A DYNAMIC MODEL OF THE HUNGARIAN FORESTS

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FOREWORD

The objective of the Forest Sector Project at IIASA is to study long-term development alternatives for the forest sector on a global basis. The emphasis in the Project is on issues of major relevance to industrial and governmental policy makers in different regions of the world who are responsible for forestry policy, forest industrial strategy, and related trade policies.

The research program of the Project includes an aggregated analysis of long-term development of international trade in wood products, and thereby analysis of the development of wood resources, forest industrial production and demand in different world regions. The other main research activity is a detailed analysis of the forest sector in individual countries. Research on these mutually supporting topics is carried out simultaneously in collaboration between IIASA and the collaborating institutions of the Project.

This article represents a case study carried out by the Hungarian collaborating team of scientists. The issue studied in this work is the dynamics of the forest resources in Hungary.

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ABSTRACT

This paper details the submodel that describes the development of growing stock in the Hungarian Forest Sector Model — a case study of IIASA's Forest Sector Project. The model was originally elaborated for the Hungarian Biomass Study and concentrates on the relationships between the extension of the forest area, harvesting policies and the development of forests.

ACKNOWLEDGMENT

Special tribute is paid here to Wolf Dieter Grossmann of IIASA for his methodological help in constructing the model. The extent of this help is illustrated by the fact that it was not until Wolf's visit to Budapest in 1982 that the authors first encountered the systems dynamics technique. Modeling work was carried out by the authors with a heavy reliance on the advice and data provided by Aladár Halász and József Gémesi. The model has been implemented in DYSMAP on the IIASA VAX computer, using the X25 link from Budapest.

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1. INTRODUCTION

In 1981, a research program coordinated by the Hungarian Academy of Sciences under the title "Long-term Perspectives in Utilization of Materials of Biological Origin," or Biomass Study for short, was started. The project constituted the natural progression from a former study, "Survey of the Agro-ecological Potential of Hungary" and is now nearing completion. The Biomass Study looked at the problem of how, taking into account natural limits (known from the Agro-ecological Survey), should production and utilization of the biomass be structured in order to achieve different strategic targets. In other words, the dynamics of the biomass production–transformation–utilization system were the focus of the investigation, with special attention given to the interactions between human activities and natural conditions. The notion of biomass comprised, in this study, materials of biological origin; that is, the whole phytomass — including the forests — as well as domestic animals, their by-products, both useful and otherwise, and the wastes of animal husbandry and human settlements. An up-to-date account of the total biomass stock and production in the country has been compiled by the Hungarian Central Statistics Office, within the framework of this study. For more information on the Biomass Study, see Láng *et al.* (1984).

The aim of this paper is to describe a model used in the Biomass Study to predict the development of Hungarian forest resources. According to plans of the Hungarian collaborating group with IIASA's Forest Sector Project, the model will play the same role in the Hungarian Forest Sector Model. Therefore, it can be regarded as a tool for obtaining answers to the questions raised by Bencze *et al.* (1984). Another aspect of the Hungarian Forest Sector Model has been studied by T. Bencze; for an account see Bencze (1984).

2. PLANTING AND HARVESTING POLICIES IN HUNGARY

During the past 35 years the forest area in Hungary has increased considerably. Forests now occupy about 1,690 thousand hectares, or 18% of the territory of the country in contrast to 12% in 1945; growing stock has doubled during the same period, achieving 250 million m^3. Despite the dynamic increase in domestic wood consumption, 60% of the needs are now met by domestic sources.

A significant amount of broadleaved timber is exported by harvesting, at present about 90% of the annual growth. Exceptionally large resources have been devoted to the extension of pine forests, which are now being planted in the plains — a break with earlier practice. Owing to ecological conditions, the proportion of pine forest is still very low, and therefore about 90% of domestic needs must be met by imports.

Dynamic planting policies have led to a shift in the direction of younger forests. The corresponding harvesting policies were aimed at moderating this, by building up reserves and harvesting from different age groups according to specified proportions. In recent years, however, the area of new plantations has substantially decreased. According to previous proposals (as formulated, for example, in the final report of the Agro-ecological Survey), in the period between 1980 and 2000 the forest area was to be increased by some 280 thousand hectares. However, if we use the trend of the current five-year plan, only about 130 thousand hectares will be added. Therefore, the forest area will not expand by the 20% considered desirable by 2000, but it probably will some decades later — depending on future planting policies. (The "desirable" forest area is that area not used for other activities.) In the long run, the aim of afforestation and harvesting policies is to develop a species structure that corresponds to the ecological conditions and that has an evenly distributed age range over the desirable area. This would mean reaching and maintaining a high level of equilibrium. These are the main features that we intend to model in providing a tool for checking the different long-term afforestation and harvesting policies.

Owing to the nature of the forest sector, non-linear relationships and effects that spread over extended periods are of considerable importance. Examples are the relations between harvesting and growth of forests on the one hand, or rotation periods, ranging from 25 to 130 years, determining the effects of planting policies, on the other. As a consequence the systems dynamics approach seemed most appropriate here. Therefore our simulation uses actual values from 1980 as initial conditions, and incorporates various policies, principles, and natural relationships to compute the state for the next year. The time horizon is 100 years. The model represents forest areas according to seven categories (see the formal model description, p.6).

In addition to the above, forests are divided into four age groups, depending on the species. The first is the period when thinning is predominant, and the other three are characterized by the final harvest. In describing the harvesting policies we refer to the annual growth of the growing stock in the age group, meaning the effect of biological growth and that of updating the age groups as time passes.

Present harvesting policies are formulated in terms of the age groups. Harvest in the first age group, or thinning, is proportional to the standing volume of the group. Final harvest is 90% of the annual growth of the three upper age groups in the case of broadleaved forests; in pine of the hilly regions the figure is the same. The age distribution of lowland pine forests is very uneven, and therefore final harvest is determined for each age group separately, amounting to 50% of the net annual growth.

This harvesting policy cannot be maintained for a very long period, since the oldest age group would become too large. This is partly due to the sharp decrease in the planned extension of the forest area, as well as to the harvesting policy itself. Therefore, at given intervals, the increase in growing stock must be halted, and when an acceptable age structure is achieved one has to change to harvesting the annual growth by individual age groups. In this case, for soft, broadleaved and fast-growing, hard, broadleaved forests 100% of the annual growth is harvested from the fourth age group, and the increase in standing volume is supplied from the second and third age groups. For those forests with short rotation, the age structure present in 1980 is already acceptable. In the slow-growing, hard, broadleaved forests, the increase in growing stock and the modification of age structure will be halted in 1995. The harvesting of pine forests in the hilly regions remains unaltered, while in the lowlands the increase in growing stock will be stopped in 2040.

The above outlines two harvesting policies that provide for one of the principles in Hungarian forest management: growing stock must not decrease. The same principle prevails relative to the forest area, and so when a particular area is removed from forest cultivation during the final harvest, an equal amount of land has to be afforested in exchange. In addition, a national afforestation program plans that the total forest area will increase. The model uses four scenarios to assess the effects of different, feasible afforestation policies. The proportion of species in the afforested area is supposed to be constant, equal to that given in long-term projections for the Hungarian forest sector.

The growth of forests is modeled in detail, and depends on the species, age, density of the forest, and the pollution level. This work was first done by W.D. Grossmann (1982), and more details of the mechanism are given in the formal description of the model.

To construct the model, the following requirements were established:

- very detailed data for the year 1980 should be used (standing volume and area for every age group and species; thinning; total harvest of the final three age groups for every species).
- the projections for the forest sector up to the year 2000 should be accepted as consistent; i.e., supposing the originally planned afforestation program is implemented and the original harvesting policies are in force, then growing stock will reach 300 million m^3 and total harvest 10 million as specified there (see Appendix).

Thus, the model now combines the four afforestation scenarios with the two harvesting policies.

3. FORMAL MODEL DESCRIPTION

The Hungarian Forest Dynamic Model is a systems dynamics model, with the program written in DYSMAP (Ratnatunga 1980). As is well-known (see, e.g., Forrester 1961) systems dynamics is a widely used simulation technique based on solution by successive integration of the first order difference equations:

$$\boldsymbol{x}_{t+\mathrm{d}t} = \boldsymbol{x}_t + \mathrm{d}t f(\boldsymbol{x}_t, t)$$

$$\boldsymbol{x}_{t_0} = \boldsymbol{x}_0$$

Here the vector $\boldsymbol{x}_t$ represents the state of the system, the (non-linear) function f describes the rules and relations in the system, and the vector $\boldsymbol{x}_0$ is the vector specifying the state of the system in the initial period.

The model consists of three main blocks, which describe the development of growing stock, forest area, and harvest. Forests are divided into subsectors according to species and age groups. The division according to species is as follows:

(1) Soft, broadleaved forests (poplar and other soft broadleaved)

(2) Fast-growing, hard, broadleaved forests (black locust)

(3) Slow-growing, hard, broadleaved forests (oak, beech, hornbeam, and other hard broadleaves)

(4) Pines in hilly regions

(5) Pines on lowlands (the counties Pest, Bács-Kiskun, Csongrád, Békés, Szolnok, Hajdú-Bihar, Szabolcs, and the area of Budapest)

(6) Other forested areas

(7) Bare land.

As the list shows, the geography of the country is treated as one unit, except for pine forests. The division of pines into two classes is due to substantially differing ecological conditions and age compositions. Other areas and bare land are given as constants, and are represented only to account for the total area. To allow the formulation of harvesting policies, each species is represented in four age groups, one where thinning is predominant, and the subsequent three where final harvest is predominant. In the notation, the subscript X (= S,F,H,P,B) refers to groups of species (see Appendix, Table A.7) and the subscript i ($i=1,2,3,4$) to age groups. In addition, we also use the subscripts j (= $i+1$) and k (= $i-1$), and the symbol t_0 for 1980.

3.1 Growing Stock

$$V_{X,i,t+\mathrm{d}t} = V_{X,i,t} + \mathrm{d}t(B_{X,i,t} - N_{X,i,t} - P_{X,i,t}$$

$$+ Y_{X,k,t} - O_{X,j,t} - H_{X,i,t}) \tag{1.1}$$

$$V_{X,i,t_0} = V_{0,X,i} \tag{1.2}$$

Here $V_{X,i,t}$ is the volume of growing stock in the i-th age group of the X–th species. Equation (1.1) states that growing stock increases by biological growth ($B_{X,i,t}$) and transfer from the lower age group ($Y_{X,k,t}$), and decreases by natural decay ($N_{X,i,t}$), by decay due to pollution ($P_{X,i,t}$), by transfer to the next age group ($O_{X,j,t}$), and by harvest ($H_{X,i,t}$).

Biological Growth

Biological growth is a highly non-linear quantity, described by equations (1.3)–(1.7).

$$B_{X,i,t} = F_{X,i,t} M_{X,i,t} R_X \tag{1.3}$$

$$F_{X,i,t+\mathrm{d}t} = F_{X,i,t} + \frac{\mathrm{d}t}{A_t}\left[G_{X,i,t} U_X - F_{X,i,t}\right] \tag{1.4}$$

$$F_{X,i,t_0} = F_{0,X,i} \tag{1.5}$$

$$M_{X,i,t} = Q_X C_{X,i,t} \tag{1.6}$$

$$C_{X,i,t} = V_{X,i,t} / G_{X,i,t} U_X \tag{1.7}$$

The variable $F_{X,i,t}$ represents the potential volume of growing stock, set equal to the actual volume in the initial period (1980), and (depending on the delay parameter or adaptation time, A_t) manipulated to give the highest volume possible for a given species. The growth of $F_{X,i,t}$ is proportional to the difference between it and the maximum possible volume, which is the product of the area of the actual (1980) age and species' group ($G_{X,i,t}$) and the maximum possible growing stock per unit area (U_X). Biological growth is then obtained from the potential growing stock by the forest growth multiplier ($M_{X,i,t}$).

The growth multiplier is a non-linear function of the crowding ratio of a given class ($C_{X,i,t}$), derived from functions that describe the annual growth of the individual species (see Appendix Table A.6). The crowding ratio is defined as the ratio between the actual and maximum possible growing stock. B_X is the mean rotation in a given group of species. The hypothesis behind the formulae is that for ideal growth, a 100% crowding ratio is reached at an age which equals the mean rotation time.

