MULTIRESOLUTION MODELING OF HYDRO-THERMAL SYSTEMS

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Abstract: This paper discusses how modeling and solution techniques can be combined in relation to solving large hydro-thermal models. It is discussed how detailed production unit data from a specific geographical area can be converted for use in a less-detailed model covering a larger geographical region. A computational case is included where the technique is used on the Nordic countries (large area, low resolution) including Elkraft System area (small area, high resolution).

Keywords: hydro-thermal systems, multiresolution modeling, optimization, approximation.

1. INTRODUCTION

An important implication of liberalization of the power markets as seen in e.g. Northern Europe has been that international trade has increased. While it earlier often was sufficient for many purposes to consider the power system at a national level, now multi-regional, multi country analyses of trade and environmental policies are of greater interest. In pace with this, the need for methods for analyzing larger power systems has become urgent.

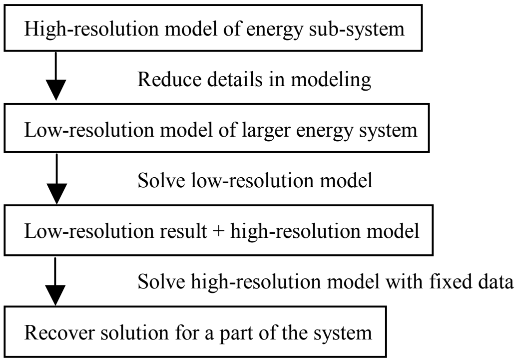
Still such systems are very large and can not always be modeled in as much detail as wanted or as traditionally used. The reasons are among others the lack of detailed data and the lack of computational methods. However, a reason may also be that limited insight in and feeling with the power systems of neighboring countries makes it impossible to validate and interpret the results of simulations at a very detailed level of representation. In Denmark, for instance the power system is primarily based on thermal fuels supplemented with renewable energy (in particular wind energy) while in the neighboring Nordic countries hydropower is much more important. Hence, Danish analysts may not be interested in a very detailed model for the other countries, but rather prefer a model that is in sufficient detail to permit analysis of only those international phenomena that influence the performance of the Danish system.

Modeling should therefore permit a differentiated representation according to the needs. In relation to the above example, it would be required to have many details in the representation of the Danish system, while less detail should be included in the Nordic model.

In [1] this goal was pursued by using a Lagrangean relaxation type method in relation to a detailed unit commitment problem of a limited area in order to derive appropriate price signals to be used in a hydro-thermal model covering the Nordic countries. Solution of the latter then provided transmission quantities, which were taken as input to the unit commitment problem, which then provided a detailed solution for the limited area.

Within other application areas approaches toward such problems have been developed. A common technique and methodology in optimization is aggregation and disaggregation [2]. However, as the approach in [1] indicates this is not the only way to handle the underlying problem described at the beginning this introduction. Therefore the terminology multiresolution modeling [3] has been adopted to emphasize that the issue is primarily one of modeling, and also to avoid any indication that the most detailed modeling is necessarily the best one.

The present paper discusses a method suited for analyzing a power system in a geographically small area in much detail related to time and technology. The area is part of a larger area with which it interacts through transmission. The idea is to split the problem into two – a detailed thermal part and a more aggregated hydro-thermal system. The multiresolution method presented in this paper can be outlined as:



In the next section a mathematical model of the problem will be formulated followed in Section 3 by a discussion on how to convert elements in the high-resolution representation of the energy system into the lower resolution needed for the multi-regional model. Section 4 is a short introduction to the Balmorel and SEVS models, which are used in the case in Section 5. This case covers the system in the Nordic countries at a low-resolution level with a detailed solution for the Elkraft System area. Finally in Section 6 some conclusive remarks are made.

