supplied totals showed a significant negative trend in the last fifteen years with a clear break point in year 2006, when the companies merged; while the pre-2006 trend is due to depopulation, deindustrialization, two phenomena characteristic of the recent history of the Genoa area, as well as reduction of individual consumption thanks to renewal in households’ plants and devices, the merging has had the effect to allow reduction of the supplied volumes, while keeping consumption constant, through reorganization and improvement of service at the level of the distribution network. After 2006 supplied totals have kept oscillating around an average value. For modelling purposes, the supplied monthly volumes of year 2011 were selected as a reference value, as they are the highest of period 2006-2011. These monthly totals have then been disaggregated into the different sub-networks by analysing volumes supplied by the three companies prior to 2006, when supplied volumes to each network still reflected the actual water demand of certain areas of the city, as interconnection was limited or non-extant. As water deficits producing scarcity costs are related to the water consumed by customers, rather than that supplied, an average level of losses of 30% was considered, consistent with recent data. As a results, non-linear expressions linking scarcity costs to water deficits are available for each sub-network of the city. Such relationships have been also stepwise linearized and introduced in the objective function.

Model application and results

Genoa now counts around 600,000 inhabitants together with important, although declining in terms of water consumption, industrial activities. Total active storage capacity is 37.8 Mm^3, mainly concentrated in Brugneto reservoir (reservoir 1 in Figure 1) with a capacity of 24.5 Mm^3. The other four reservoirs (two of which in series) have similar capacities ranging from 4.6 to 3.0 Mm^3 each. Overall, the ratio between average yearly inflow and storage is around 2.0, indicating that reservoirs have no over-year carryover function, but they are rather designed to provide seasonal or sub-seasonal carryover capacity. This holds particularly true for the smaller reservoirs, although also Brugneto reservoir has an inflow/capacity ratio of 1.6. Besides reservoirs, the system is also supplied by water intakes from rivers and wells, the latter constituting the costliest resource. In the average, supply is presently made up of reservoir water by 58%, of water from river intakes by 29% with the rest (13%) being supplied by groundwater.

As was observed in the previous section, volumes supplied to the system have been decreasing owing to a number of factors, among which improvement of water distribution networks' management plays an important role, especially in the last years. In the model, the target yearly supply is set to 101.4 Mm^3, with an even pattern along the months according to historical records. Hydropower production takes place in a number of plants, six of which, adding to around 90% of the total energy produced in the system, were considered in the model. Yearly average production is around 50 GWh. The hydrological input consists of 40-yr. monthly series of inflows to reservoirs, reconstructed from both historical operation data (1970/71 – 2009/10) and simple regression rainfall-runoff models, and of streamflow series at the three main water intakes, which were reconstructed by regression rainfall-runoff models.

The model identifies the pattern of reservoir releases, river intakes and storage levels that minimizes equation (1). As previously mentioned, while model constraints are almost all linear, a number of functions necessary to compute (1) are non linear and need to be linearized; as linearization is performed using binary variables, this turns the model into a mixed integer model. However, non-linearities in the mixed integer model stem from eq. (11) and from (4) so that in its most general formulation the model is a MINLP (Mixed Integer Non Linear Programming). This specific problem contains 66,721 variables, of which 6,240 are integer (binary). It was written in GAMS (General Algebraic Modeling System) and solved through a SBB (Simple Branch and Bound) solver (GAMS, 2012).

Results

Model outcomes provide a lot of information on the pattern of optimal storage levels, releases from reservoirs, groundwater extraction and hydropower production. Although these results cannot be used directly to derive operation rules, given the “hydrologic omniscience” of the model, they certainly open to interesting managing scenarios and provide benchmark values for revenues from hydropower production and costs from groundwater extraction.

In the first place, the model confirms the existence of very limited drought issues for the system, given the current demand levels, with an average water deficit of 0.6 % on the yearly target supply and a maximum of 2.5% over the 40 yr. time sequence. Also environmental demand is met in almost all instances with an average yearly deficit of 0.7%. Secondly, the model states that average hydropower production can be increased, in the average, to around 68.0 GWh/year, as reported in greater detail in table 1.

Table 1 Average optimal and recorded (2006-2011) turbinated volumes, and energy produced at the hydropower plants considered in the model

Hydropower Station	Average Turbinated water volumes [Mm^3/year]		Average Hydropower production [GWh/year]	
	Optimal (40 yr.)	Recorded (2006-2011)	Optimal (40 yr.)	Recorded (2006-2011)
#1(Brugneto dam)	37.6	32.8	3.5	2.8
#2(Canate)	39.5	25.2	45.0	25.2
#3(Busalletta dam)	9.3	6.1	0.8	0.4
#4(Mignanego)	27.8	27.3	4.2	3.8
#5(Lavezze)	17.3	16.0	1.2	0.8
#6(Isoverde)	17.3	16.0	13.6	11.9
TOTAL	149.6	123.5	68.3	48.7

This is obtained by exploiting reservoirs more effectively, giving up a carry-over function for longer time spans that they are not designed to provide. Figure 2 reports the pattern of average monthly optimal reservoir levels (average over the 40 yr. time sequence) compared to the average monthly storage recorded during operation in years 2006 – 2011. Although comparison is not feasible under all respects, because of the different time windows employed, Figure 2 nonetheless shows that the model indisputably suggests keeping reservoirs emptier than presently preformed. This also has consequences on the amount of extracted groundwater, that drastically decreases to less than 6.0 Mm^3/year, as shown in table 2.

