Project LELEC2520

A. Introduction

The project concerns the 34 nodes CIGRE system illustrated in the following figure. This net is modelled with the python `pandapower` module (www.pandapower.readthedocs.io).

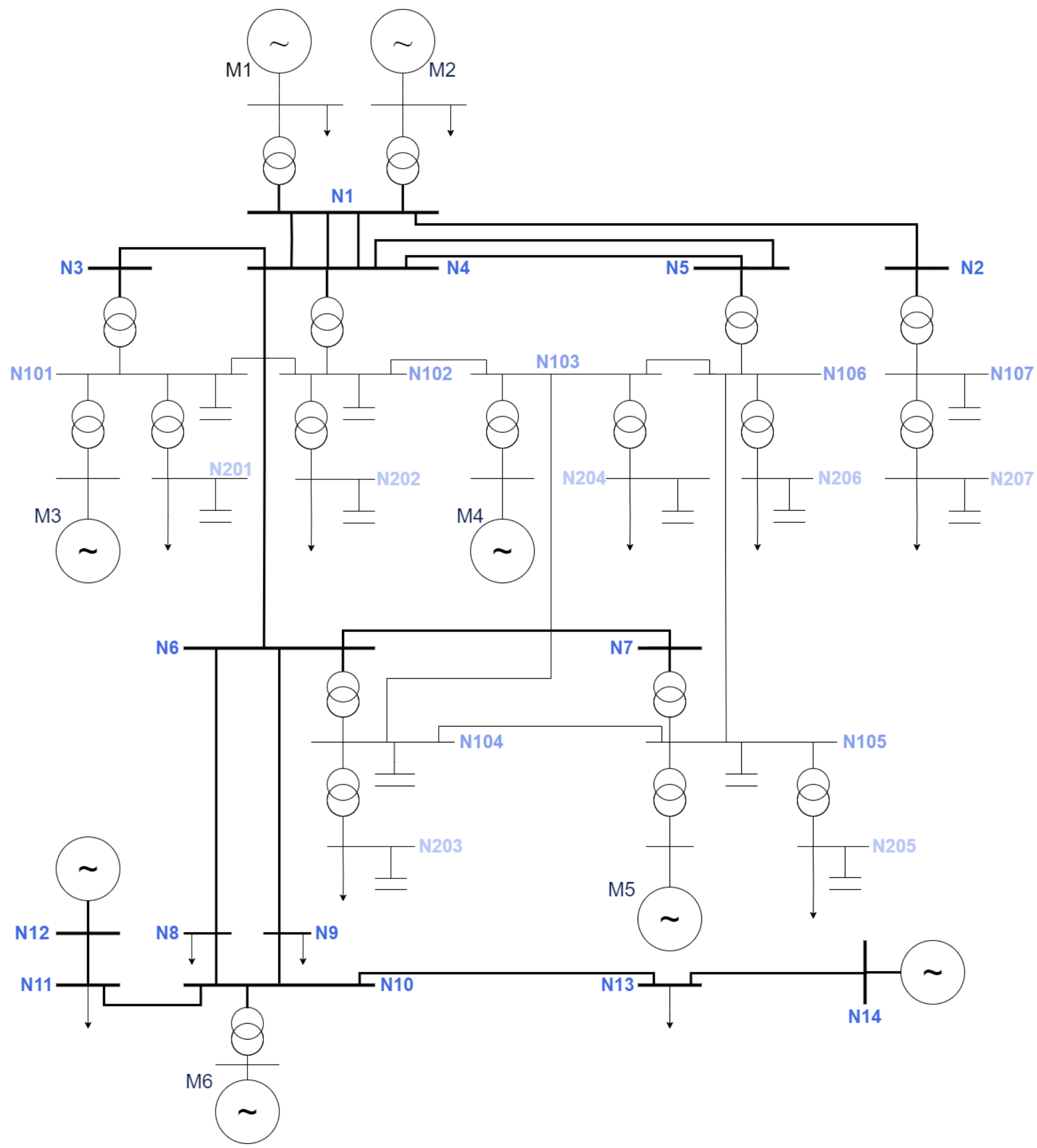

Figure 1: 34-node Cigre System redrawn by Liam Dauchat and Mathieu De Jonge in 2023.