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2. MATHEMATICAL MODEL

A hydro-thermal energy system with multiple regions can be modeled as:

$$\min \sum_r \sum_s \sum_h \sum_u c(r,u,p_E(r,s,h,u) + p_H(r,s,h,u)) \qquad (1)$$

$$\forall r,s,h \qquad \sum_u p_E(r,s,h,u) = d_E(r,s,h) + \sum_{r' \neq r} x(r,r',s,h) \qquad (2)$$

$$\forall r,s,h \qquad \sum_u p_H(r,s,h,u) = d_H(r,s,h) \qquad (3)$$

$$\forall r,r',s,h \qquad \underline{x}_{r',r} \le x(r,r',s,h) \le \bar{x}_{r',r} \qquad r \neq r' \qquad (4)$$

other thermal constraints (5)

$$\forall r,s,u' \qquad R(u',s+1) = R(u',s) + I_{u',s} - \sum_{u'} p_E(r,s,h,u') \qquad (6)$$

other hydro constraints (7)

The symbols used have the following meaning:

r	region index
s	season index
h	hour index
u	production unit index – all units
u'	production unit index – hydropower only (i.e. $u' \subseteq u$)
$c(r,u,p(...))$	production cost, region r, unit u, production level p
$p_E(r,s,h,u)$	electricity production level, region r, season s, hour h, unit u
$p_H(r,s,h,u)$	heat production level, region r, season s, hour h, unit u
$x(r,r',s,h)$	Transmission between regions r' and r
$\underline{x}_{r,r'}$	Minimum transmission level
$\bar{x}_{r,r'}$	Maximum transmission level
$d_E(r,s,h)$	Electricity demand, region r, season s, hour h
$d_H(r,s,h)$	Heat demand, region r, season s, hour h
$R(u',s)$	Reservoir level of hydropower unit u' at start of season s
$I(u',s)$	Inflow to reservoir of hydropower unit u' at season s

The model above has a representation of time consisting of hours, to indicate the shorter time intervals e.g. hours of the day, and seasons to represent the variations over the year. The former is in particular important in the thermal subsystem, and the latter in relation to hydro systems with capacities big enough to save water throughout a year. In a simple version, at year could be modeled as two seasons (summer and winter) each with two representative hour types (day and night). That level of detail might be sufficient for some analyses, but a more detailed level, e.g. 52 seasons (all weeks) each of 168 hours (all hours of the week) might be appropriate for other analyses. See [4] for one such analysis.

The production costs in (1) are individually specified for the units, even if they are technically identical due to regional variations in fuel prices (e.g. of biomass, natural gas, etc.). In addition to fuel costs, operation and maintenance costs are included. In particular this includes startup costs, although this is not explicitly specified in the model above. Production of electricity and heat in each region should equal the demand, cf. (2) and (3). Transmission of electricity between regions is possible within the limits given by (4). The thermal constraints mentioned in (5) can include capacity limits, ratio between electricity and heat on CHP units, ramping rates, spinning reserve constraints, etc. [5], [6].

Restriction (6) is the hydro energy constraint that models the variation of the water inflow over the year. Other hydro constraints, which could be included in (7) could be maximum and minimum reservoir levels depending on the seasons, minimum water flow requirements, etc.

As is easily imagined, the model (1) - (7) may be large if a large geographical area is covered (many regions) and if the time is represented in a detailed way (many seasons and many hours). An additional problem related to a large-scale version of the model (1) – (7) is that it may be difficult to get reasonably accurate data. Therefore it may be relevant to consider an aggregate or otherwise simplified version of model (1) – (7), this will be considered next.

3. APPROXIMATION OF DATA

A basic element in the modeling of thermal systems is the unit commitment, [5], [6]. In a unit commitment startup costs are included as well as integer constraints in relation to the modeling of minimum (positive) production levels, minimum up and downtime, and other aspects. The practical implication of this is that the time required to solve such optimization problems to true optimality grows exponentially with the problem size. Therefore often heuristics are used to speed up solution time towards a near optimal solution.

Relaxing the integer constraints (i.e., disregarding the units commitment aspect of the problems) speeds up the solution time considerable.

In this paper one step further is taken. The low-resolution model as described in the next section is a linear programming (LP) model. Such a model is faster to solve than non-convex and/or non-linear models and that makes it possible to model very large systems within the limits of LP. Since it often will be impossible to obtain data for larger regions with a precision that justifies use of non-linear programming, this approximation is often acceptable. The rest of the section presents how the restrictions and the objective function can be modeled as a convex LP problem and more specifically how it is done in the low-resolution model.

The principles in the transformation that will be presented here is that a linear model should be obtained. There are two main reasons for this. One is that for linear programming (LP) optimization problems there exist software that permits fast and reliable solution. Another is that in many cases there does not exist data that permit a nonlinear modeling. The emphasis in the presentation here will be on the transformation of the constraints on the thermal production units, represented in (5), where in particular combined heat and power (CHP) units will be considered.

