Teacher Demand Model for Basic Education

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Abstract

For many years the Portuguese Ministry of Education and Science (MEC) has been accused of using temporary contracts instead of permanent ones to satisfy the system's needs for teachers. By the end of 2013 the European Commission demanded the termination of this discriminatory treatment of temporary hired teachers. We developed a system dynamics model of teacher demand to help MEC estimate the teacher needs for the education system, how long will these needs last, and to provide insights to the development of a teacher hiring policy.

We simulated the evolution of teacher needs until 2063 through the use of birth rate predictions from Statistics Portugal (INE). The hiring policies tested were (1) the absence of new hires, (2) hiring teachers to keep the student to teacher ratio constant and (3) hiring based on teaching hours needs.

Our main conclusions were that teachers should be hired using a real assessment of teacher needs, for example, through teaching hours needs; and that the estimated number of teachers needed in a given moment can be hired permanently because these needs will not reduce with time.
Keywords: Teacher Demand, Education, Policy Design, System Dynamics

1. Problem Context

Historically Portugal has always had a very centralized education system, possibly since it is a relatively small country without substantial regional differences. One of the centralized components is a unified teacher hiring process, which is used to guarantee that the best teachers are hired, and only in the amount necessary to satisfy the system's needs for teachers.

In Portugal there are two main types of teachers: board teachers and hired teachers. Board teachers have a "permanent" contract that is very difficult to end and hired teachers only have one-year contracts, that may or may not be renewed depending on whether these are still needed. The logic underlying this is that there are *permanent system needs*, which last for a reasonable amount of time and justify the hiring of a board teacher; and *temporary system needs*, which have a short time duration before they disappear and so can be satisfied by a hired teacher.

For several years, Ministry of Education and Science - Ministério da Educação e Ciência (MEC) has been accused of using temporary hired teachers to satisfy permanent system needs [3]. In the end of 2013 the European Commission demanded that the hired teachers that have already worked in public education for several years would join the board, and Ministry of Education and Science - Ministério da Educação e Ciência (MEC) proposed a semi-automatic hiring process for teachers [7]. Besides these demands the national association of hired teachers (Associação Nacional de Professores Contratados) is also going to file a complaint to the European Commission to know the criteria for the number of vacancies that were opened for new board teachers and about their distribution for the various subjects [8].

As can be seen, an important problem of MEC in the present times is justifying their teacher hiring processes. When this problem was first presented to us by the vice director of Directorate-General for Education and Science Statistics - Direcção-Geral de Estatísticas da Educação e Ciência (DGEEC) the question presented was "What will be the needs for teachers in the coming years?". But even during that first meeting he also stated that all estimations could become completely wrong if new legislations were approved. That any changes in a legislated parameter such as the class size, number of teaching hours required per subject or any other would eliminate the validity of any prediction.

But despite that fact, many countries have been

In an article by [16] in which he discusses what are policy insights he states that "It seems that few things are more desired than an ability to know the future—and few things are more strongly derided than a forecast of that future."

1.1. Literature Review

Similar goals have also been pursued in other countries, and a variety of methods were used to estimate how many teachers were needed, either for recruitment or for training purposes.

In the United Kingdom a planning effort has been made with respect to how many teachers should be trained, starting with a report in 1990 [4]. Two more technical descriptions of the model were published in 1998 [6] and in 2013 [5]. Their demand forecasts were made by using student to teacher ratios individualized for the different subjects. Early retirements rates were also estimated by age, gender and school level (primary or secondary) through the use of time series.

In the USA predictions regarding the number of elementary and secondary teachers were also made [19]. This model used linear regression to estimate the future evolution of student to teacher ratios which were then used to predict the future demand for teachers.

In Australia several governmental studies have been published from 1998 [17] to 2004 [18] which estimated teacher supply and demand by using student enrollment levels and student to teacher ratios. With it they presented aggregate national data for the total number of teachers, but not for each recruitment group independently. Estimations of the demand generated from retirements were also made for the total teacher workforce.

Portugal had, approximately 20 years ago, one of the most developed planning models for education. LINSSE [14] was an educational planning model developed by Professor Luís Valadares Tavares while he was director of the statistics department of the Portuguese Ministry of Education. This model predicted the number of students in each grade, the number of classes, number of teachers and number of classrooms required.