Forest Decay

A proportion of the growing stock decays every year, which is represented as a sum of two components. The first is natural decay $N_{X,i,t}$ and the second is decay caused by pollution $P_{X,i,t}$. Decay is proportional to the growing stock and here is assumed to be 1% for natural and 0.25% for pollution-generated decay. Pines are twice as sensitive as the broadleaved species. Equations (1.8) and (1.9) describe this process

$$N_{X,i,t} = V_{X,i,t} n_{X,i} \tag{1.8}$$

$$P_{X,i,t} = V_{X,i,t} p_{X,i} \tag{1.9}$$

Aging

Standing stock in new plantations (i.e., in areas where compensation or additional afforestation occurs, is taken to be zero, and so does not enter our equations. Of course, there is no growing stock transferred from the fourth age group. For the rest of the age groups the transfer of growing stock is described by equations (1.10) and (1.11).

$$O_{X,j,t} = T_{X,i\to j,t} D_{X,i+j,t} \tag{1.10}$$

$$D_{X,i+j,t} = \left[L_{X,i} \frac{V_{X,i,t}}{G_{X,i,t}} + L_{X,j} \frac{V_{X,j,t}}{G_{X,j,t}} \right] / \left[L_{X,i} + L_{X,j} \right] \tag{1.11}$$

$T_{X,i\to j,t}$ is the area transferred from the i-th to the j-th age group. $D_{X,i+j,t}$ is the average of the actual forest densities in the two groups weighted by the time period of the groups involved ($L_{X,i}$ and $L_{X,j}$).

3.2 Harvesting

As has already been mentioned, age groups were aggregated according to current harvesting policies. The first age group, therefore, is that of thinning, so the harvest in this group is proportional to the growing stock, equation (2.1).

$$H_{X,i,t} = V_{X,i,t} E_X \tag{2.1}$$

Final harvest according to current harvesting policies is given by equations (2.2)–(2.6).

$$H_{X,i,t} = S_{X,t} W_{X,i} \tag{2.2}$$

$$S_{X,t} = 0.9 (Z_{X,2,t} + Z_{X,3,t} + Z_{X,4,t}) \tag{2.3}$$

$$Z_{X,2,t} = B_{X,2,t} - N_{X,2,t} - P_{X,2,t} + Y_{X,1,t} - O_{X,3,t} \tag{2.4}$$

$$Z_{X,3,t} = B_{X,3,t} - N_{X,3,t} - P_{X,3,t} + Y_{X,2,t} - O_{X,4,t} \tag{2.5}$$

$$Z_{X,4,t} = B_{X,4,t} - N_{X,4,t} - P_{X,4,t} + Y_{X,3,t} \tag{2.6}$$

The equations (2.4)–(2.6) define the change in growing stock, while (2.3) gives the total volume to be harvested from the final three age groups of a given species, equal to 90% of the annual growth of broadleaved forests and of pines in the hilly regions. The role of the parameter $W_{X,i}$ is to control the age composition of the growing stock.

The plantation of pines in lowlands started some 35 years ago. As a consequence of this and the different ecological conditions, the age composition is very uneven. Therefore, the harvest policies are also different, and allow for final harvesting of 50% of the increase of standing stock in each age group.

Final harvest according to this modified policy is similarly 90% of the stock increase for soft and fast-growing, broadleaved forests. The distribution between age groups is, however, different, equation (2.2) being replaced by equation (2.7)–(2.10).

$$H_{X,2,t} = \frac{1}{3} I_{X,t} \tag{2.7}$$

$$H_{X,3,t} = \frac{2}{3} I_{X,t} \tag{2.8}$$

$$H_{X,4,t} = Z_{X,4,t} \tag{2.9}$$

$$I_{X,t} = S_{X,t} - Z_{X,4,t} \tag{2.10}$$

For the slow-growing, broadleaved forests we have (again instead of equation (2.2)), equation (2.11)

$$H_{X,i,t} = \begin{Bmatrix} S_{X,t} W_{X,i} & \text{if } t < 1995 \\ Z_{X,i,t} & \text{if } t = 1995 \end{Bmatrix} \tag{2.11}$$

For pines in the lowlands equation (2.2) is replaced by equation (2.12).

$$H_{X,i,t} = \begin{cases} 0.5\, Z_{X,i} & \text{if } t < 2040 \\ 1.0\, Z_{X,i} & \text{if } t = 2040 \end{cases} \tag{2.12}$$

Equation (2.12) implies halting the build-up of these pines after 2040.

3.3 Forest Area and Afforestation Scenarios

The change in forest area is described by equations (3.1)–(3.6).

$$G_{X,1,t+dt} = G_{X,1,t} + dt(T^{*}_{X,4\to1,t} + T_{X,0\to1,t} - T_{X,1\to2,t} + T^{*}_{X,2\to1,t} + T_{X,3\to1,t}) \tag{3.1}$$

$$G_{X,2,t+dt} = G_{X,2,t} + dt(T_{X,1\to2,t} - T_{X,2\to3,t} - J_{X,2,t} - T^{*}_{X,2\to1,t}) \tag{3.2}$$

$$G_{X,3,t+dt} = G_{X,3,t} + dt(T_{X,2\to3,t} - T_{X,3\to4,t} - J_{X,3,t} - T^{*}_{X,3\to1,t}) \tag{3.3}$$

$$G_{X,4,t+dt} = G_{x,4,t} + dt(T_{X,3\to4,t} - J_{X,4,t} - T^{*}_{X,4\to1,t}) \tag{3.4}$$

$$G_{X,i,t_0} = G_{0,X,i} \tag{3.5}$$

$$T_{X,0\to1,t} = K_{X,1,t} + J_{X,2,t} + J_{X,4,t} \tag{3.6}$$

In these equations $T^{*}_{X,i\to1,t}$ is the area transferred to the first age group as a consequence of final harvest (i=2, 3, or 4); $T_{X,i\to j,t}$ is the area transferred to the next age group to update the age of the forest (i=1, 2, or 3); $J_{X,i,t}$ is the area taken out from forest management for utilization in other sectors (i=2, 3, or 4); $K_{X,1,t}$ is the area planted under the afforestation program; and $T_{X,0\to1,t}$ is the total newly planted area.

These equations ensure that the following principles are observed: (1) No area is removed from the first age group. (2) In other age groups areas may be removed, but an equal area must be replanted the following year. (3) Final harvest takes the form of clear-cutting, and an equal area is replanted similarly. Updating the area of the age group is determined by equation (3.7) ($i=1, 2$, or 3):

$$T_{X,i\to j,t} = G_{X,i,t} / L_{X,i} \tag{3.7}$$

The area removed from forest management is 0.01% of the total, as given by equation (3.8) ($i=2, 3$, or 4):

$$J_{X,i,t} = 0.0001 G_{X,i,t} \tag{3.8}$$

The values of the parameters, including the added areas, for the four scenarios, are given in the Appendix.

4. VALIDATION AND RESULTS

The state variables of the model are dependent, which means that they can be divided into two groups, the vectors $\boldsymbol{x}_t$ and $\boldsymbol{y}_t$. These two vectors are connected by the functional relationship $\boldsymbol{y}_t = g(\boldsymbol{x})$ for all t, where the function g depends on the parameters discussed above. Another feature of this model is that a projection of the forest sector up to the year 2000 is available, which we assume is consistent. Hence there is a function h that gives the values for these projections (like total growing stock, or total harvest), which we denote by $\boldsymbol{z}_1$. Formally, $h(\boldsymbol{x}_{t_1}) = \boldsymbol{z}_1$ for $t_1 = 2000$. Therefore the model has the abstract form given by equations (4.1)–(4.5).

$$\boldsymbol{x}_{t_0} = \boldsymbol{x}_0 \tag{4.1}$$

$$\boldsymbol{y}_{t_0} = y_0 \tag{4.2}$$

$$h(\boldsymbol{x}_{t_1}) = \boldsymbol{z}_1 \tag{4.3}$$

$$x_{t+dt} = x_t + dt f(x_t, t) \tag{4.4}$$

$$y_t = g(x_t) \tag{4.5}$$

In these equations, the functions f, g, and h depend on the parameters and equations (4.4) and (4.5) are applicable for all t. Now, as a consequence of the dependent nature of this system, calibration required the parameters to be selected in such a way that:

(1) Equation (4.5) holds for $t = t_0$, so that the complete set of initial conditions is met.

(2) Equation (4.3) holds, so that the projections are consistent.

The zero-th scenario corresponds to the original afforestation plan, namely the extension of the forest area by 280 thousand hectares by the year 2000. By contrast, lower rates of extension are envisaged in the other scenarios, which, of course, affect the total growing stock and total harvest. Table 1 illustrates this effect which seems virtually independent of the two harvesting policies.

Table 1. Effects of slower afforestation (the year 2000).

Scenario	Standing stock	Harvest
0	100%	100%
1	96%	92%
2	96%	92%
3	95%	90%

Comparison of the two harvesting policies reveals that current policies result in a dynamic growth of the growing stock and an undesirable shift in the age structure, with definitely unfavorable effects in the long run (after about 30 years), such as a decline in total harvest.

The results obtained using the modified harvesting policies, which are more in keeping with the changes in afforestation rate, show that these unfavorable effects can be reduced and the whole forest sector can be stabilized at a relatively high level of annual harvest.

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List of Variables Used in Main Text

A_t	Delay parameter or adaptation time
$B_{X,i,t}$	Biological growth of species X and age group i at time t.
$C_{X,i,t}$	Crowding ratio
$D_{X,i+j,t}$	Average of forest densities
E_X	Thinning multiplier
$F_{X,i,t}$	Potential volume of growing stock
$G_{X,i,t}$	Area of age and species group
$H_{X,i,t}$	Final harvest
$I_{X,i,t}$	Harvest in age groups 2 and 3
$J_{X,i,t}$	Area removed from forest management (i=2, 3 or 4)
$K_{X,1,t}$	Area planted under afforestation program
$L_{x,i}$	Growth period of species involved
$M_{X,i,t}$	Forest growth multiplier
$N_{Xj,t}$	Loss due to natural decay
$n_{X,i}$	Natural decay multiplier
$O_{X,i,t}$	Loss due to removal to next age group
$P_{X,i,t}$	Loss due to pollution
$p_{X,i}$	Pollution decay multiplier
Q_X	Function of crowding ratio and relative growth
R_X	Mean rotation
$S_{X,t}$	Total harvest of last three age groups
$T_{X,i \to j,t}$	Area transferred from i-th to j-th group (i=1, 2 or 3)
$T_{X,i \to 1,t}$	Area transferred to first age group because of harvest (i=1, 2 or 3)
$T_{X,0 \to 1,t}$	Area newly planted
U_X	Maximum possible growing stock per unit area
$V_{X,i,t}$	Volume of growing stock
$W_{X,i}$	Parameter to control age composition of growing stock
X	Group of species
$Y_{X,k,t}$	Gain due to transfer from lower group
$Z_{X,i,t}$	Harvest from each age group.

Table A.1 Initial conditions (t_0 = 1980)

(a) Growing stock in 1980 (million m^3)

	Age group			
	1	2	3	4
Soft, broadleaved	6.540	4.130	6.393	10.246
Hard, broadleaved, fast	15.064	6.936	9.156	2.354
Hard, broadleaved, slow	105.751	23.336	25.304	8.472
Pines, hills	16.390	4.359	1.208	0.745
Pines, lowlands	4.450	0.147	0.153	0.670

(b) Forest area in 1980 (thousand hectares)

Soft, broadleaved	109.7	39.6	34.2	39.9
Hard, broadleaved, fast	159.2	47.1	50.1	12.1
Hard, broadleaved, slow	600.6	76.1	72.2	24.0
Pines, hills	141.1	11.0	2.6	1.5
Pines, lowlands	49.5	0.8	0.7	2.6
Other areas (do not refer		101.4		
Bare land to age grops)		111.7		

(c) Harvest in 1980 (million m^3)

	Thinning	Final harvest	Total
Soft, broadleaved	0.489	1.034	1.523
Hard, broadleaved, fast	0.240	1.730	1.970
Hard, broadleaved, slow	1.298	2.215	3.513
All pines	0.282	0.252	0.534
Total	2.309	5.231	7.540

Table A.2. Long term projections (t_1 = 2000)

Growing stock	300 million m^3
Forest area	19.800 thousand km^2
Total harvest	10 million m^3

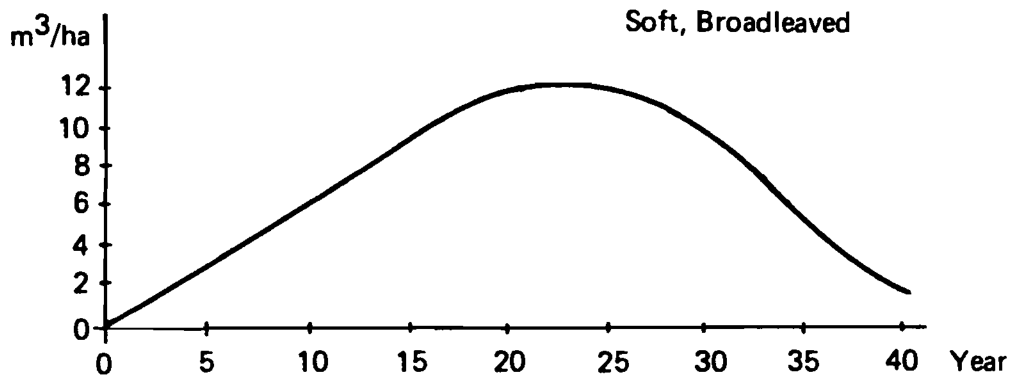
Table A.3. Afforestation scenarios (Share of species in the afforested area (percentages): soft, broadleaved, 22; hard, broadleaved, fast, 12; hard, broadleaved, slow, 26; pines, hills, 10; pines, lowlands, 30.)