Table 2 Average optimal and recorded extraction (2006-2011) from system’s wells

Well	Average extracted volumes [Mm^3/year]		Well	Average extracted volumes [Mm^3/year]	
	Optimal (40 yr.)	Historical (2006-2011)		Optimal (40 yr.)	Recorded (2006-2011)
Gavette	0.66	1.15	Pietra	0.32	3.36
Giusti	0.90	4.39	Torbella	2.83	2.48
Trebisonda	0.40	0.94	Voltri	0.68	2.38
TOTAL	1.97	6.47	68.3	3.82	8.22

Assuming a unit revenue from hydropower production of 7 €cent/kWh (GME, 2012), the model indicates a potential increase of revenue of around (68.4 – 48.7)*0.07 = 1.38 M€/year. In eq. (10) unit extraction costs of groundwater range from 0.068 to 0.12 €/m^3 – the model hence indicates potential savings from less pumping of around 0.9 M€/year.

It will never be stressed enough that that the above efficiency increase estimates must be considered as ideal benchmark values; optimization, however, has played a fundamental role in pointing out how these improvements may be achieved. To obtain more realistic estimates of the efficiency gains, that can be substantially less than those indicated by the optimization model, information from optimization, first of all reservoir rule curves expressed by average optimal monthly levels, should be introduced in simulation software packages, such as AQUATOR (OSS, 2001) or AQUATOOL (Andreu *et al.*, 1996) to name but a few. Such software packages route the hydrologic input step by step, so that hydrologic omniscience is no longer an issue, although they still assume knowledge of the hydrologic input for the present time step, which is still not the case in the real world, but is certainly a lighter assumption than that of perfect foresight along the entire simulation period.

Conclusions

The paper has introduced an optimization model of the Genoa water resources system; such a model must be considered as the first step of a strategy ultimately leading to the development of a decision support system for the daily operation of the system. The objective function is minimization of the average yearly variable cost due to scarcity and groundwater extraction, net of hydropower production over a 40 yr. period with a monthly time step. Model outcomes confirm the little scope for reservoir hedging in a system with relatively abundant water resources, especially compared to present demand levels, and relatively small active capacities, and encourage adopting more daring policies oriented to increasing hydropower production and reducing groundwater extraction. The very promising figures of efficiency increases, in terms of enhanced revenues (≈ + 1.4 M€/year) and reduced costs (≈ - 0.9 M€/year), must however be carefully scrutinized through a simulation model which does not rely upon the assumption of perfect foresight of future hydrologic events, that is inherent to mathematical programming. Although net benefits deriving from a change in the operation policy of the system are likely to be considerably less than those predicted by the model, optimization has played the a fundamental role in pointing out how and where such changes should be performed.

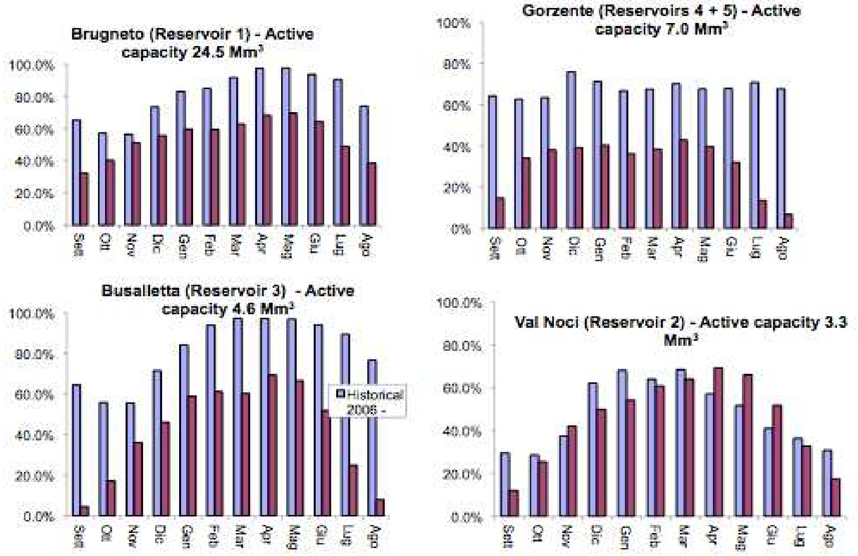

Figure 2 Monthly optimal storage levels (average over the 40 yr. period, in red) and monthly historical storage levels (average over period 2006-2011, in blue) for the five reservoirs of the Genoa Water Resources System (Res.4 and 5 are merged, as in the practice of the utility)

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