1.2. Adapting the Research Question

All the previously mentioned models aimed at obtaining predictions for certain variables. Based on these predictions decision-makers will plan accordingly and develop policies which best fit their goals. But should predictions really be the goals of modeling?

In a paper by [2] he discusses why this "naive planning" fails. He states that forecasts fail not only because of unpredictable events, which were not considered in the plan, but also because we make predictions wrong by responding to them. If there are predictions that unemployment will rise governments will act to prevent it (successfully or not) and invalidate the prediction itself.

During the first meeting with the direction of Directorate-General for Education and Science Statistics - Direcção-Geral de Estatísticas da Educação e Ciência (DGEEC), one thing they told me was that all of my estimations could become completely wrong if new legislations were approved. That any changes in a system parameter such as the class size, number of teaching hours required or any other would eliminate the validity of any prediction.

To prevent this issue we have decided to adapt our research question to one that had a *robust* answer: "What teacher hiring policy should be applied to minimize the teacher deficit but guarantee that no teachers are hired that later cease to be needed?"

But what is the difference between the two? If policies are based on model predictions then why is this a better research question?

To answer these questions let us define what we consider to be a *policy* and a *decision*. [10] states that "[...] "policy" is a rule that states how day-by-day operating decisions are made. "Decisions" are actions taken at any particular time and result from applying policy rules to particular conditions that prevail at the moment."

As stated here, decisions come from the application of policies (policy rules). For example, a teacher hiring *decision* would state in a *specific moment* how many teachers should be hired of each recruitment group. A teacher hiring *policy* states how many teachers should be hired at *any moment* as a function of the available information at that time.

This is a definition of policy that originates from control theory. In control engineering, no person is responsible for constantly regulating the systems. For example, when a rocket went to the moon, it had sensors to measure whether it was on the right trajectory or not. These measurements were not interpreted by a human that would correct the rocket's trajectory. What control engineers do is to design a *controller* that would automatically decide which corrections are necessary as a function of the available information.

Considering the above definition of policy, this second research question becomes one of *feedback controller design*. None of the traditional econometric models allow these kinds of analysis because to design a feedback controller we need a causal model of the system to estimate its behavior in new situations. This limitation of econometric models is discussed by [20].

To apply control theory in management sciences, other tools are needed, and these applications founded the field of *System Dynamics* which will be the methodology used in this work.

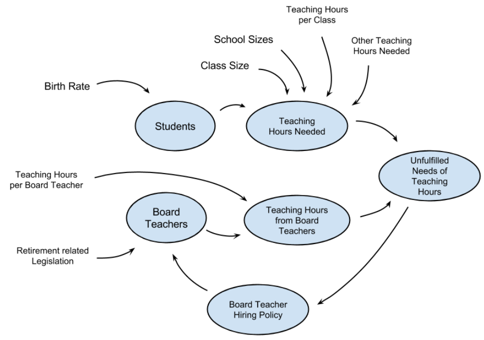

Figure 1: Simple subsystem diagram showing how the different model components relate to one another.

2. System Dynamics

2.1. History

System Dynamics started being developed by Jay Wright Forrester after discussing some irregular hiring patterns with people from General Electric.

He discovered that the undesirable behavior verified was not a consequence of external factors, outside of our control, but of our own hiring policies that were badly designed. A compilation of the results obtained through these dynamical models was then published in *Industrial Dynamics* [9] that founded the field of System Dynamics.

2.2. System Dynamics Applications to Education

The first educational application published was by [1]. In it they discovered that policies aimed at equalizing educational expenditures in city school districts were only effective for one or two years, and had their effect diminished or vanished in the long run (for more than 7 years).

System Dynamics was also applied to model the higher education and professional labor force requirements in Australia [11] and later to study the impact of government incentives on competition between faculties and schools [12]. Many other educational applications of system dynamics are reviewed by [15].

[13] also made a study of the supply and demand of teachers in Australia, in which he reinforced that accurate predictions shouldn't be the goal of modelling.

3. Model Structure

3.1. Subsystem Diagram

To obtain a general view of the model components and their relations we present a simple diagram in figure 1. Blue circles represent model components and the remaining variables outside of the circles are exogenous to the model. All of them except the Birth Rate (number of births per year) are controlled by policy options and their values were either based on historical data or on the legislation itself.