B. Global Organization

– **Groups:** This work has to be performed by groups of **3** people. Please register your group on Moodle. Each group will have to analyse different elements of the CIGRE system. Refer to Fig. 4 and 5 (see Appendix) to know which elements are assigned to your group.

- **Codes:** The file `cigre_net.py` in the folder Fixed_script should not be modified. It is duplicated 6 times (for each question) in the Student_script folder and these copies can be modified.
- **Submission:** Submit your report (.pdf), and a .zip file with all your python codes (.py). With the following names:
  `Project_LELEC2520_Report_GroupXX.pdf` and `Project_LELEC2520_Codes_GroupXX.zip`.
  Your report should contain your answers to the questions asked in this project.
- **Advised Planning:** You will not be able to work on every part of the project when you receive the project statement at the beginning of the year. Indeed, each part of the project corresponds to specific parts of the courses. Organise yourselves accordingly.
  - Part 1: Basics.
  - Part 2: Transformer theory.
  - Part 3: Power Sources & Load Flow theory.
  - Part 4: Load Flow theory can help.
  - Part 5: Load Frequency Control from Power System Control theory.
  - Part 6: Power Flow theory can help.

C. Additional Data of Generators

The generators characteristics are given in Fig. 2.

Machine	X (pu, machine base)	X" (pu, machine base)	S_N (MVA)	P_N (MW)	σ
M1	2.2	0.25	1000	850	0.04
M2	2.2	0.25	1000	850	0.04
M3	2.2	0.25	450	405	∞
M4	2.2	0.25	300	270	∞
M5	2.2	0.25	450	405	∞
M6	2.2	0.25	1000	850	0.04
N12	-	-	-	5000	0.04
N14	-	-	-	2450	0.04

Figure 2: Additional data of Generators of the 34-node Cigre Test System - $X = X_d = X_q$ is the synchronous reactance - $X'' = X''_d = X''_q$ is the subtransient reactance - S_n is the rated apparent power - P_n is the rated turbine power - σ is the droop of the speed controller.

- N12 and N14 are equivalent machines representing external grids. In load flow calculations, it is supposed that they can supply an unlimited reactive power. They also contribute to the frequency primary control as indicated in Figure 2.
- The capability curves of machines M1 to M6 are such that, at $V = 1\ p.u.$ (rated conditions), the stator, rotor and turbine limits reach the same operating point.
- M6 is chosen as slack node.
- All loads are supposed to be insensitive to the frequency.
- `pandapower` module does not consider primary frequency control. Any active power unbalance is compensated by a power injection at the slack bus. However, for Question 5, some questions will be related to primary frequency control and will not have to be done with `pandapower`.

D. Preventative Tips for writing the report

- When adding Figures or Tables in your report, they should be introduced in your text - if not referenced, they will not be taken into account, and explained - it not the reader's role to guess the messages of a Figure or a Table.
- Whenever you modify/add a line code for a question, add it to your answers. Example: if I change the value of load M1, I add the following code line in the report:

```
LOAD_M1 = pp.create_load(net, bus=M1, p_mw=100.0, q_mvar=40.0, name="M1",
in_service=True, max_p_mw=50., min_p_mw=50.0, max_q_mvar=40., min_q_mvar=40.,
controllable = True)
```

E. Questions

- The Cigre Test System (Fig. 1) is modeled in the `cigre_net.py` python file. Read it carefully before starting your work in order to understand the methodology used by `pandapower`.
- In the `cigre_net.py` script, controllers are implemented to control the voltage. Make sure you activate these controllers when you launch your power flow. They are only taken into account when introducing the correct argument in the `runpp()` command. They should stay activated for Part 2,3,4, and 5.

Part 1: Check of load flow results

From voltages computed by the program and by calculation without using the program, compute (with details):

Question 1.1: the active and reactive power transits ('from' side) in the line Na-Nb (see Fig. 4 column 2).