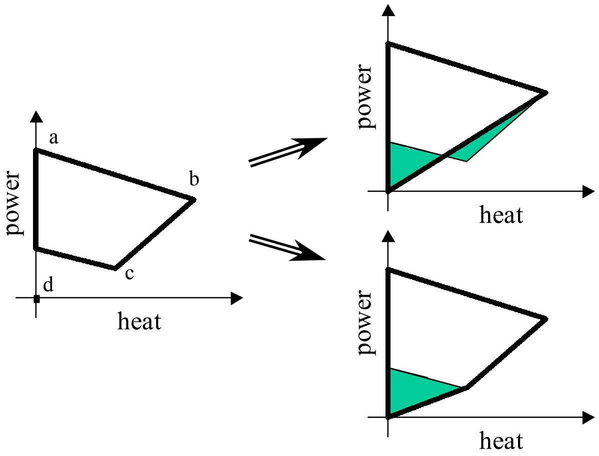

Fig. 1. Different ways of modeling the possible production of heat and power of a thermal CHP plant.

On Fig. 1 the left graph shows the production area (viz. the feasible combinations of production of heat and electricity) of an extraction type CHP plant, while the two graphs to the right show two ways of modeling this in an LP model. The production area is the point d and the area within the thick lines. The shaded areas show the modeling error done in each case. In the upper right graph the production area has been transformed into a triangle. The lower right graph includes one restriction more, but makes sure that all of the original production area is included in the resulting model. This latter representation is the so-called convex hull i.e. the representation is the smallest convex set that contains all the original production area.

Whether one approximation is better than the other depends on the role of the unit in the energy system. Base load units will normally produce at near full electricity load given the heat load that may vary considerable during the year. In this case the modeling error between the points a and b should be minimal. Regulating units, which main purpose is to make (2) and (3) hold, may on the other hand need a better representation at lower loads, e.g. around point c.

Fig. 2 shows how the fuel usage varies for different loads of a typical condensing thermal power plant. The representation of this curve in a linear model poses two difficulties. One is that the curve is nonlinear. This may be overcome by using a piecewise representation is in Fig. 3. However, this does not solve the other difficulty, which is that the rate of fuel usage (and the proportional marginal production cost) should be non-decreasing. Therefore, only one value could be used, corresponding to e.g. point c in Fig. 2. However, using point c for peak load units, which seldom produces at full load, gives an optimistic view of the use of such units. A better representation is indicated in Fig. 4. Here, the approximation is quite good for points between b and c, but optimistic for points between a and b.

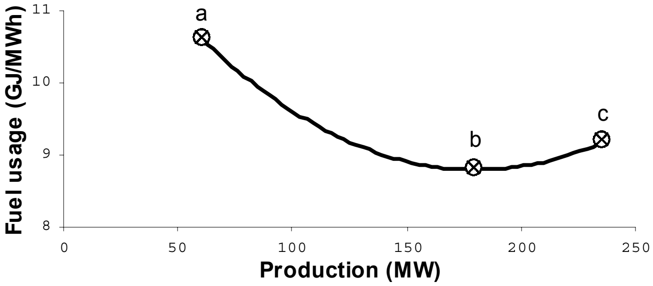

Fig. 2. The fuel usage as a function of the power output of a thermal power plant.

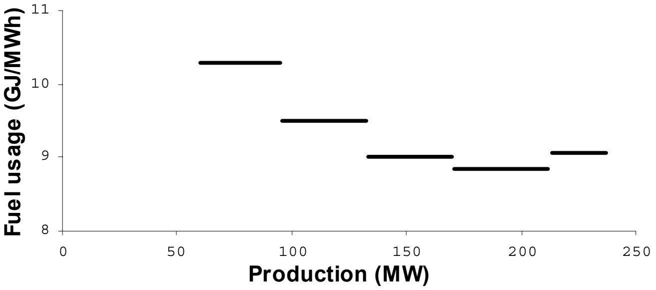

Fig. 3. Piecewise linear representation of the unit from Fig. 3.