The birth rate is used as input to the *Student Model*, which predicts how many students are enrolled in each grade over time. By using information about the legislated class size and the number of students of the schools we can estimate the number of classes these students will require. Since we know approximately how many teaching hours are needed per class and how many hours are required for the remaining activities performed by teachers we can estimate the *Teaching Hours Needs*.

By knowing how many teachers will be hired and how many will retire (which depend on the hiring policy and the retirement legislation respectively) we predict the number of board teachers over time in the *Board Teacher Model*. Since it is legislated how many teaching hours each board teacher provides we can obtain the *Teaching Hours from Board Teachers*.

The difference between the teaching hours needs and the teaching hours from board teachers will be the unfulfilled teaching hours (or excessive if we have too many teachers). The goal of my work is to test different *Board Teacher Hiring Policies* and observe whether these generate unfulfilled or excessive teachers for several external conditions.

3.2. Student Model

To predict the number of students enrolled in each grade in the public education system we will start by considering the flow of students through stocks as years advance. Once a school year is over students either advance to the next grade or remain in the same but one year older. The model schematics is displayed in figure 2.

This equation states that the outflow in a given time t is the sum of the inflows delayed by one year multiplied by the a fraction - the pass (or fail) fraction. The general equations are:

The student flow entering the first grade will be determined by a sequence of stocks depicting a child's aging from birth to their 6th birthday. The model schematics is displayed in figure 3.

The outflows are now given by the inflow delayed by one year ($outflow(t) = inflow(t-1)$).

The birth rate is an exogenous variable imposed using the data from Statistics Portugal (Instituto Nacional de Estatística - INE).

Since the purpose of the model is to estimate the teacher hiring needs for the public education system we need to restrict the student population to the ones that enroll in it. We considered that the student inflow into the public education system only happened in the first grade (no one transfered between education systems) and that the fraction of students enrolling in public education was constant for the duration of the simulation and equal to its value at the start of the simulation.

This model has the following assumptions:

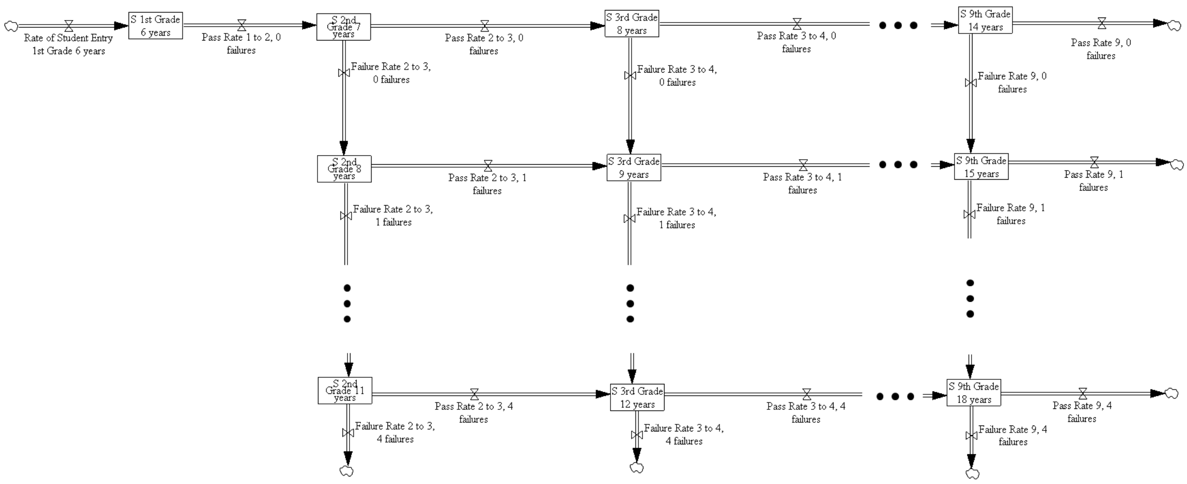

Figure 2: Stock and flow diagram reflecting the student flow through the grades.