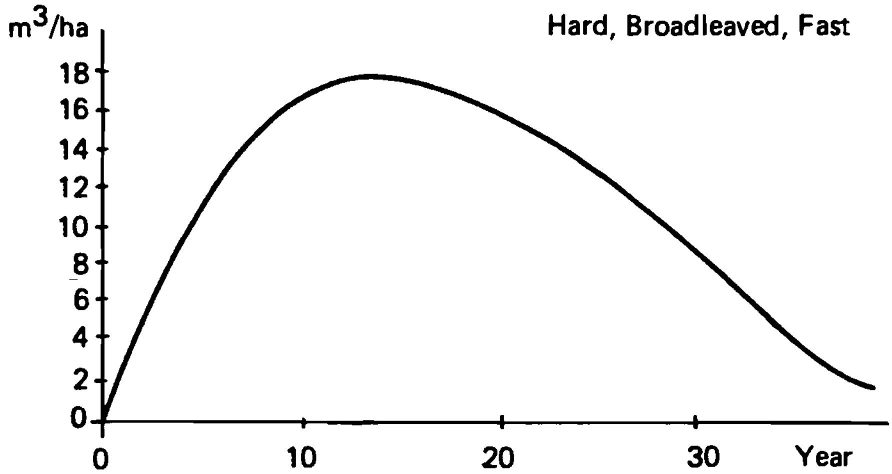
Scenarios	Period	Area increase (thousand hectares)
Zero-th	1980–2000	280
	2000–2070	0
First	1980–2000	130
	2000–2020	130
	2020–2070	0
Second	1980–2000	130
	2000–2070	130
Third	1980–2000	75
	2000–2070	0

Table A.4. Age groups and final harvest proportions ($L_{X,}$, $W_{X,i}$)

	Thinning	Final harvest		
	1	2	3	4
Soft, broadleaved	0–15	15–20 (40%)	20–30 (40%)	30–40 (20%)
Hard, broadleaved, fast	0–25	25–30 (10%)	30–40 (60%)	40–45 (30%)
Hard, broadleaved, slow	0–70	70–80 (40%)	80–100 (40%)	100–120 (20%)
Pines, hills	0–60	60–80 (80%)	80–90 (10%)	90–100 (10%)
Pines, lowlands	0–30	30–40	40–45	45–50

Figure A.1. Total annual growth





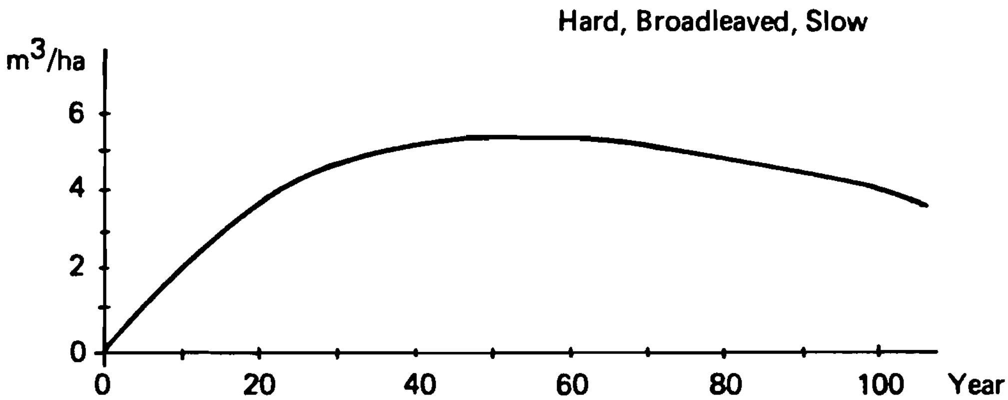
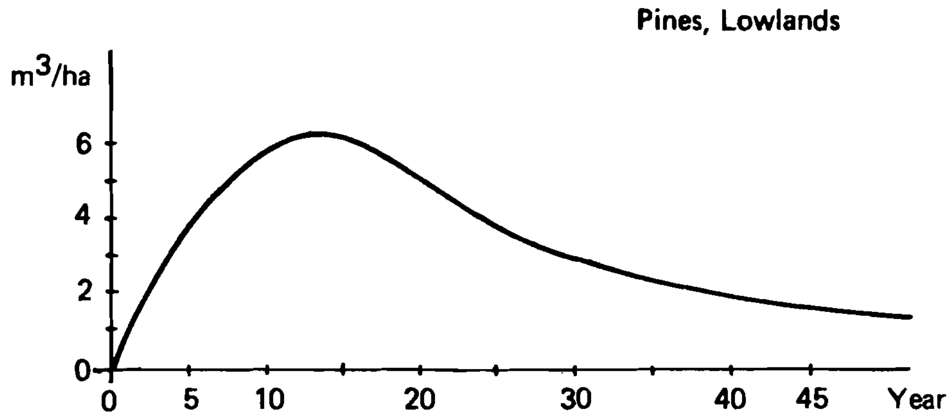


Figure A.1. (Cont.)



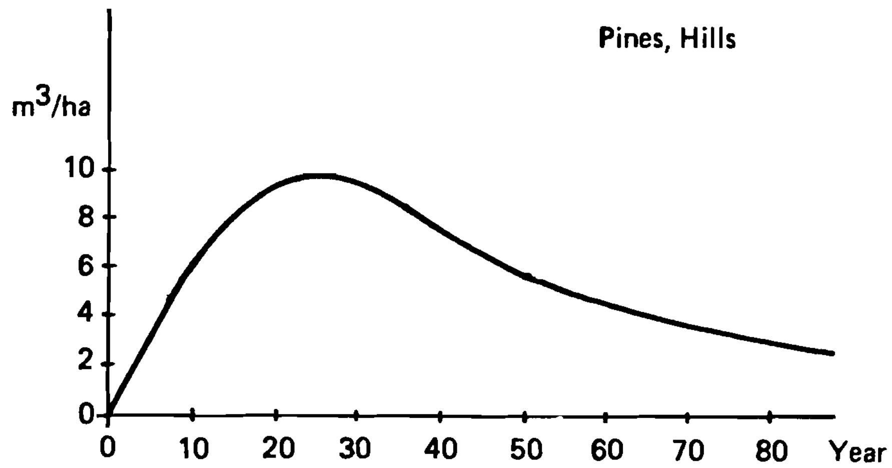


Table A.5. Total production for the different groups of species.

	Thinning (m^3)	Final harvest (m^3)	Total production (m^3)
Soft, broadleaved	87	150	237
Hard, broadleaved, fast	220	380	600
Hard, broadleaved, slow	340	580	920
Pines, hills	164	320	484
Pines, lowlands	98	192	290

Table A.6. Relative growth of growing stock as a function of crowding ratio (the function Q_X)

Age (year)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
$C_{S,i,t}$	0.01	0.03	0.06	0.08	0.16	0.24	0.33	0.39	0.55	0.67	0.8	0.93	1.07	1.19	1.31	1.42	1.51	1.58	1.63	1.66
$M_{S,i,t}$	25	12.5	8.33	6.25	5.0	4.08	3.78	3.54	2.82	2.94	2.04	1.75	1.54	1.31	1.09	0.87	0.63	0.48	0.29	0.21
$C_{F,i,t}$	0.01	0.05	0.1	0.17	0.25	0.34	0.43	0.52	0.6	0.68	0.76	0.83	0.89	0.95	1.00	1.04	1.07	1.09	1.11	1.12
$M_{F,i,t}$	30	14.2	9.5	6.9	5.1	3.9	3.1	2.5	2.1	1.73	1.46	1.2	0.99	0.85	0.66	0.5	0.38	0.27	0.17	0.13

Age (year)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
$C_{H,i,t}$	0.01	0.04	0.07	0.12	0.18	0.24	0.30	0.37	0.44	0.51	0.58	0.65	0.73	0.8	0.87	0.94	1.00	1.06	1.12	1.18
$M_{H,i,t}$	34	15.45	9.82	7.35	5.67	4.46	3.7	3.17	2.79	2.4	2.1	1.78	1.68	1.53	1.34	1.19	1.09	0.99	0.89	0.80
$C_{P,i,t}$	0.02	0.07	0.14	0.22	0.32	0.41	0.51	0.6	0.67	0.74	0.80	0.85	0.89	0.93	0.97	1.00	1.03	1.05	1.07	1.09
$M_{P,i,t}$	32	16	9.07	6.52	4.99	3.80	2.32	2.21	1.66	1.34	1.11	0.78	0.93	0.63	0.54	0.46	0.38	0.35	0.31	0.26

Age (year)	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35	37.5	40	42.5	50		
$C_{B,i,t}$	0.02	0.07	0.14	0.22	0.32	0.41	0.51	0.6	0.67	0.74	0.80	0.85	0.89	0.93	0.97	1.00	1.03	1.05	1.07	1.09
$M_{B,i,t}$	32	16	9.07	6.52	4.99	3.80	2.32	2.21	1.66	1.34	1.11	0.93	0.78	0.63	0.54	0.46	0.38	0.35	0.31	0.26

Table A.7. Other parameters.

	X	R_X	A_t	$N_{X,i,t}$	$P_{X,i,t}$	Specific weight (t/m^3)
Soft, broadleaved	S	25	13	0.01	0.0025	0.85
Hard, broadleaved, fast	F	30	15	0.01	0.0025	1.01
Hard, broadleaved, slow	H	85	15	0.01	0.0025	1.03
Pines, hills	P	80	15	0.02	0.005	0.80
Pines, lowlands	B	40	7.5	0.02	0.005	0.80

Notations Used in Computer Printouts

The number in the title refers to the number of the afforestation scenario. JELENLEGI refers to current and MODOSITOTT to alternative harvesting policies.

X = S,F,H,P,B, denotes the group of species (referring to soft, fast- and slow-growing hard broadleaves, pines hills, and pines, lowlands respectively);

I = 1,2,3,4, the code of age group;

LFFOT, total forest area (km^2)

LFXFT, the area occupied by the X-th species (km^2)

LFXTI, XITOT, the area and growing stock of the age groups from the 1st to the i-th, for the X-th species (km^2 and tons), respectively,

XFORM, total growing stock, X-th species (m^3);

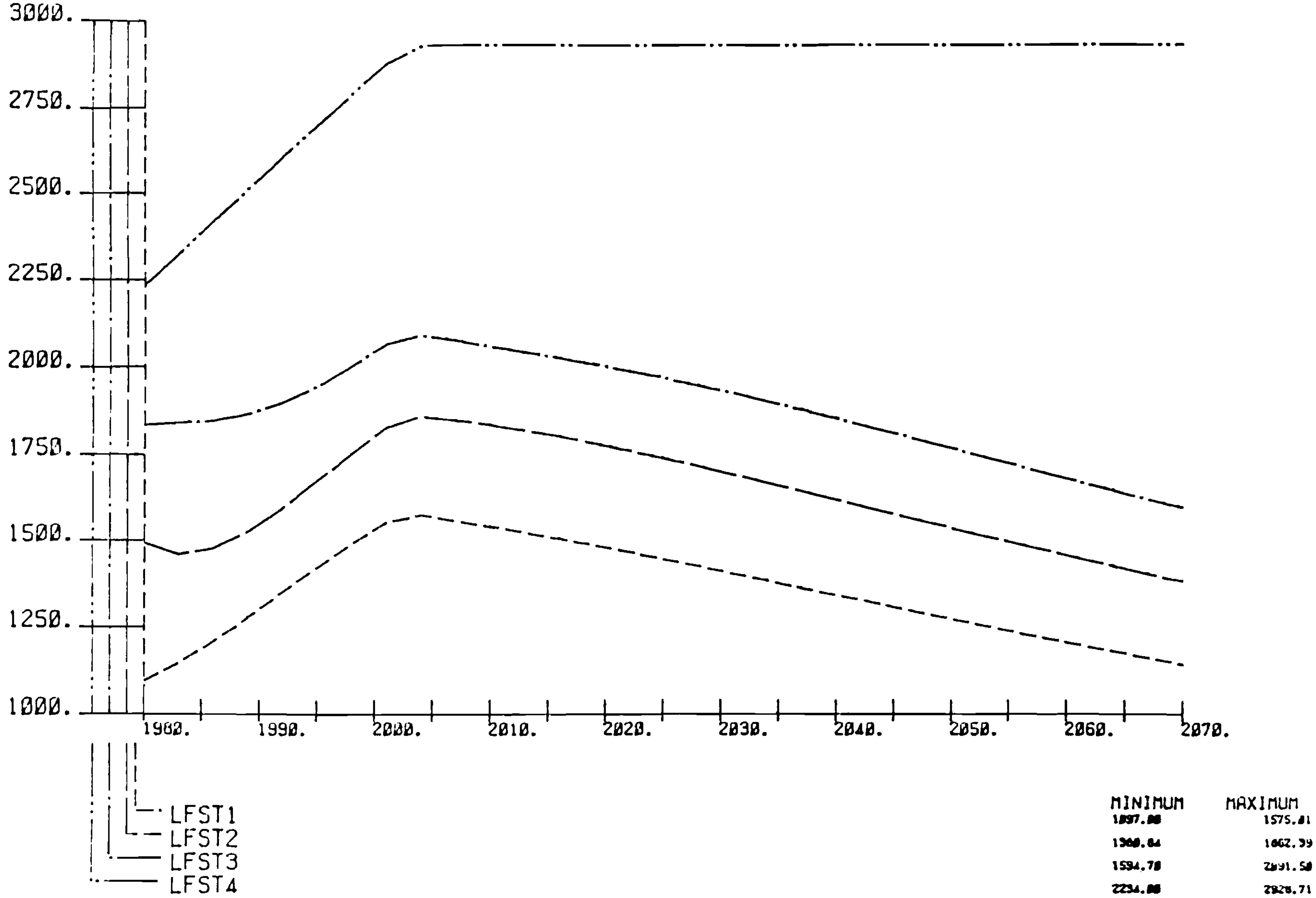
FORTM, total growing stock (m^3);