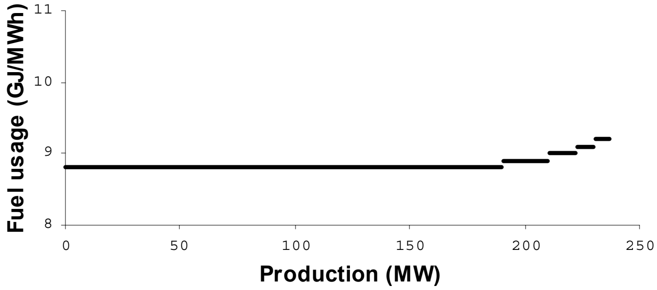

Fig. 4. Piecewise linear representation of the unit from Fig. 3. Here with increasing fuel usage.

As concerns the start costs for thermal units, these must be neglected, as they are impossible to represent in a satisfactory way in a linear model. However, some other elements found in unit commitment and economic dispatch modeling [5], [6], e.g. ramping constraints, are linear in their nature or may be given a linear representation in a satisfactory way and can therefore be included in the aggregate model.

4. THE MODELS

The multi-resolution modeling technique presented in this paper is based on two models used by Elkraft System. A thermal unit commitment model SEVS and a slightly modified version of the Balmorel model [7]. They will be briefly described below.

SEVS has been developed for analyzing the heat and power production system in the scale of one month or one year, using a time resolution of one hour. SEVS is an optimization model minimizing the overall production given technical constraints. Optimization is based on Lagrangean relaxation that determines the unit commitment. The economic dispatch is then made, using the committed combined heat and power plants (CHP). The model includes transmission constraints to neighboring countries, wind power, stochastic forced outages, emission constraints and other features relevant for daily operation and it has been in continuous operation for several years.

The low-resolution model covering a geographical larger area and—if wanted—a longer time span was developed from the Balmorel model. However the modified model has a more detailed modeling of hydropower but excludes the investment decisions otherwise found by the Balmorel model. The model is multi-regional with transmission constraints between each region. Within each region the district heating production is modeled due to the large proportion of combined heat and power production in Denmark and the neighboring countries. The model is solved for one year with the year subdivided into seasons and each season divided into different hour types composing a diurnal profile. The number of seasons and hour types can be chosen freely but influences of course the computation time.

5. CASE – THE NORDIC COUNTRIES

This section will present a case where the multi-resolution technique has been applied to system consisting of four Nordic countries, viz. Denmark, Finland, Norway, and Sweden. The region is interesting as test case because of its mixture of production technologies (hydropower, nuclear power, thermal condensing, and CHP), cf. Table 1. Also as per October 2000 the power pool Nord Pool covers the whole region with the national electricity markets liberalized or under liberalization.

Table 1. Production capacities in MW by different technologies in the Nordic countries and the Elkraft System area, which covers Eastern Denmark [8].

	Elkraft System Area	Nordic Region
Nuclear power	0	12092
Thermal cond.	1153	9471
Thermal CHP	3120	15979
Hydropower	0	46756
Windpower	386	2033

This case presented may be briefly described as follows. First SEVS unit data for 1999 was converted for use in the Balmorel model as described in Section 3. For the three other countries in the model, other data sources, giving the appropriate level of detail, were used. Then the Balmorel model was solved for the Nordic countries with some countries being divided into several regions to reflect bottlenecks in the national transmission network. Thus a total of 11 regions were used in the model. The year was divided into 6 bimonthly seasons for which the inflow to the hydro reservoirs was specified for each country. Each season was further subdivided into 12 hour types giving diurnal load profiles as shown in Fig. 5 and 6.

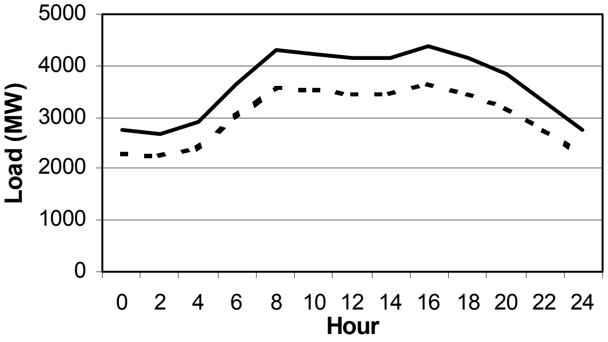

Fig. 5. Danish power load profile for the January/February season (upper) and the July/August season (lower).