$$
\begin{cases}
\text{Pass Flow } i \text{ to } i+1 \text{ with j failures}(t) = \text{Pass Fraction } i \text{ to } i+1 \\
\quad * \left[\text{Pass Flow } i-1 \text{ to } i \text{ with j failures}(t-1) + \text{Failure Flow } i \text{ to } i+1 \text{ with j-1 failures}(t-1)\right] \\
\text{Failure Flow } i \text{ to } i+1 \text{ with j failures}(t) = (1 - \text{Pass Fraction } i \text{ to } i+1) \\
\quad * \left[\text{Pass Flow } i-1 \text{ to } i \text{ with j failures}(t-1) + \text{Failure Flow } i \text{ to } i+1 \text{ with j-1 failures}(t-1)\right]
\end{cases}
\tag{1}
$$

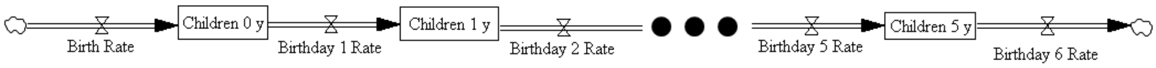

Figure 3: Stocks and flows representing the aging of children until their 6th birthday.

- Constant fail rates
- Absence of failures in first grade
- Absence of dropouts
- Fail rates independent of the previous number of failures
- Absence of deaths, immigration or emigration
- All students that enter first grade are 6 years old
- Absence of students transferring between education systems (ex: public to private)
- Constant fraction of students entering each education system
- After 5 failures through the 9 grades students abandon the system

After analysing the historical data kept only the following assumptions:

- Constant fail rates
- Absence of deaths, immigration or emigration
- All students that enter first grade are 6 years old
- Absence of students transferring between education systems (ex: public to private)
- Constant fraction of students entering each education system
- After 5 failures through the 9 grades students abandon the system

The final results are displayed in figure 4.

3.3. Teaching Hours Needs

After having the student enrollment forecasts we can estimate the needs for teachers. Through this work we will consider needs for teachers as needs for teaching hours. The teaching hours considered will be the hours of actual classes and all other hours equivalent to them (such as providing support to students). Activities that allow teachers to reduce the number of hours they need to teach will also be

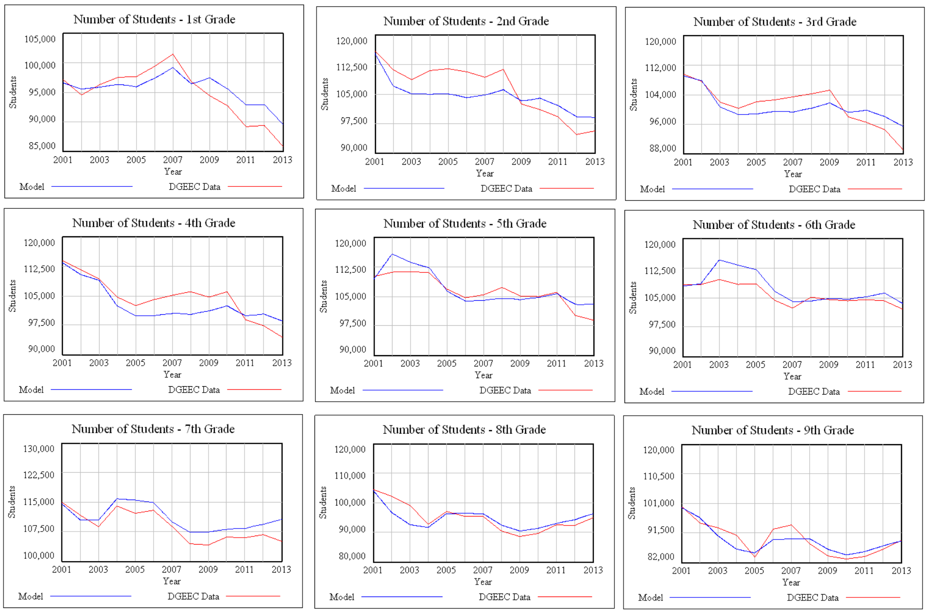

Figure 4: Model results (blue) compared with the measured data (red) for the number of students in each grade in the public education system. This model considers the historical reduction of fail rates and their dependency with age, failures for first grade students and dropout rates.

considered as teaching hours needs. This includes all reductions to the teaching hours of teachers excluding age related reductions, which are considered as a reduction in the number of hours board teachers provide.