Question 1.2: the balance of power (active and reactive) of this line Na-Nb (see Fig. 4 column 2).

Question 1.3: the surge impedance (magnitude and phase) loading of this line (see Fig. 4 column 2).

Question 1.4: the current at one end of the line Na-Nb ('from' side) and compare it to the maximum current corresponding to the rated power of the line.

Question 1.5: the active and reactive power transits ('high-voltage' side) in the transformer Nc-Nd (see Fig. 4 column 3).

Question 1.6: the balance of power (active and reactive) of this transformer Nc-Nd (see Fig. 4 column 3).

Question 1.7: the currents on primary and secondary sides of the transformer and compare them to the maximum currents corresponding to the rated power of the transformer Nc-Nd (see Fig. 4 column 3). Deduce the loading factor of the transformer.

Question 1.8: the power factor of the load connected on the node Ne (see Fig. 4 column 4), with and without the shunt compensation.

NOTE : When it is possible, compare the obtained values with the ones given by the program. Do not hesitate to add some lines in the code to gather all the informations you need !

Part 2: Transformers settings

Question 2.1: Knowing that each 380/150 kV transformer is star-star connected, change transformer Nf-Ng (see Fig. 4 column 5) to a star-delta (Yd11) connection and launch a power flow with the correct `pandapower` command. Is it an acceptable configuration? If not, what is the theoretical concept that explains this phenomenon?

Line code: Insert the modified line code in your answer.
Note: Do not touch the ratio value (taps). In real situations, the taps of star-delta transformers are adapted automatically and thus the voltage remains the same.

Question 2.2: Observe and analyse the effect of a modification of the transformation ratio modulus of transformer Nh-Ni (see Fig. 4 column 6) on the power flows. Consider a variation of at the most 10% around its initial value. What electrical quantity is the most impacted by this ratio modulus variation ? Demonstrate it theoretically.

Line code: Insert the modified line code in your answer.
Note: To change the ratio value, look carefully at the taps. What are taps?

Question 2.3: Observe and analyse the effect of a modification of the transformation ratio phase angle of the same transformer on the power flows. Consider a variation of at the most 10° around its initial value. What electrical quantity is the most impacted by this ratio phase angle ? Demonstrate it theoretically.

Line code: Insert the modified line code in your answer.

Question 2.4: Perform the same operations (Q2.2 and Q2.3) on transformer Nj-Nk (see Fig. 4 column 7). Compare the effects with those of the previous case and justify.

Part 3: Voltage control and shunt compensation

Note: If not specified into the `runpp()` command, the reactive power limits are not taken into account. For Part 3, activate the correct argument in `runpp()` to take into account the reactive power limits into the power flow.

Question 3.1: Calculate by hand the maximum reactive power that can be produced by generator Mx (see Fig. 5 column 2) due to physical limits and compare it to the value provided in `pandapower`.

Question 3.2: Vary the voltage set point of generator Mm (see Fig. 5 column 3) gradually upwards and downwards. What do you observe on this generator and on the others?

Line code: Insert the modified line code in your answer.

Question 3.3: Deactivate all the shunt capacitors <u>connected at 150kV</u> busbars and analyse the effect on the balance of active and reactive power of the system. Calculate the overall power factor of the system and discuss how it is impacted by the removal of shunt capacitors.

Line code: Insert the modified line code in your answer.
Note: The power factor should be independent of the generators power production. It characterises the set-up of a grid. Considering that all loads are non-flexible, it should be possible to calculate it without launching a power flow.

Part 4: Power transmission and losses

Situation: It is supposed that in order to cover a load increase of 100MW/50MVAr at the node Nn (see Fig. 5 column 4), the involved distribution grid operator signs a contract with the producer owning generator No (see Fig. 5 column 5). According to this contract, No will have to supply the active load increase as well as the whole additional active losses caused by this power transfer.

Reminder: Remove the reactive power limits of the generators (Part 3) but keep the voltage controllers inside the system.

Question 4.1: Determine, with an error of at the most 0.5MW, the active power that No has to produce. Explain your methodology to find this additional power production.