FRHTM, total harvest (m^3);

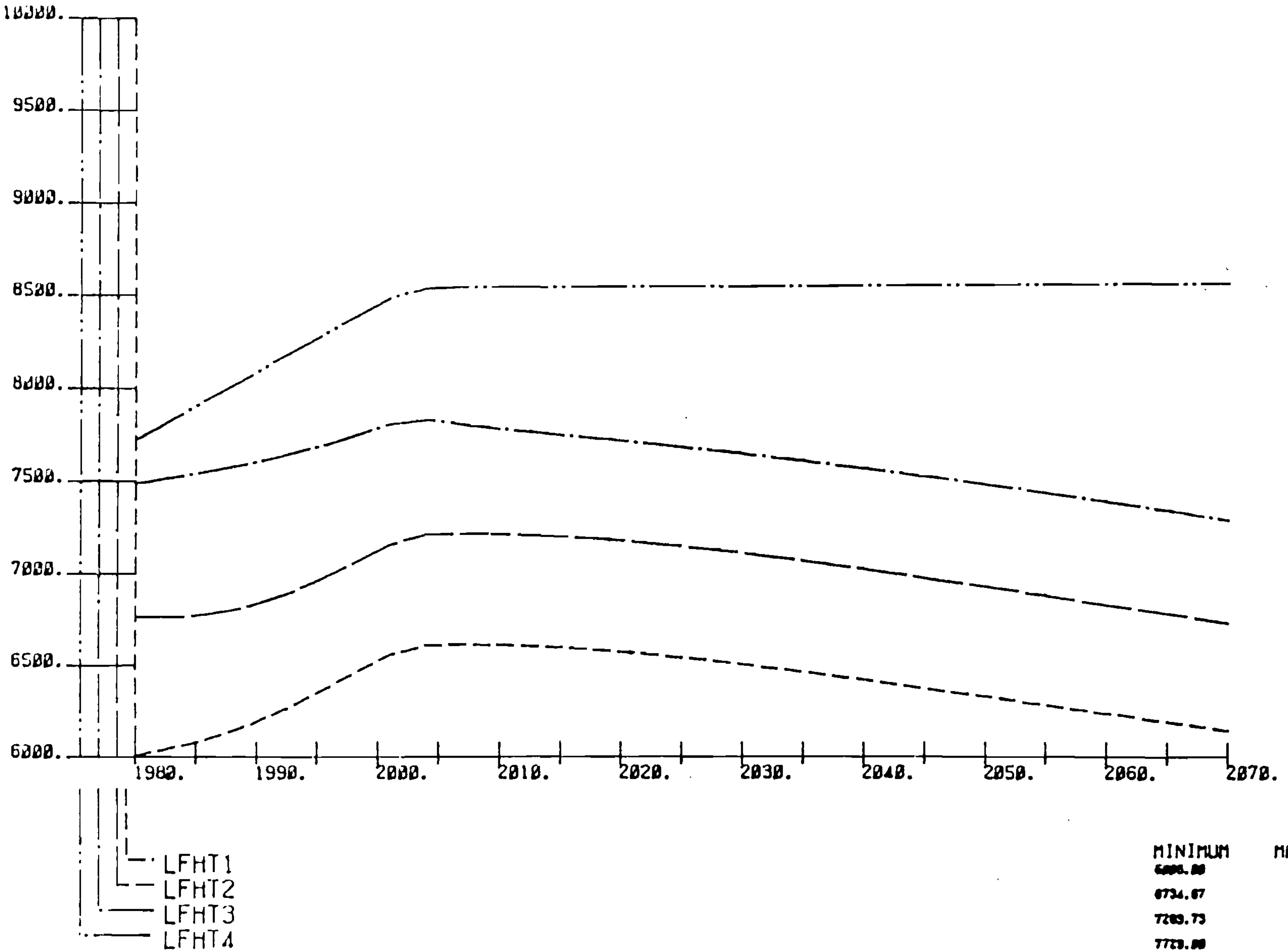
FRHEM, thinning (m^3);

XTOHM, total harvest, X-th species (m^3);

XELOM, thinning, X-th species (m^3).



Ø-TH JELENLEGI
ERDESZET



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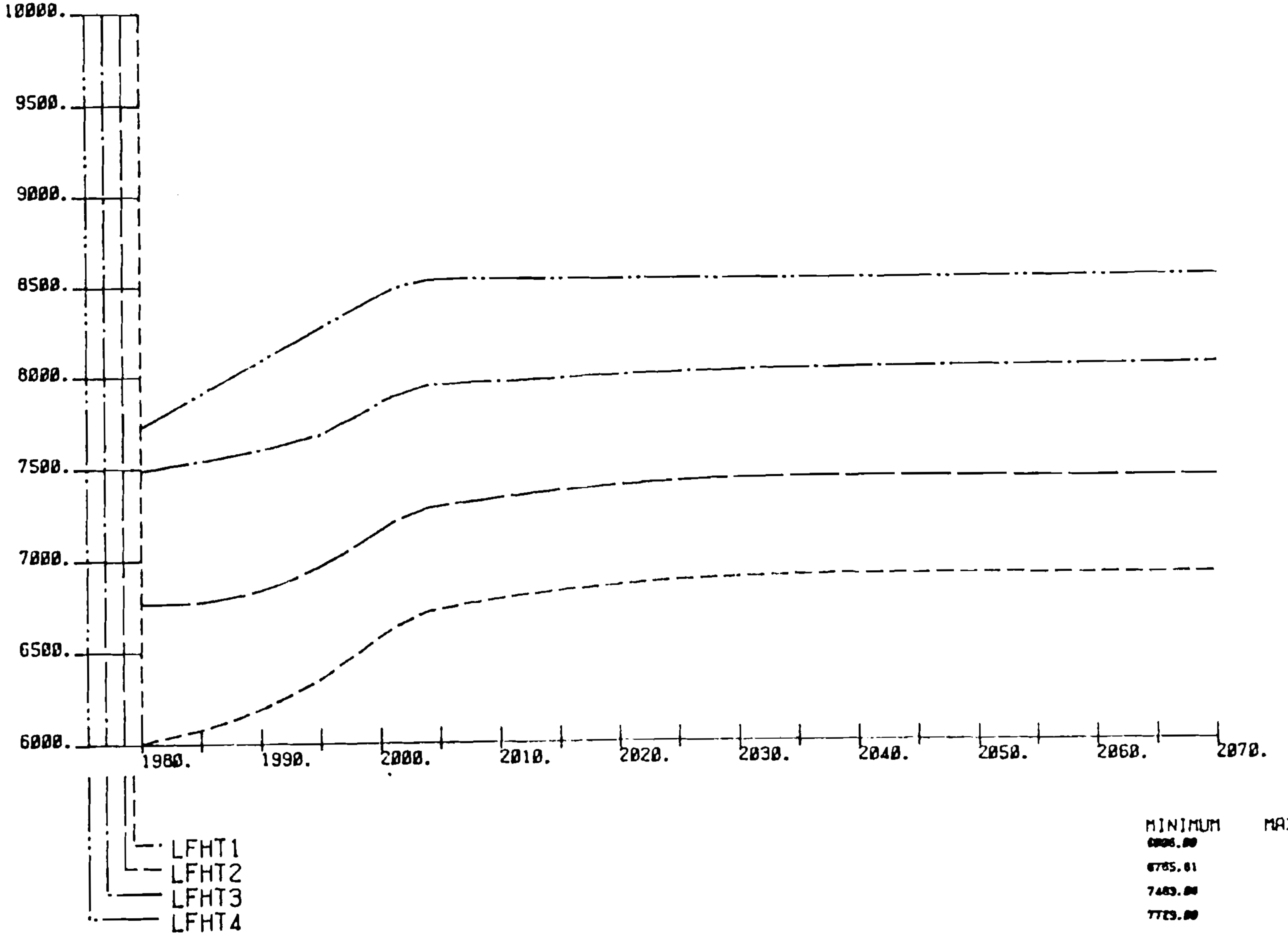
7203.73	7841.84
7720.00	8558.62

Ø-TH JELENLEGI
ERDESZET



MINIMUM	MAXIMUM
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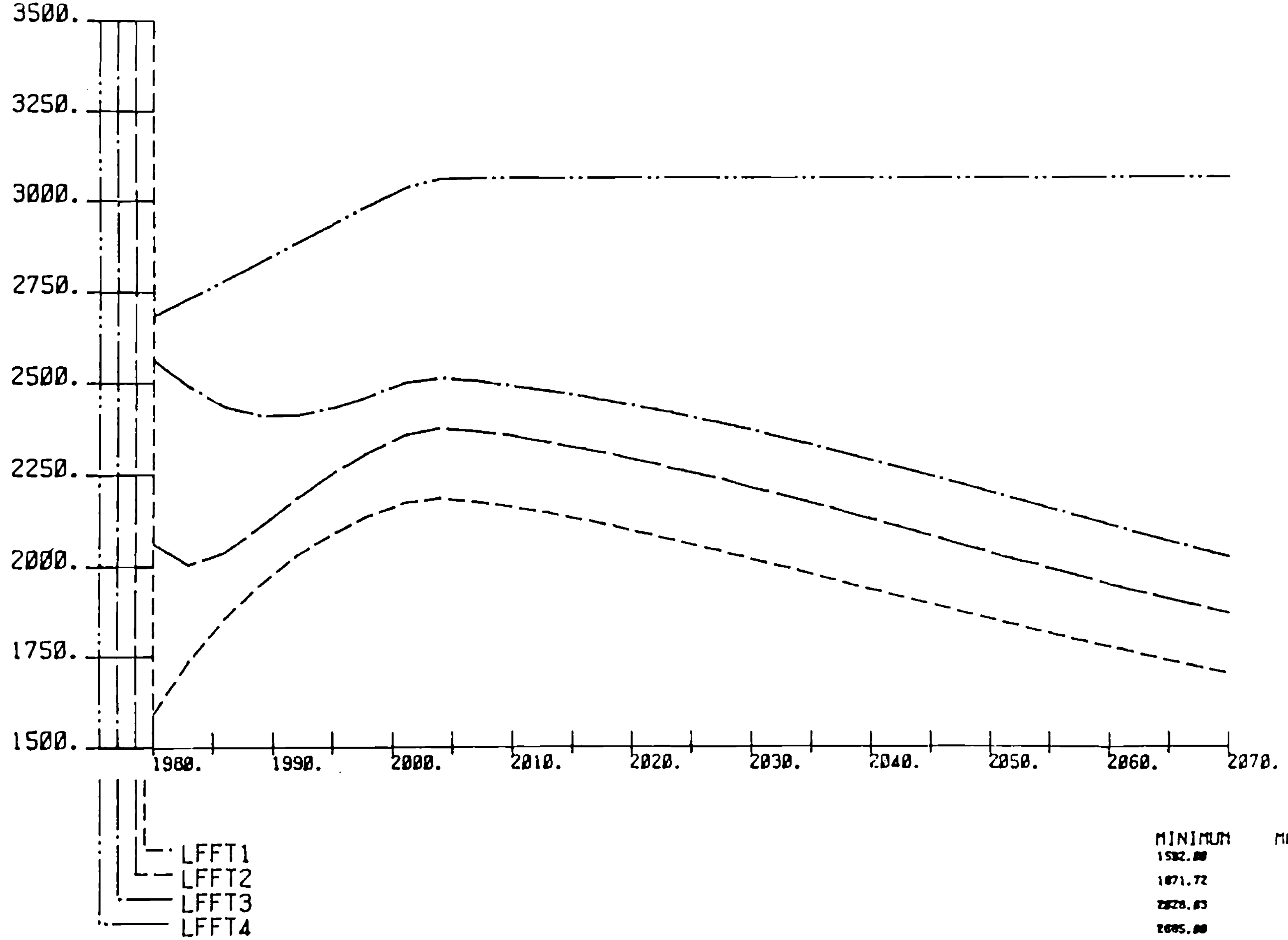
7729.00	8558.62