3.3.1 Teaching Hours for Lessons - Regular Education

To know the teaching hours that are needed for (regular eduction) lessons we will use the number of classes. For that we have to develop an estimator for the number of classes of students in a given grade as a function of the number of students in that grade (determined in the previous section).

A simple estimator would be a division for the class size that is stated in the law. This was also the estimator used in the LINSSE model developed by GEP [14].

But this estimator assumes, implicitly, that the extra students from all schools that didn't fill a class could be merged to create classes with students from multiple schools. Since each school organizes its students independently this assumption was not valid and can be the cause of the observed deviations.

To account for that effect we developed an estimator in which each school has to have an integer number number of classes that contain all of its students.

This estimator will use the student distribution function through schools of different sizes (size being the number of students per school).

The variable names to be used in the equations are displayed in table 1.

The estimator calculates for each school size how many classes are needed. This number is rounded up and multiplied by the number of schools with that size. The total number of classes is obtained by summing these results for all school sizes:

$$N_C = \sum_{N_{S/Sc}} ceil\left(\frac{N_{S/Sc}}{c_s}\right) N_{Sc}(N_{S/Sc}) \qquad (2)$$

The number of schools with $N_{S/Sc}$ students per school can be obtained by dividing the number of students in schools with a given size by the number of schools with that size:

$$N_{Sc}(N_{S/Sc}) = \frac{N_S(N_{S/S})}{N_{S/Sc}} \qquad (3)$$

Combining the above equations we obtain:

$$N_C = \sum_{N_{S/Sc}} ceil\left(\frac{N_{S/Sc}}{c_s}\right) \frac{N_S(N_{S/S})}{N_{S/Sc}} \qquad (4)$$

We will now make a change of variables so that the estimator is explicitly dependent on the total number of students N_S. For this purpose we will use the following variables:

N_C	Number of Classes
$N_{S/Sc}$	Number of Students per School
$N_S(N_{S/S})$	Number of students in schools with $N_{S/Sc}$ students per school
$N_{Sc}(N_{S/Sc})$	Number of schools with $N_{S/Sc}$ students per school
c_s	Number of students per class

Table 1: Variable names used in the equations.

$$\begin{cases} z = \frac{N_{S/S}}{N_S} \\ f(z) = \frac{N_S(N_{S/S})}{N_S} \end{cases} \tag{5}$$

The variable z represents the fraction of the total student population served by a school of a given size and the function $f(z)$ represents the probability distribution function of students. By applying this change of variables to equation 4 we obtain:

$$\begin{aligned} N_C = \sum_z ceil\left(\frac{z\,N_S}{c_s}\right)\frac{f(z)\,N_S}{z\,N_S} \Leftrightarrow \\ N_C = \sum_z ceil\left(\frac{z\,N_S}{c_s}\right)\frac{f(z)}{z} \end{aligned} \tag{6}$$

To know the number of teaching hours required for lessons of each subject we can now multiply the number of classes by the teaching hours per subject defined in Decreto-Lei n.º 139/2012 de 5 de Julho.

3.3.2 Other Needs for Teaching Hours

To understand the remaining needs for teaching hours we used data that discriminated in which types of activities these were used, which was only available in 2013/2014. In this data we ignored teachers that were marked as being Senior Technician with Teacher Contract (Técnico Superior com Contrato de Docente) and the ones that had specific situations stated (such as waiting for retirement, maternity leave, etc.).

In this data we noticed that there were substantial differences in the amount of reduction to teaching hours that the different recruitment groups receive. These can be caused by an excessive amount of teachers of some groups that since they belong to the board the school principals have to assign them schedules. For example, we noticed that the group 240, that recently had its need for teachers reduced (there used to be two teachers in a classroom and now it's just one) has a substantially larger fraction of reductions than the 350 Spanish group, that has only recently been getting more students.

For our planning to be fair to the different recruitment groups we should consider that all have equal right to the reductions in teaching hours. After discussing this matter with the DGEEC direction we came to the conclusion that a 5 year transition period should be used after the hiring of teachers started in which the reductions provided to each recruitment group would linearly change from the present one for each teaching specialty to the average one for all.

3.4. Teaching Hours from Board Teachers

Since we have already obtained the teaching hours needs we will now estimate the teaching hours offered by board teachers. The difference between the two will represent the unfulfilled needs of teaching hours (or excessive ones).