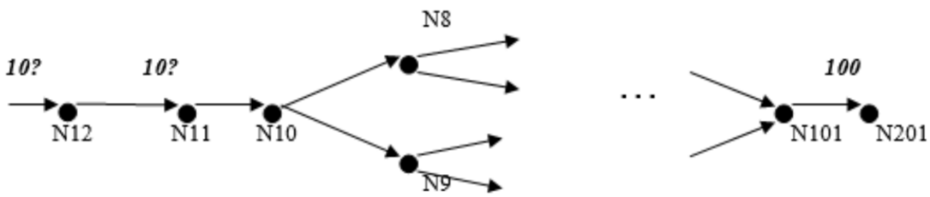

Figure 3: Example of branch power flow for Question 4.2.

Question 4.2: Determine how this additional active power flows through the grid. For that purpose, make a graph as drawn in Fig. 3, in which each branch represents a branch of the grid followed by the power and each number represents the power arriving to the next node through this branch.

Part 5: Incidents simulation and security analysis

Situation: In this fifth part, the loss of elements in the system is simulated. As stated previously, some generators have a droop coefficient σ and thus participate to the Frequency Containment Reserve (FCR). However, `pandapower` does not offer this functionality and compensates with the slack node. FCR analysis cannot be simulated with `pandapower` and has to be analysed theoretically.
Note: Keep the reactive power limits of the generators and the controllers inside the system.

Question 5.1: Assume that the generator My (see Fig. 5 column 6) is lost.

(a) FCR analysis: Calculate the frequency deviation. Justify.

(b) Load Flow analysis with `pandapower`: If the load flow computation converges, explain the impact and give the power system state schematic (i.e. line loading, bus voltages). If not, explain why.

Question 5.2: Assume that the generator Mz (see Fig. 5 column 7) is lost (with My connected to the grid).

(a) FCR analysis: Calculate the frequency deviation. Justify.

(b) Load Flow analysis with `pandapower`: If the load flow computation converges, explain the impact and give the power system state schematic (i.e. line loading, bus voltages). If not, explain why.

Question 5.3: Assume that line Nr-Nt (see Fig. 5 column 8) is lost (with My and Mz connected to the grid).

(a) FCR analysis: Calculate the frequency deviation. Justify.

(b) Load Flow analysis with `pandapower`: Give the power system state schematic (i.e. line loading, bus voltages). Explain with relevant values the consequence of loosing Nr-Nt.

Question 5.4: Assume that transformer Ns-Nq (see Fig. 5 column 9) is lost (with My, Mz and Nr-Nt connected to the grid).

(a) FCR analysis: Calculate the frequency deviation. Justify.

(b) Load Flow analysis with `pandapower`: Give the power system state schematic (i.e. line loading, bus voltages). Explain with relevant values the consequence of loosing Ns-Nq.

Part 6: Optimal Power Flow

Situation: Until here, we have performed load flows where generators were considered as PV nodes, i.e. with a fixed operating power P and a fixed operating voltage V. Those values were given as inputs when creating the generator in `pandapower`. However, there might be some situations where the grid operator wants to minimize the power system's cost. To do so, an optimization problem is developed, i.e. the minimization of a cost function subject to operating constraints (e.g. maximum line loadings, transformer loadings, and power flow). This is called an optimal power flow.

$$\textbf{Minimize } CostFunction$$
$$\text{subject to } \begin{cases} Constraint_1 \\ Constraint_2 \\ ... \\ Constraint_n \end{cases}$$

Note: This part is completely independent of the previous ones (i.e. you have to drop the controllers and the reactive power limits).

Part 6.1: All generators with similar cost functions

Let's run an optimal power flow rather than a power flow with all generators having the same marginal cost in script `part6min.py`.

> **Question 6.1.1:** Before implementing it in your code, describe with your own words which generators will produce more or less than others. What quantity is actually optimised if they all have the same cost function? Justify your answers.