Ø-TH MODOSITOTT
ERDESZET



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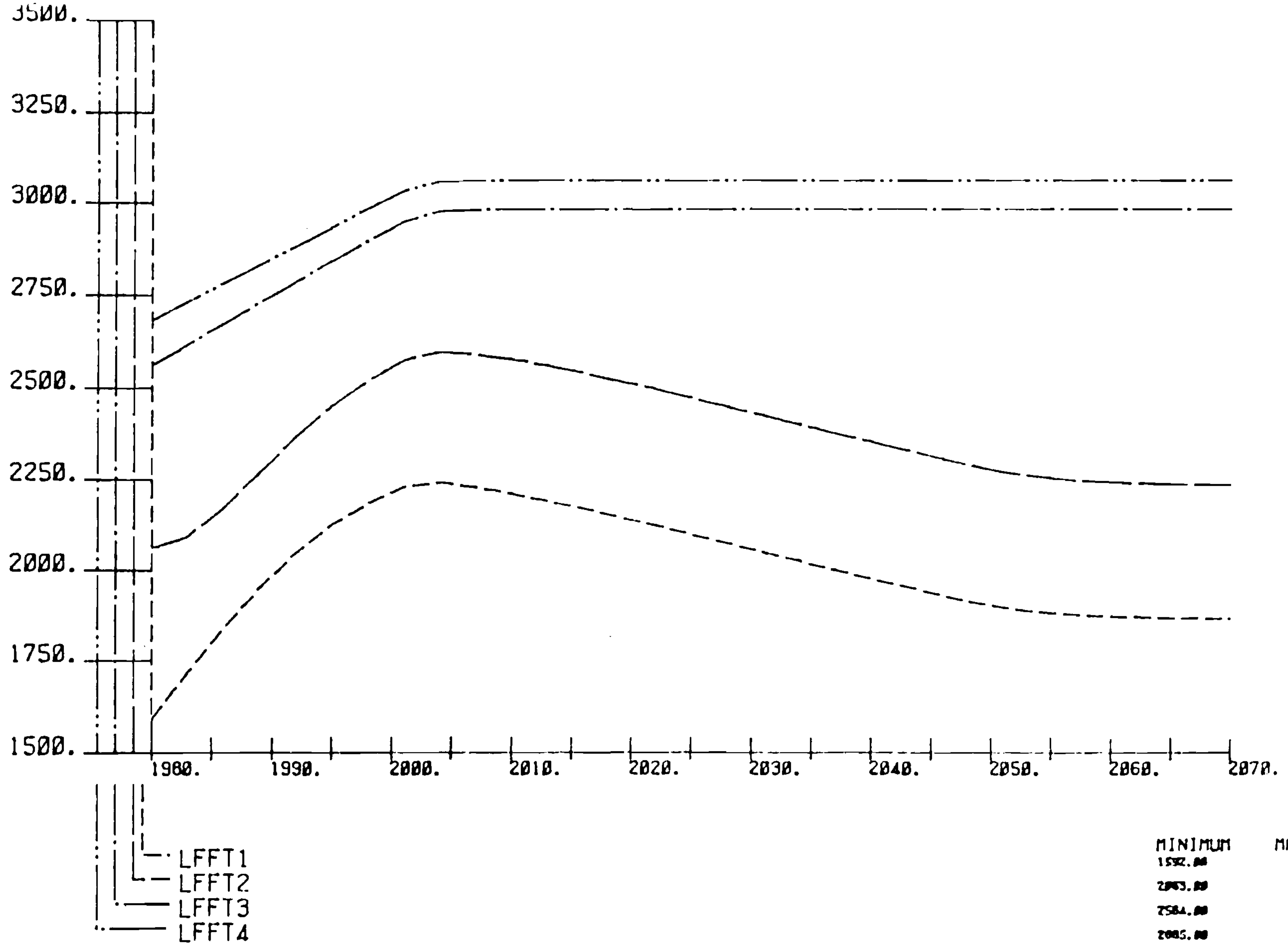
Ø-TH JELENLEGI
ERDESZET



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Ø-TH MODOSITOTT
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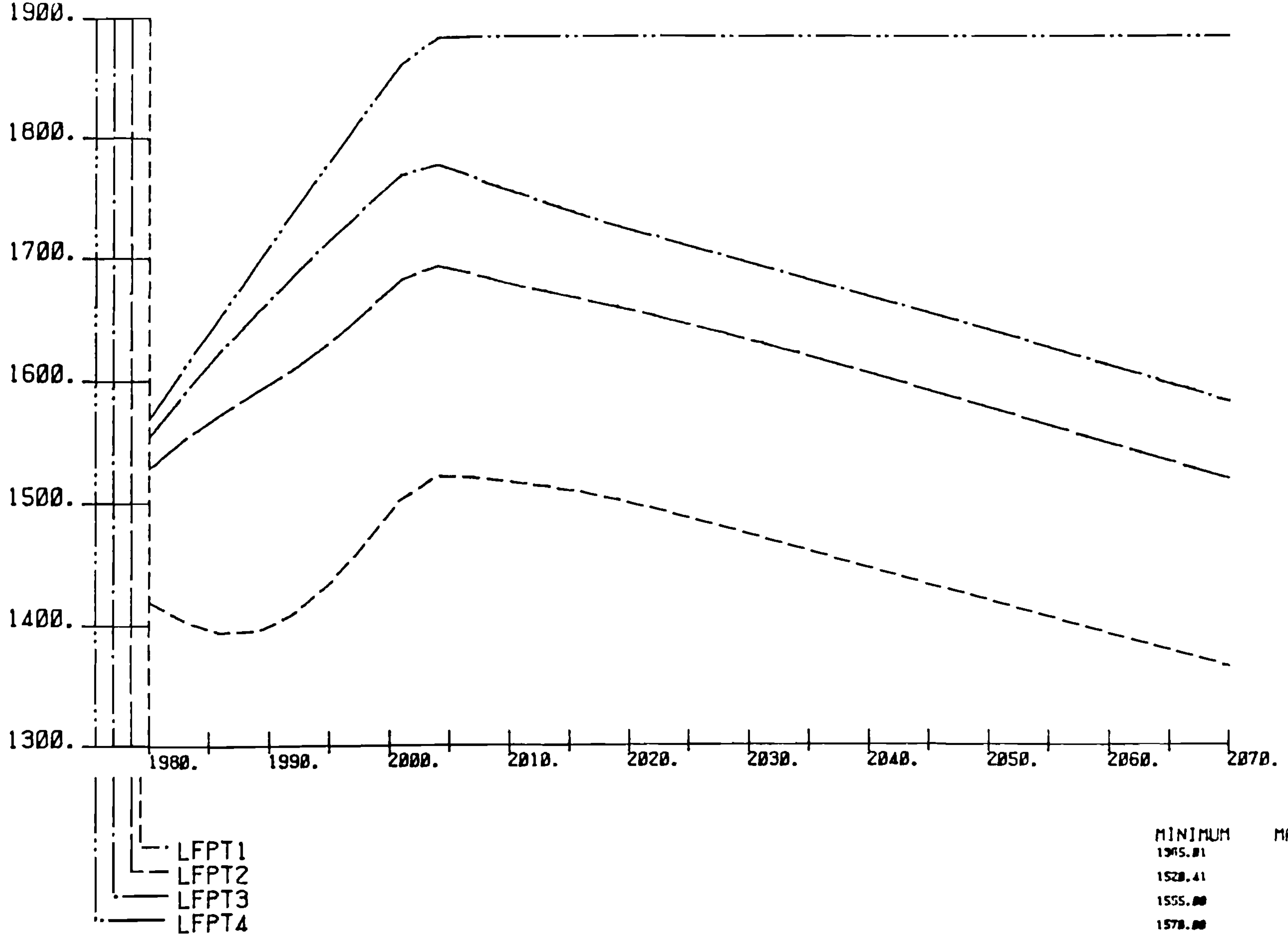

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Ø-TH JELENLEGI
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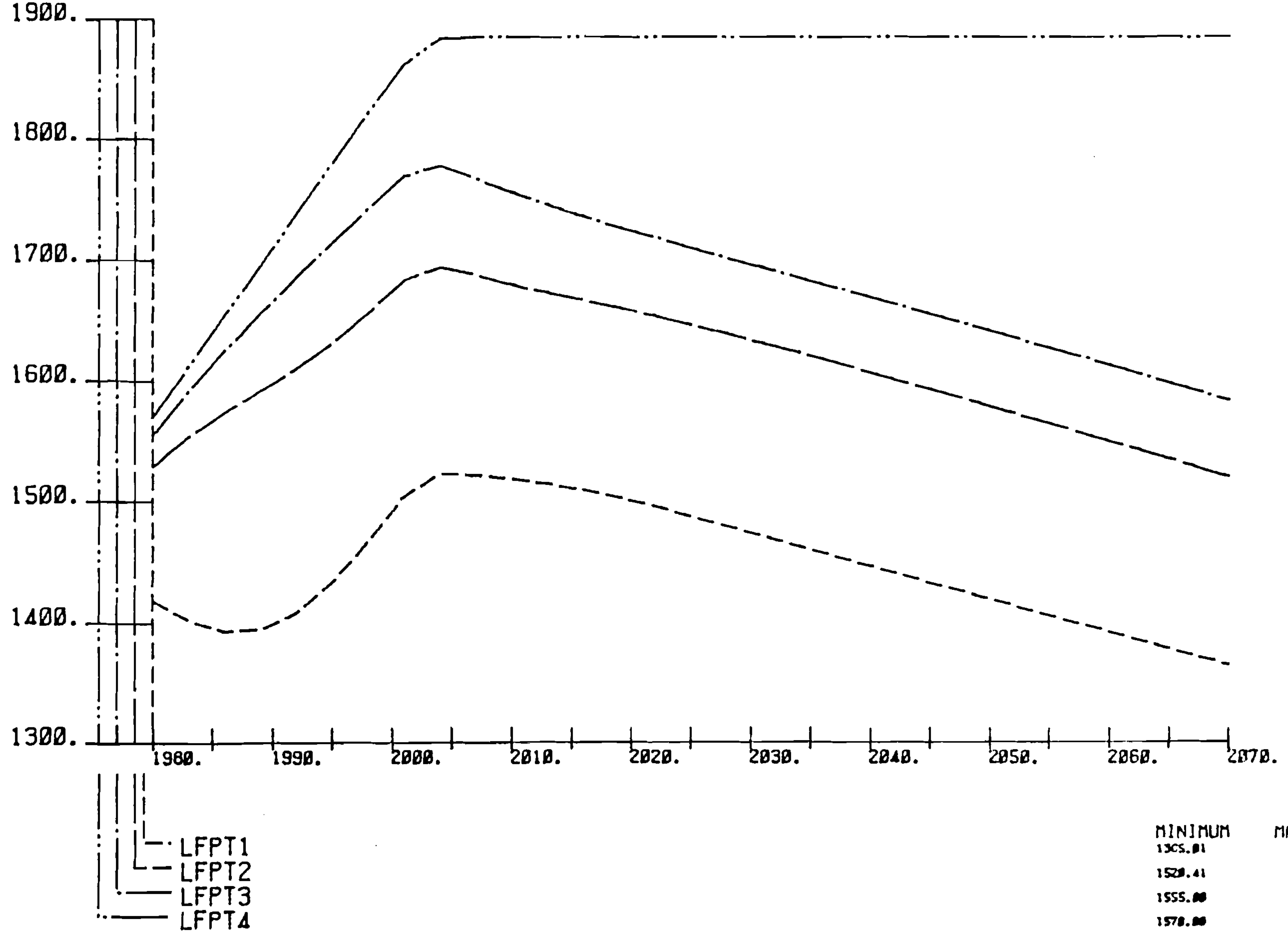