We started by developing a model to simulate the aging and retirement of board teachers. Since the teacher data was only individualized from 2007/2008 to 2012/2013 then these will be the years used to test and calibrate the model.

The simplest model that describes the system is a sequence of stocks that aggregate teachers by age groups. We decided to create groups of 5 years because to plan how many teachers are needed we don't need information about yearly fluctuations, only about the general behavior for which 5 year groups are adequate. The model schematics is displayed in figure 5.

The teaching hours offered by board teachers are then obtained by:

4. Policy Analysis

Since we now have a model of our system that produces reasonable results we can use it to design policies. The policy to be designed is a hiring policy for teachers in basic education.

4.1. Policies to be Tested

In this section we present the modeling of two different board teacher hiring policies. In the following section these are applied in the model so we can evaluate their results.

4.1.1 Student to Teacher Ratios

The number of teachers that need to be hired (or fired) at time t to maintain the *Student to Teacher Ratio* is then easily obtained through algebraic operations. In the model implementation of this policy we considered that we would only hire teachers yearly. We can also choose to hire just a fraction of the *Teacher Hiring Needs* each year, and this fraction will be called *Hiring Needs Fraction*.

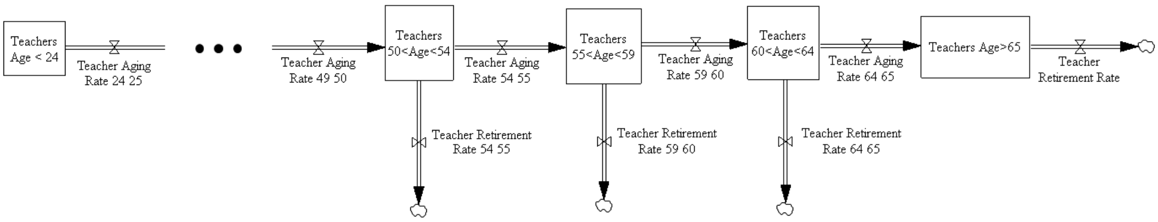

Figure 5: Stock and flow diagram that models the aging and retirement (early or not) of board teachers.

$$\text{Teaching Hours from Board Teachers} = \sum_{\text{Age Groups}} \text{Number of Teachers in Age Group} * \text{Number of Lecture Hours per Teacher in Age Group} \quad (7)$$

4.1.2 Teaching Hours

To recruit teachers based on teaching hours needs we implemented the following hiring policy. Each year we calculate the difference between the teaching hours needs and the teaching hours from board teachers. We then divide this value by the teaching hours per board teacher (assuming that the newly hired teachers still have no reduction in lecture hours) to obtain the teacher hiring needs. The number of teachers to hire is a fraction (*Hiring Needs Fraction*) of the needs just as previously stated.

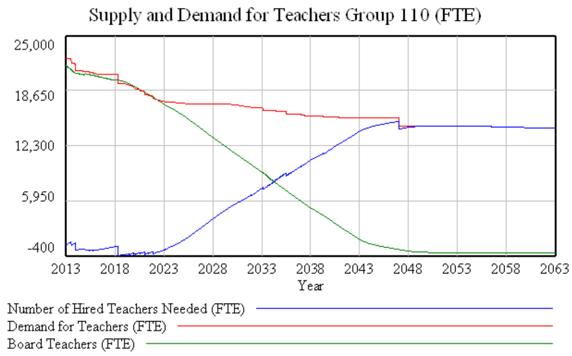

Figure 6: Model results for the supply and demand of teachers when no teachers are hired in the base scenario for group 110.

4.2. Student to Teacher Ratios vs Teaching Hours In this section we will compare the two hiring policies defined previously: student to teacher ratios and teaching hours needs. For that we will consider the base scenario with the parameters shown in table 2.

Without any changes in legislation we expect these parameters to remain constant for the duration of the simulation. We decided to run the simulation for 50 years, from 2013 to 2063, using the birth rate projections to 2060 from Statistics Portugal - Instituto Nacional de Estatística (INE). In the projection model 3 scenarios were presented, a pessimist, a central and an optimist scenario. We always consider the central one unless when explicitly stated. The simulation results in the absence of new hired teachers for group 110 are displayed in figure 6.