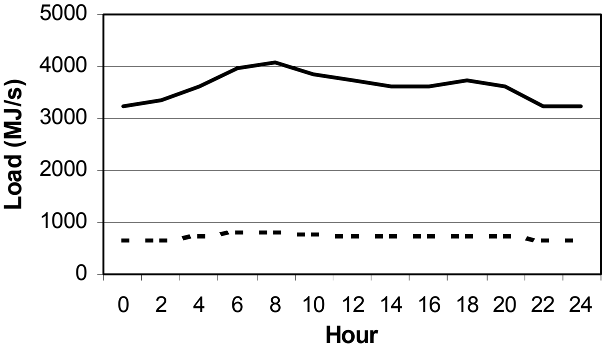

Fig. 6. Danish heat load profile for the January/February season (upper) and the July/August season (lower).

Fig. 7 shows some of the results of the Balmorel simulation. It can be seen that the model predicted a greater Finnish import while Sweden exports more, mainly due to a greater production on fossil fueled units. With respect to the fuels used for power production the figure indicates the model gives a reasonable result. A further subdivision of fuels and units, and as seen below, of the net import may show a greater difference between the model results and historical records.

While the net import/export of the counties in Fig. 7 looks close to what has been historically observed, the figures for transmission between countries, as seen in Tables 2 and 3, are less consistent. A reason for this can be an inadequate modeling of the transmission system (costs and constrains) and the use of market power by dominant producers on the market, which is not reflected in the model.

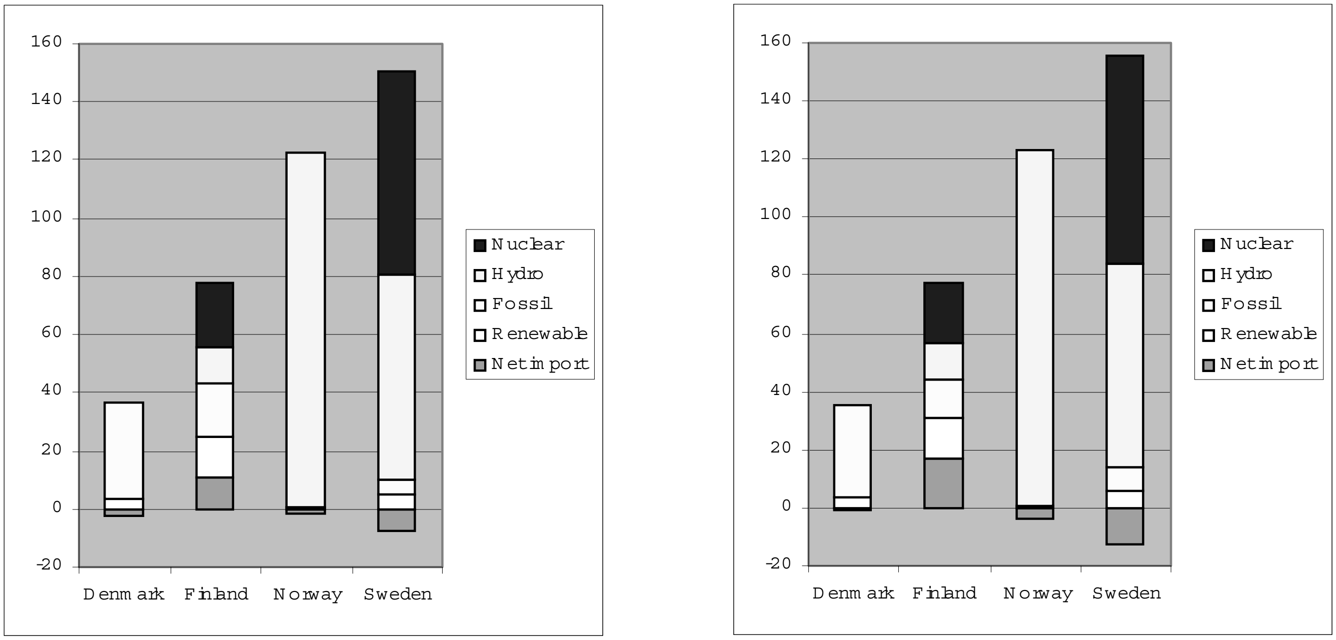

Fig. 7. Left graph shows the actual division of power production in TWh between fuels and countries [8] while the right graph shows the model result.