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Ø-TH MODOSITOTT
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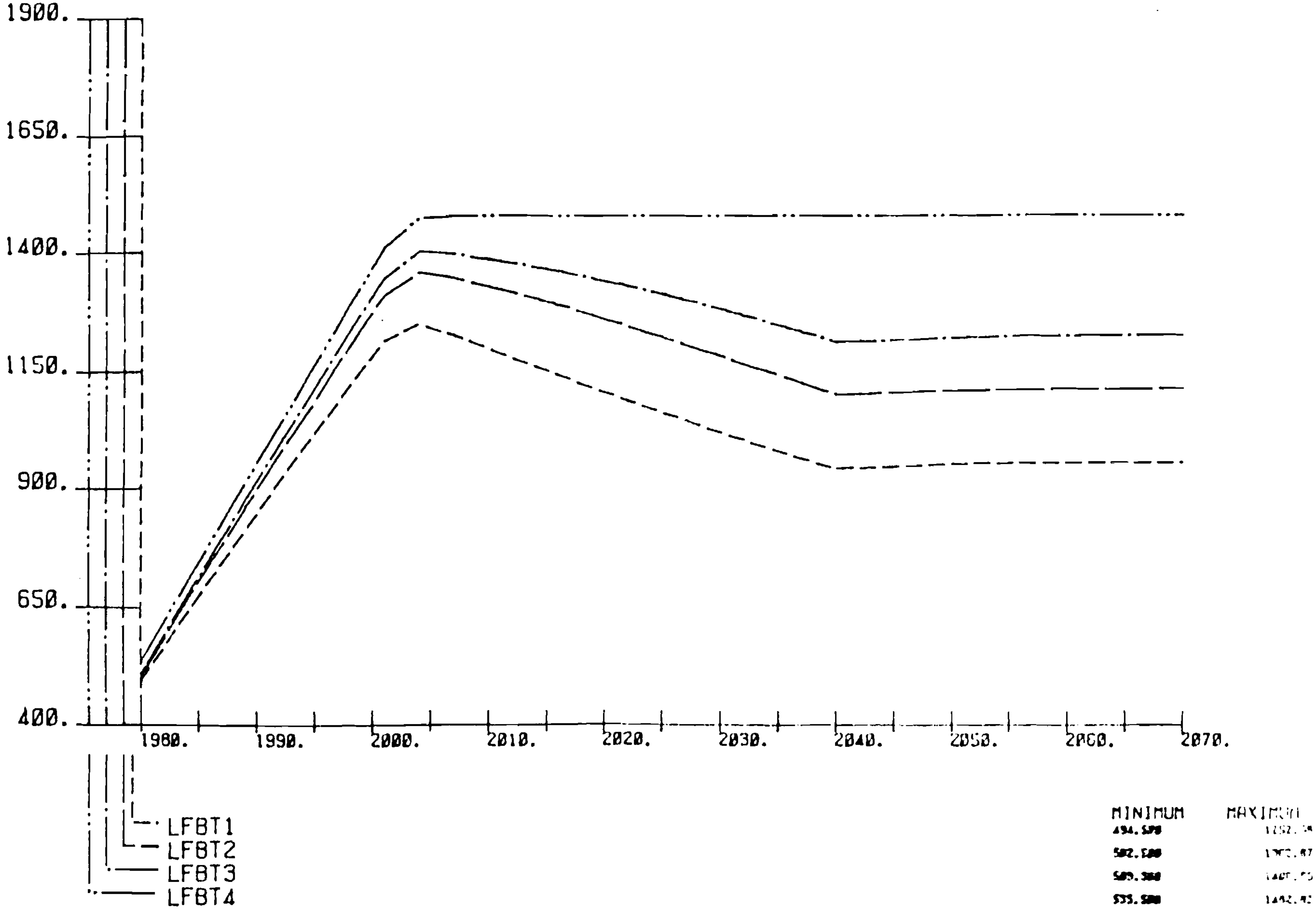

Ø-TH MODOSITOTT
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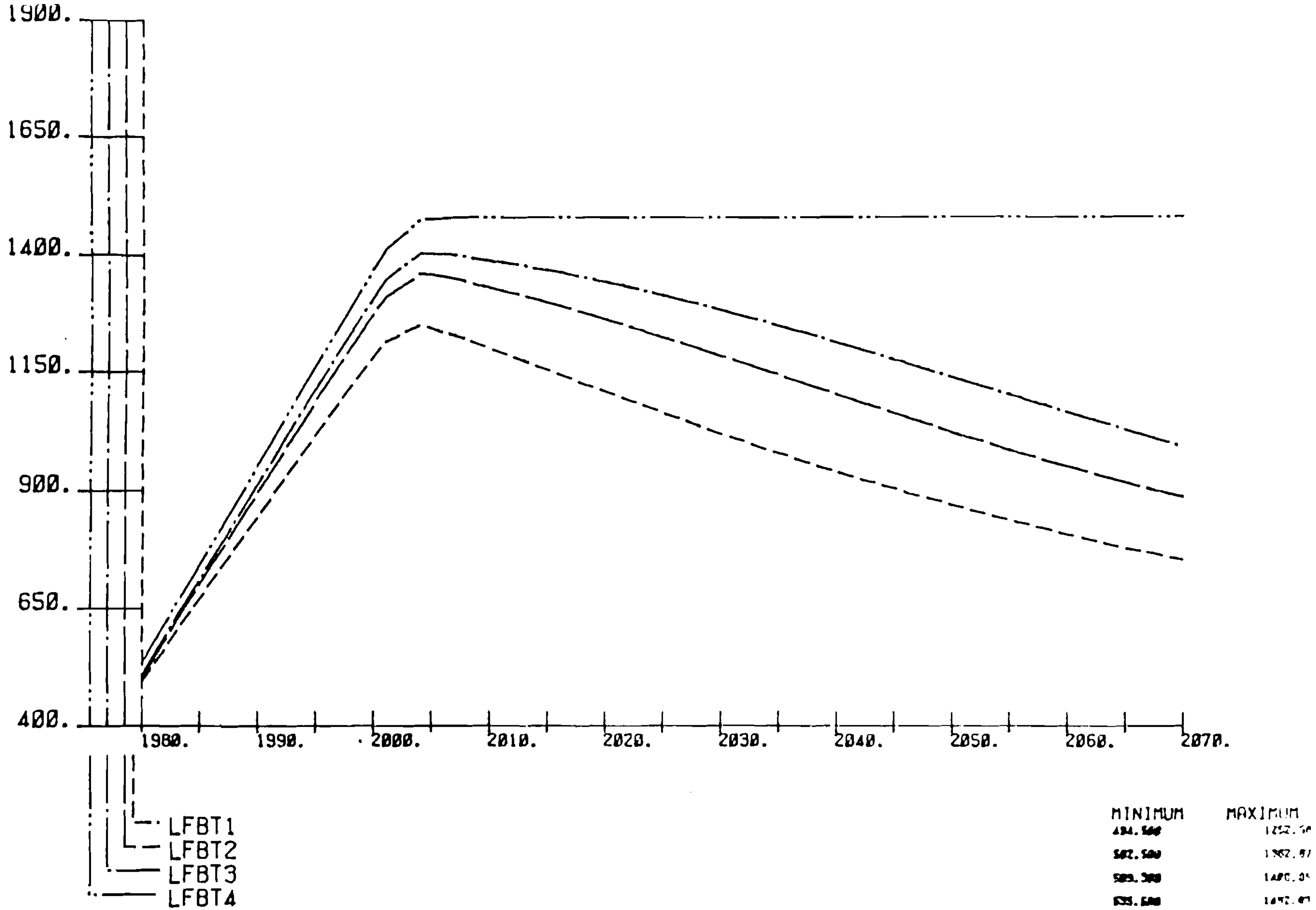

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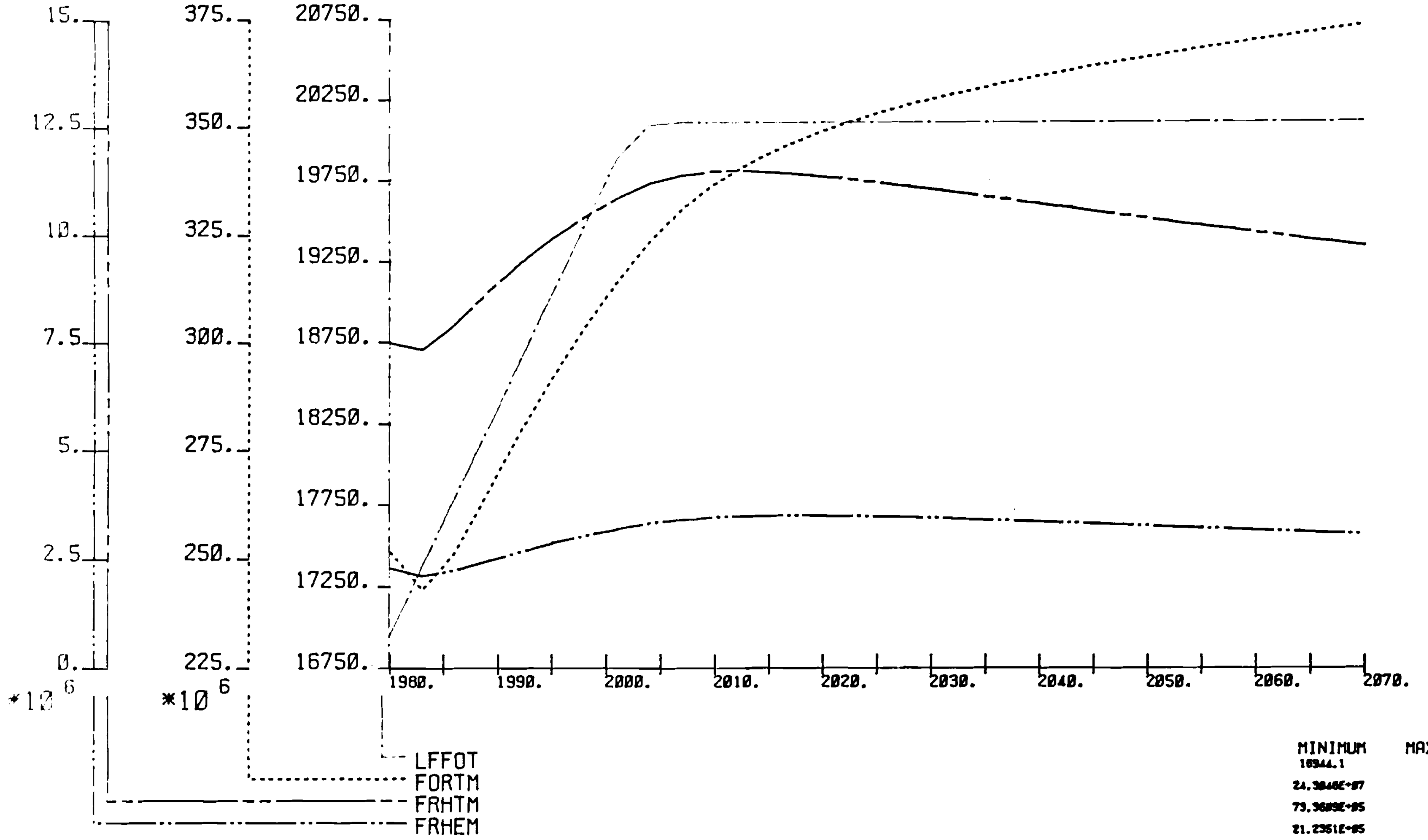