As we can see the needs for teachers tend to rise, as expected, if no more teachers are hired.

For group 110 there are only two occasions in which these are reduced: one slightly after 2018 and another before 2048. These large decreases are generated by the estimator for the number of classes since it groups schools by sizes. Large perturbations arise when a large number of schools reduce one class at the same time.

We now simulated the application of the two policies previously presented. The obtained results are displayed in figure 7. All board teachers (excluding the ones of the extraordinary hiring) were hired for the age group of 25 to 29, with ages 26, 27 and 28 all in the same proportion.

As we can see the policy of student to teacher ratios tends to generate larger deviations from the ideal number of hired teachers (zero).

For group 110 both policies generate an excessive amount of teachers until around 2025, but this excess is substantially increased by hiring based on student to teacher ratios. This occurs because the ratios ignore changes in class size which lead to an overestimation the needs for teachers.

We then conclude that hiring based on student to teacher ratios is a more robust policy alternative and so it will be the only one considered in the remaining analysis.

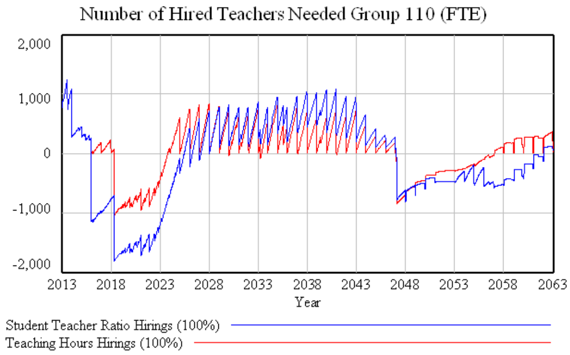

Figure 7: Model results for the expected number of hired teachers needed as a result of the different policy alternatives in the base scenario for group 110.

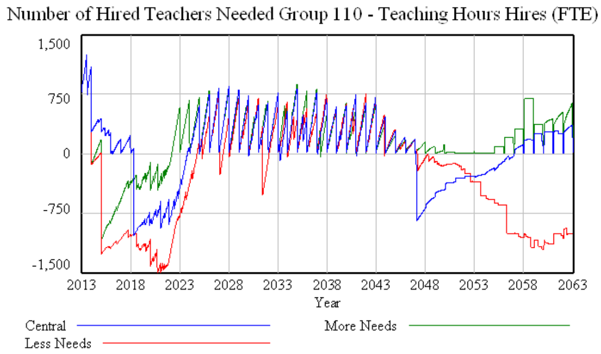

Figure 9: Model results for the expected number of hired teachers needed for group 110 in different scenarios when 100% of the teaching hours needs are hired.

4.3. Scenario Alternatives

To evaluate the uncertainty in the number of teachers needed and hired for the selected policy we decided to create 3 scenarios to contemplate the uncertainty in model parameters that will intersect with the 3 scenarios from INE regarding the birth rates. The parameters that define the three scenarios are shown in table 2.

The obtained results when no teachers are hired are displayed in figure 8.

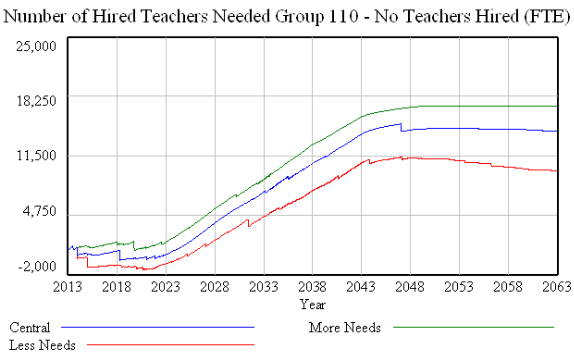

Figure 8: Model results for the expected number of hired teachers needed for group 110 in different scenarios when no teachers are hired.

As we can see, predictions always have a substantial amount of uncertainty associated with them, as stated in the introduction. Therefore, it is more robust to design a policy rule, to be applied every year, and then test that rule under different scenarios. The chosen policy was to hire 100% of all needs (measured in teaching hours) that exist each year. The obtained results for the three scenarios are displayed in figure 9.