Table 2. Export in GWh from row country to column country as predicted by model using 1999 data

	Denmark	Finland	Norway	Sweden
Denmark	0	0	0	3225
Finland	0	0	0	0
Norway	1195	613	0	2410
Sweden	5728	10879	559	0

Table 3. Export in GWh from row country to column country in 1999 [8]

	Denmark	Finland	Norway	Sweden
Denmark	0	0	622	1614
Finland	0	0	104	825
Norway	2759	107	0	5904
Sweden	2046	6737	5929	0

The model was solved using the CPLEX 6.5.2 solver and required less than 20 seconds to be solved on a Pentium III (500 MHz) computer. As it can be seen LP models can be solved very fast. Increasing the level of detail by adding new regions and more seasons and hours compared with the model run above can be done without getting an unacceptable high computation time.

The results from the Balmorel model is now used as exogenous parameters for SEVS. Two simulations with SEVS were performed. One where SEVS found the transmission given the prices in the neighboring regions as calculated by Balmorel and one where the transmission with other regions was fixed to the values given by the Balmorel model.

Table 5 shows how much electricity that was produced on different technologies. Balmorel is the results from the low-resolution model run above, while SEVS 1 is a SEVS run with the export price to southern Sweden set to 14.9 EUR/MWh, a value found by the Balmorel model. SEVS 2 on the other hand had a fixed export to Sweden of the same amount as found in the Balmorel results. (Observe that Elkraft System area in the model is connected only to Sweden.)

Table 5. Electricity production in the Elkraft area by different technologies

	Balmorel	SEVS 1	SEVS 2
Condensing	4929	6660	5366
CHP-central	9711	10268	9436
CHP-decentral	2895	2732	2732
Wind	736	737	737
Net. export	3871	5997	3871

It can be observed that the general division of the production seems to follow the same pattern for the three model runs above. The main observation when comparing the Balmorel results with those of SEVS runs is that with the export price calculated in Balmorel is used as input parameter to the SEVS simulation (SEVS 1) then SEVS overestimates the transmission to Sweden. The major explanation for the discrepancy is that it is a general observation that price signals are less accurate for such coordination than quantity signals.

In relation to the fuels used for electricity production, cf. Table 6, it can be seen that oil—generally used in peak load units—are only used in the SEVS 2 model run.

Table 6. Electricity production by different fuels in the Elkraft area.

	Balmorel	SEVS 1	SEVS 2
Coal	9866	10896	9073
Natural gas	2223	2720	2733
Orimulsion	4568	5148	4197
Oil	0	2	637
Waste	391	411	411
Straw	487	483	483
Wind	736	737	737

The profile used for transmission to Sweden made export take place at peak hours. Though this sometimes is the case, more often it is not. The oil fueled peak load units were therefore needed much more in the SEVS 2 than in the SEVS 1 scenario. This emphasis the need to be quite careful when modeling the variation over the day, viz., the load pattern and in particular the export quantities, or prices, patterns, respectively.

Making a simulation in SEVS for one year takes approximately 30 seconds, which is fast given the level of detail in this model. The use of certain heuristics to obtain close to optimal solutions, makes this possible.

Comparing the solution times for the two models it is seen that they are approximately equal. This indicates a proper balance between the level of detail and complication of the two models.

6. CONCLUSIONS

A multiresolution modeling technique has been introduced for analyses on hydro-thermal systems. Methods for converting detailed information from the high-resolution model for use in the low-resolution model has been presented. The method has been applied to the Nordic system, for which a linear programming model was used. The high-resolution subsystem was modeled as a mixed integer unit commitment problem.

Comparisons of the results show that in many respects the results are similar. Obviously details differ, however, major trends are reasonably close. In particular we have noted that care must be taken in handling the time profiles in relation to price and/or quantities.

As also shown it is important how which results from the low-resolution model are taken to be used as input to the high-resolution model. In particular, the input reflecting the transmission conditions can consist of price signals or quantity signal. As demonstrated, the quantity signal provides better correspondence, as also expected.

It should be emphasized that the case is not only one of reduction of computational time. For many real cases there is an independent point in aiming at a model that is not to complex. This may be because data is not available, or it may be because there is insufficient experience in interpreting the results of a detailed model.

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8. BIOGRAPHIES

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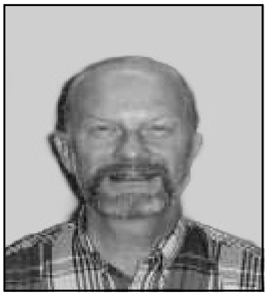

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