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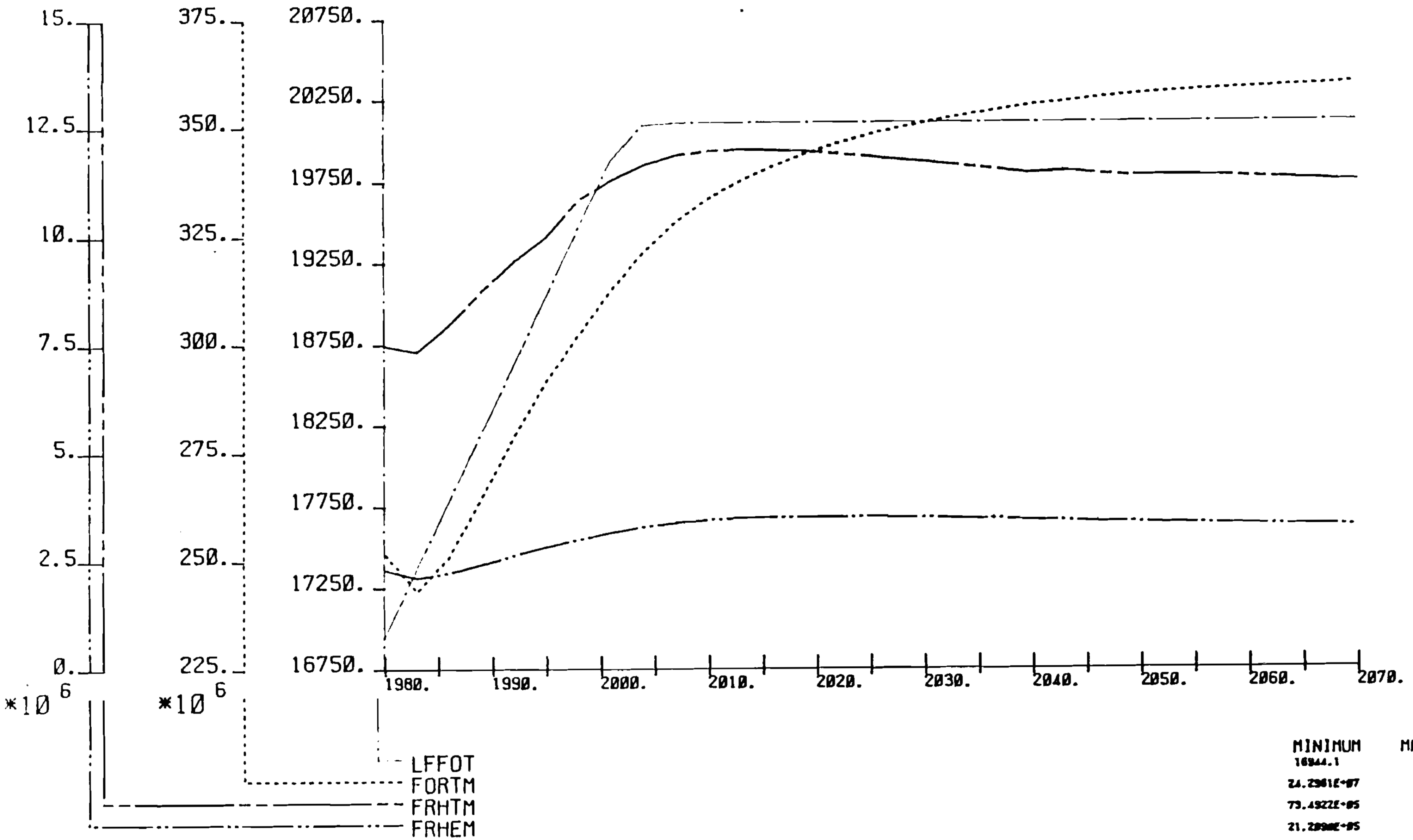
21.2351E+05	34.9865E+05

Ø-TH JELENLEGI
ERDESZET



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Ø-TH MODOSITOTT
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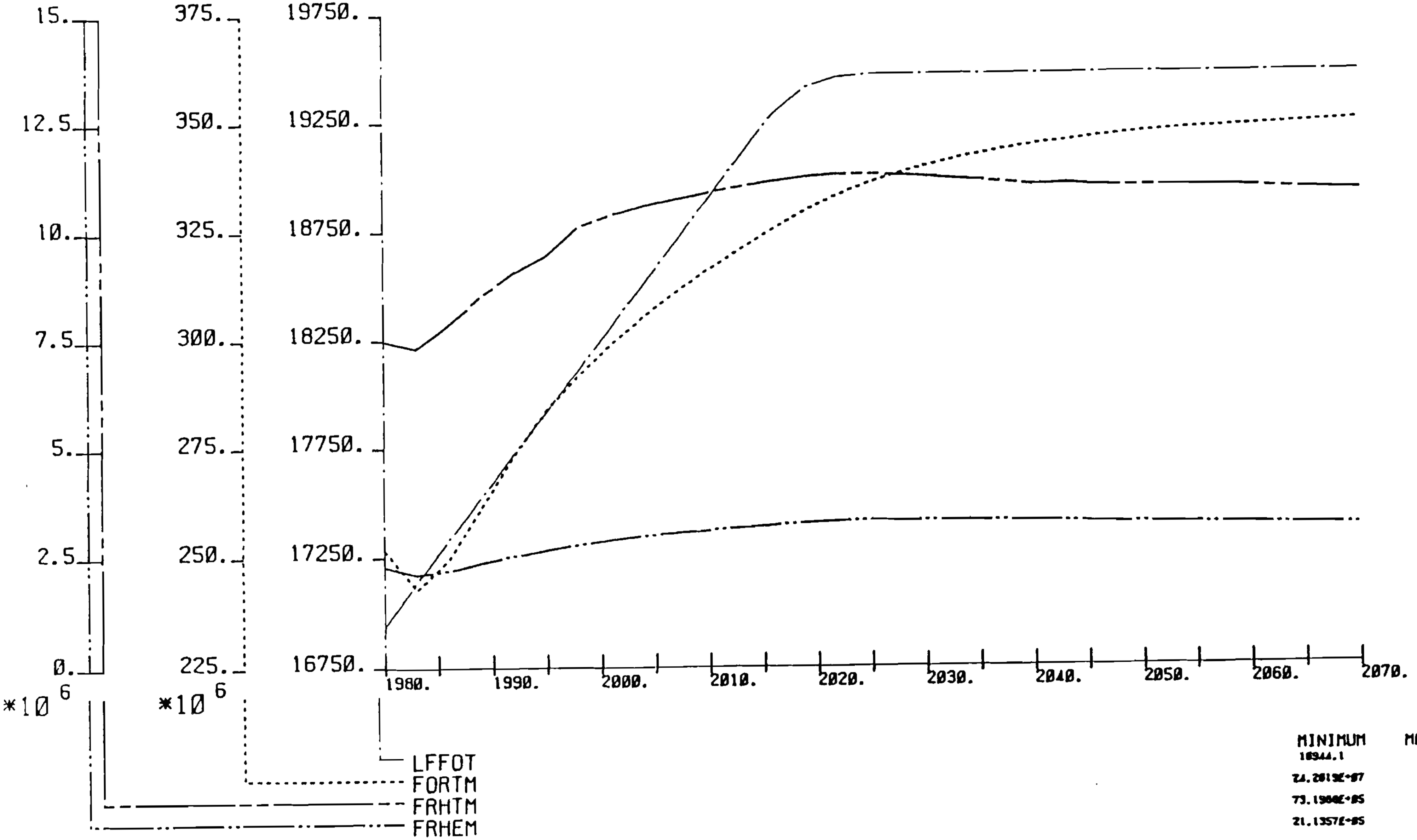

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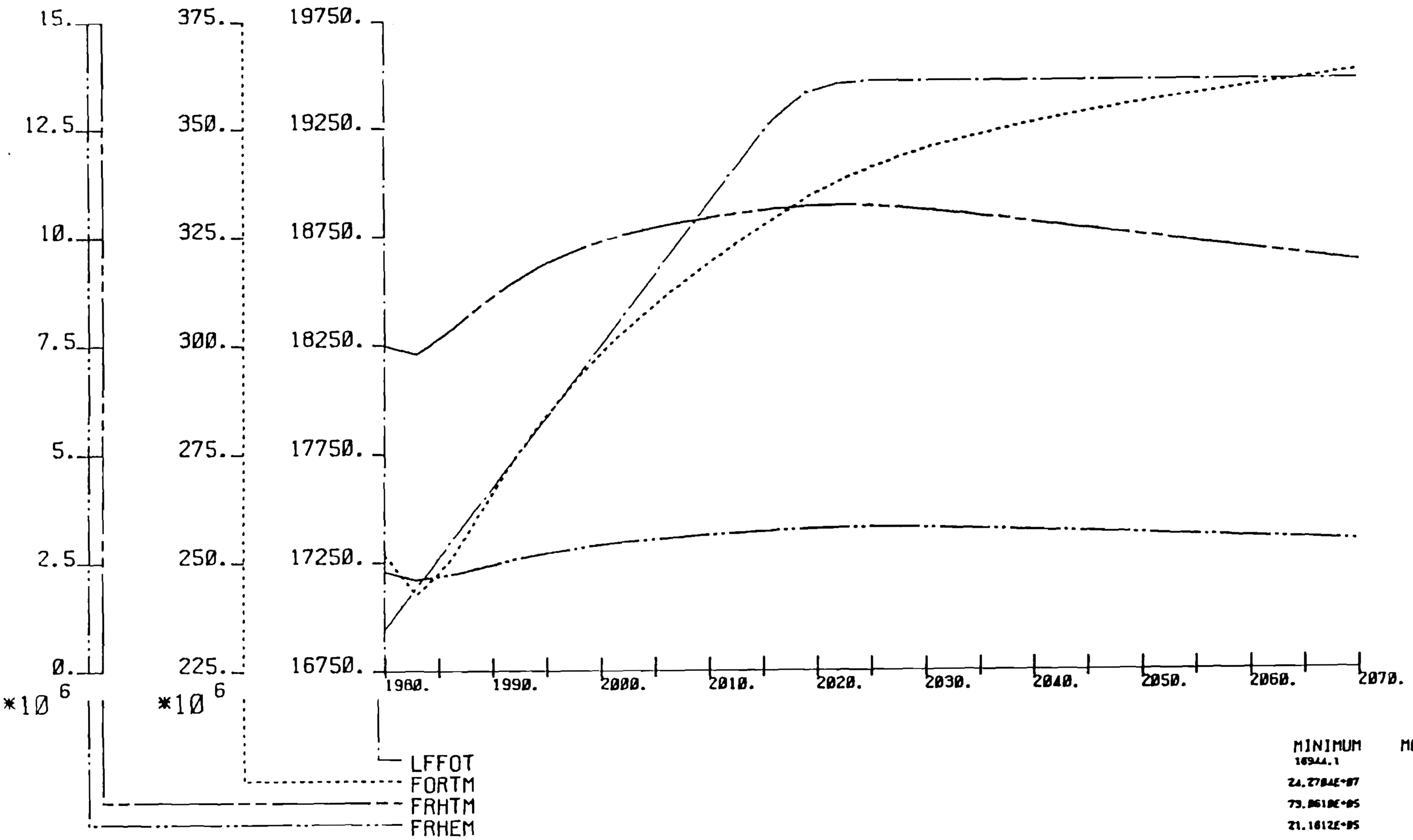
1-ST MODOSITOTT
ERDESZET



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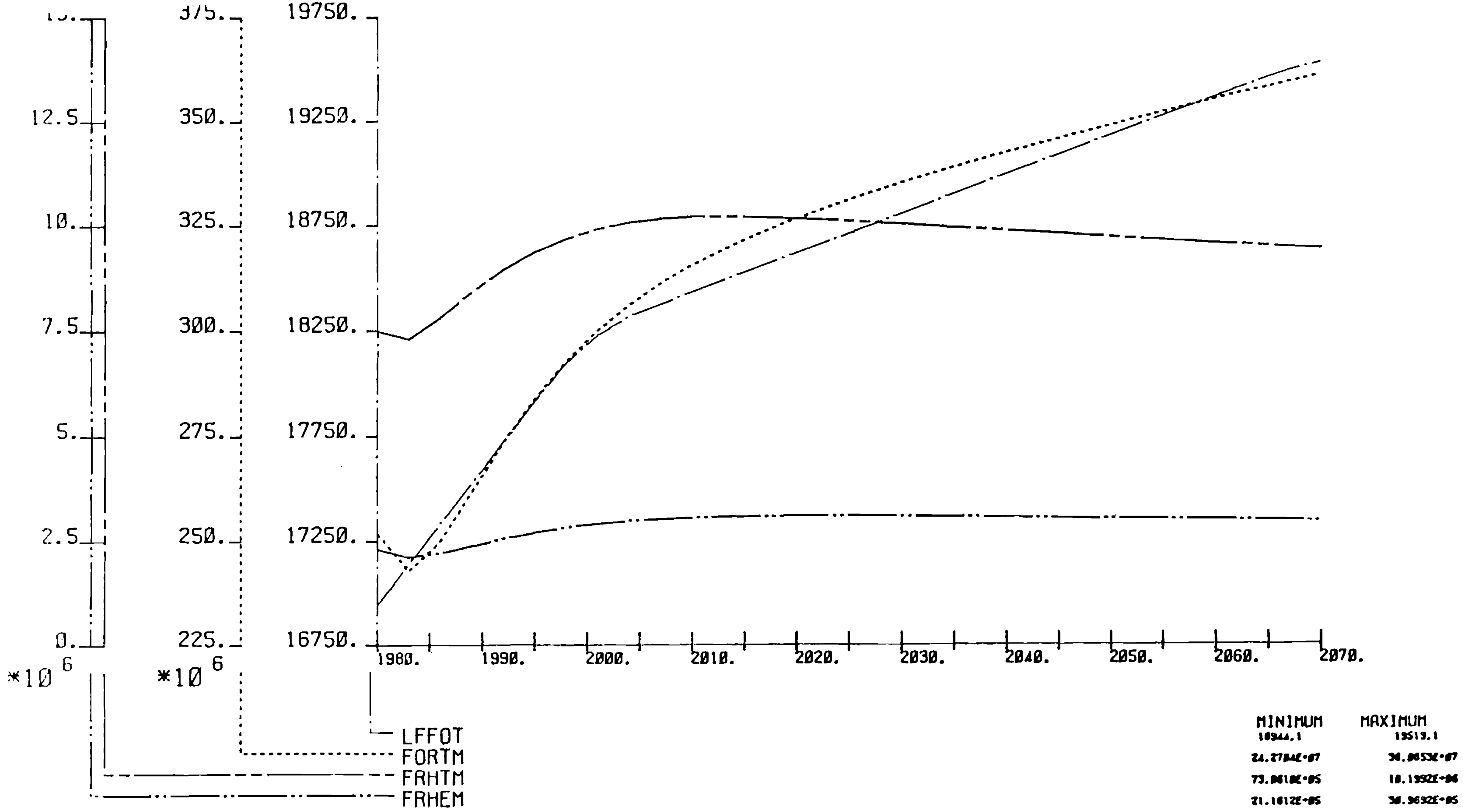
1-ST JELENLEGI