As we can verify, a policy rule can provide consistent results for all scenarios, and is therefore a much more robust way to develop policies than to base them in exact predictions.

The last variable that was considered relevant was the number of teachers that were hired for the board in each year. These results are displayed in figure 10.

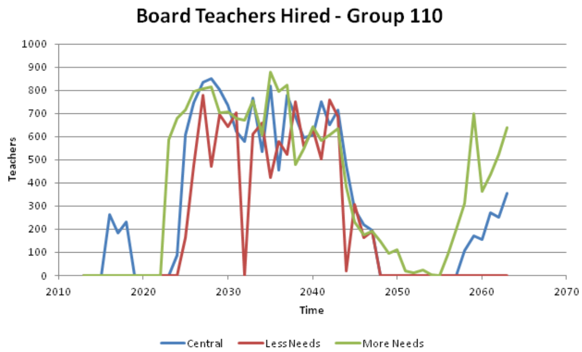

Figure 10: Model results for the board teachers hired of group 110 in different scenarios when 100% of the teaching hours needs are hired.

As we can see, for group 110 the recruitment of new teachers only starts after 2020, and from 2025 to 2045 a large amount of new board teachers are hired each year. A substantial amount of new hirings is later done starting before 2060 for the central and more needs scenarios.

The causes for this oscillations are the number of teachers in each age group - when more teachers are retiring more teachers need to be hired.

5. Discussion

Since this was a work directed at designing policies we will consider that its conclusions should be *policy insights*. The question of what is a policy insight was addressed by [16], in which he states that "[...] policy insights are qualitative statements about modes of behavior, appropriate performance

	Less Needs		Central		More Needs	
	Before 2014	After 2014	Before 2014	After 2014	Before 2014	After 2014
c_s 1st cycle	22	24	22	23	22	22
c_s 2nd cycle	24	26	24	25	24	24
c_s 3rd cycle	26	26	26	26	26	26
ERF 55 59 group 110	0.5	0	0.5	0	0.5	0
ERF 60 64 group 110	0.67	0	0.67	0.1675	0.67	0.335
ERF 55 59 group 230	0.15	0	0.15	0	0.15	0
ERF 60 64 group 230	0.6	0	0.6	0.15	0.6	0.3
Birth Rate	INE Pessimist		INE Central		INE Optimist	

Table 2: Parameters that define the three scenarios that contemplate the model's uncertainty in parameters. ERF stands for Early Retirement Fraction.

indicators and leverage points."

We will then analyze this work's contributions in the three areas.

5.1. Modes of Behavior

We have discovered that the needs for teachers will tend to grow with time in the absence of new hirings. This is an important fact because there have been some doubts whether the present needs for teachers will be permanent or if they'll disappear due to the reduction in the birth rate. The present work has shown that the nation as a whole will have it's needs for teachers always rising in the absence of hirings. Teachers can then be permanently hired until the needs for teaching hours are fulfilled.

5.2. Performance Indicators

As shown by the literature review, the most frequent indicator of teacher needs used has been the student to teacher ratio. The only study that used teaching hours was the LINSSE model [14] but it used a biased estimator for the number of classes and did not consider other activities that teachers also have to perform.

One of the contributions of this work was the development of a more accurate indicator of needs for teachers, also based on teaching hours needs. The main components of this indicator are the estimator for the number of classes, which was proven accurate in the comparisons with the existing data, and the distribution of the remaining teaching hours needs for the recruitment groups.

5.3. Leverage Points

Leverage points are the parts of a system in which small modifications create large changes in behavior. In our system we consider this to be the only feedback loop in our system - the hiring policy. As stated before, any hiring based on the previous state of the system, such as student to teacher ratios, will maintain unjustified differences in the number of teachers of each recruitment group. The number of teachers we aim to have with our hiring policy should always come from an assessment of the needs of those teachers, and not from whether these were needed in the past. One possible way to estimate these needs is to use the developed indicator of teaching hours needs.

5.4. Conclusion

The main "policy insight" or "policy suggestion" that was achieved through this work was to plan using a real assessment of teacher needs, for example, through teaching hours needs. For the Portuguese present situation we suggest recruitment based on teaching hours needs without the application of a hiring "buffer". This means that the estimated number of teachers needed in a given moment can be entirely hired because these needs will not reduce with time.

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