2-ND JELENLEGI
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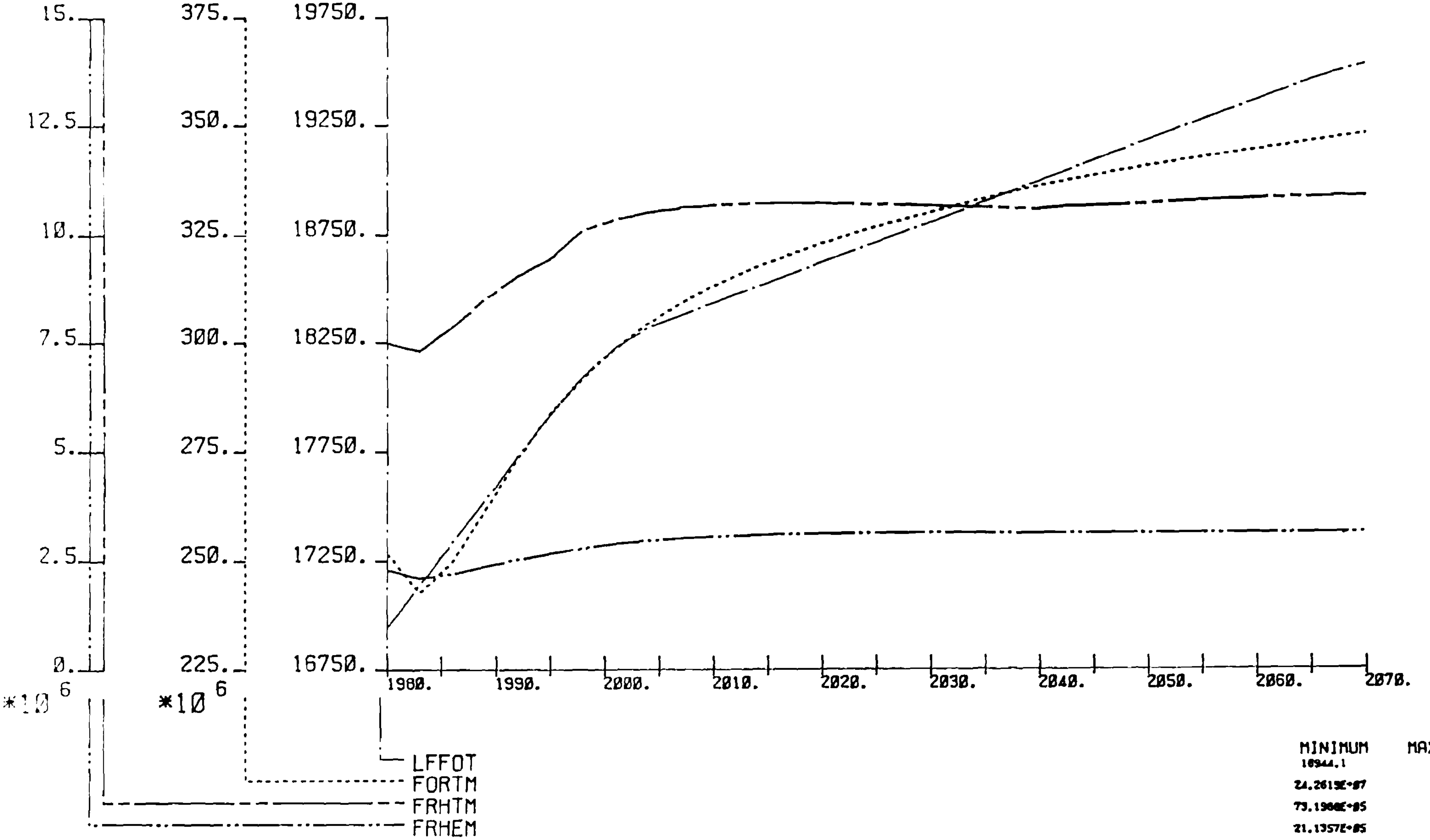

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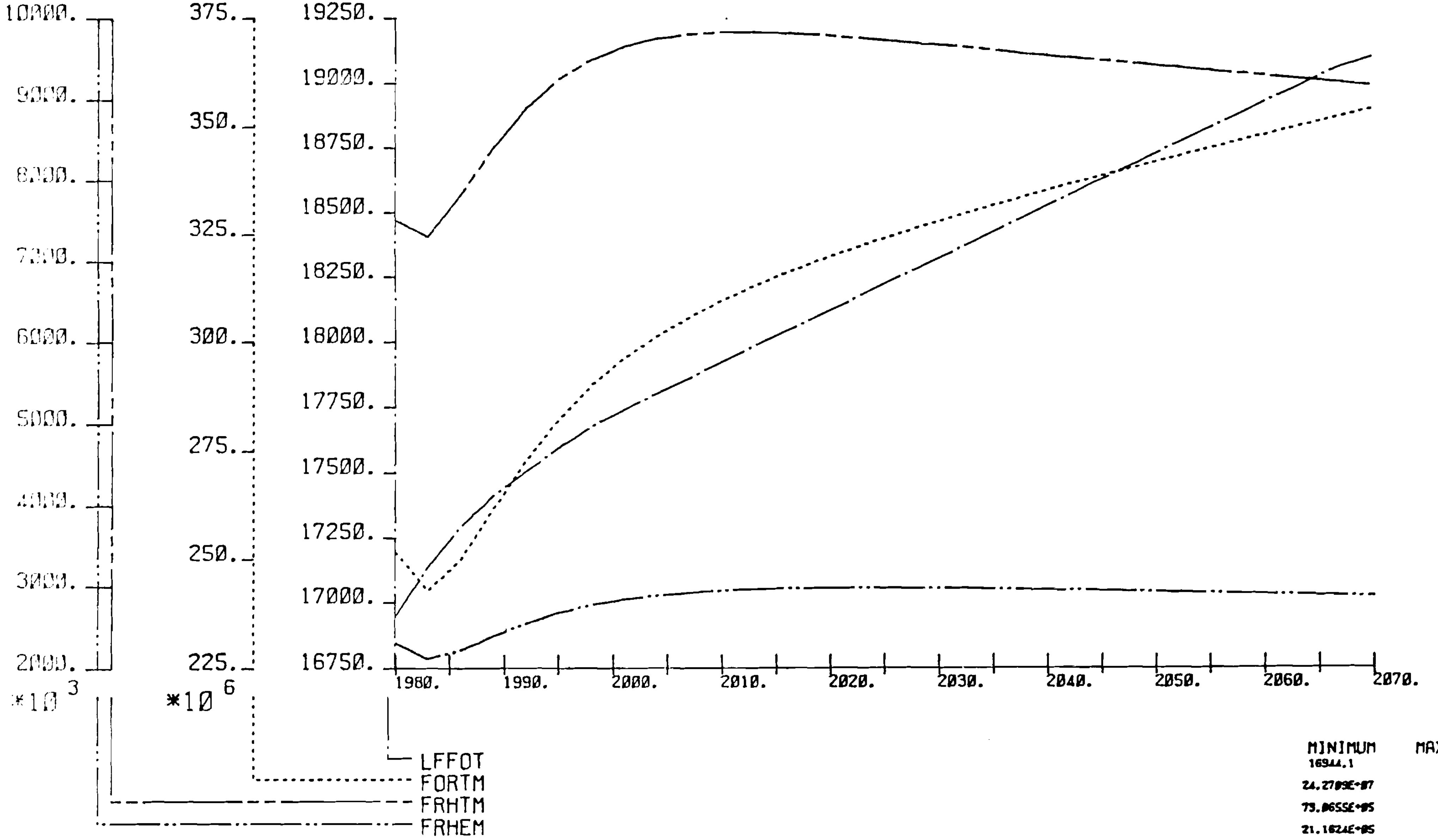
2-ND MODOSITOTT
ERDESZET



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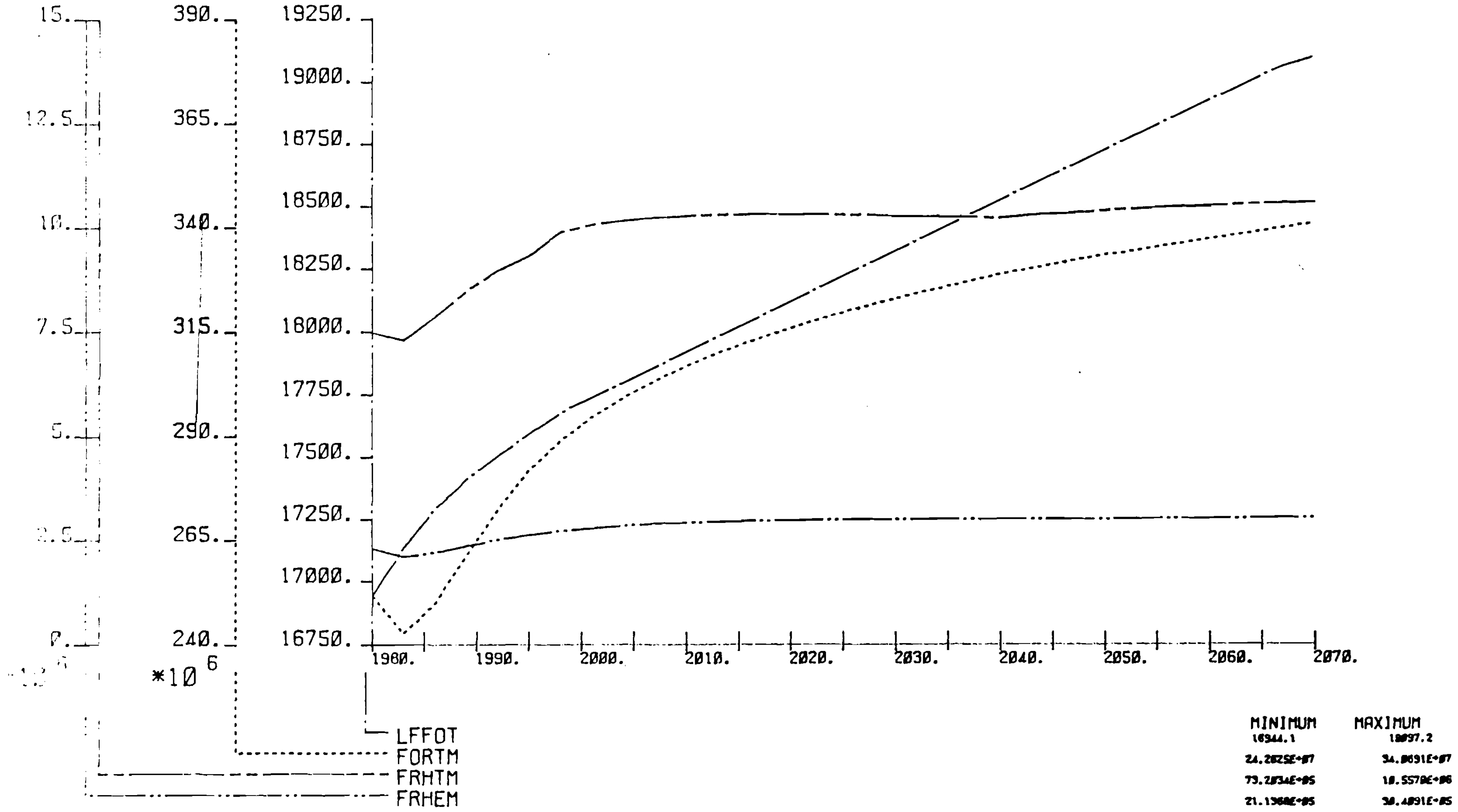
3-RD JELENLEGI
ERDESZET



3-RD MODOSITOTT
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