> **Question 6.1.2:** Use the function `create_poly_cost()` from `pandapower` to create the cost functions of the generators and launch the optimal power flow with the correct `pandapower` command. Set the cost to 60 €/MWh for each generator. Give the power production of each generator. Do the results seem relevant with your insights from previous question (Q6.1.1)?

> **Question 6.1.3:** Explain with your own words the differences between a Power Flow and an Optimal Power Flow.

> **Question 6.1.4:** Compare the production of the generators in both cases (Power Flow vs. Optimal Power Flow). How are they different ? Explain.

Part 6.2: Flexible load

Situation The load at Node Nx (see Fig. 5 column 10) is an industrial process making steel and which initially requires a power of 360 MW. Let's modify this load, and assume it can draw up to 540

MW and is flexible, i.e. the system decides what quantity is being supplied to the load [0-180 MW]. If it draws more power, it produces more steel, and thus perceives a bigger revenue. This industry is ready to pay more in order to receive the maximum power possible.

> **Question 6.2.1:** How can you convert this load into a flexible load? What can be done to maximise its consumption? Explain.

> **Question 6.2.2:** Implement your method in the `part6flex.py` script. Does the power consumption of Node Nx reach the upper limit (540 MW)? Explain.
>
> **Note:** Keep the cost functions of the generators introduced in the previous question.

Part 6.3: All generators with different cost functions

Situation: Change the cost functions of each generators in the `part6gens.py` script. Hereunder, f_{Gi} stands for the cost function [€ e.g.] of generator i and x_i for the power produced [MW] by generator i.

$$
\begin{aligned}
f_{G1}(x_1) &= 0.001(x_1 - 350)^2 + 20 \\
f_{G2}(x_2) &= 4.622 \cdot 10^{-4}(x_2 - 375)^2 + 25 \\
f_{G3}(x_3) &= 5.625 \cdot 10^{-4}(x_3 - 400)^2 + 30 \\
f_{G4}(x_4) &= 9.876 \cdot 10^{-5}(x_4 - 450)^2 + 40 \\
f_{G5}(x_5) &= 2.8 \cdot 10^{-4}(x_5 - 500)^2 + 10 \\
f_{G6}(x_6) &= 2.81 \cdot 10^{-4}(x_6 - 550)^2 + 5 \\
f_{G7}(x_7) &= 3.04 \cdot 10^{-5}(x_7 - 575)^2 + 15 \\
f_{G8}(x_8) &= 5.555 \cdot 10^{-4}(x_8 - 600)^2 + 35
\end{aligned}
$$

> **Question 6.3.1:** Run an optimal power flow with the modified cost functions of the generators. What is total cost of the system? Do the results (power produced e.g.) seem consistent ?

> **Question 6.3.2:** Find a better (not the best one, just a better one) agency of the cost functions in order to reduce the cost of production. Explain your methodology. What is the new total cost of the system?

F. Appendix

Group	Line (Q 1.1 to 1.4)	Transformer (Q 1.5 to 1.7)	Node (Q 1.8)	Transformer (Q 2.1)	Transformer (Q 2.2 to 2.3)	Transformer (Q 2.4)
Gr 1	N1-N4 (1)	N4-N102	N202	N3-N101	N5-N106	N2-N107
Gr 2	N6-N9	N7-N105	N206	N7-N105	N6-N104	N2-N107
Gr 3	N6-N7	N3-N101	N201	N4-N102	N3-N101	N2-N107
Gr 4	N6-N4	N5-N106	N204	N5-N106	N7-N105	N2-N107
Gr 5	N6-N7	N7-N105	N202	N3-N101	N5-N106	N2-N107
Gr 6	N6-N8	N6-N104	N207	N6-N104	N4-N102	N2-N107
Gr 7	N4-N5 (1)	N3-N101	N206	N5-N106	N7-N105	N2-N107
Gr 8	N4-N3	N4-N102	N205	N6-N104	N4-N102	N2-N107
Gr 9	N1-N4 (2)	N5-N106	N204	N7-N105	N3-N101	N2-N107
Gr 10	N4-N3	N4-N102	N207	N4-N102	N6-N104	N2-N107
Gr 11	N6-N9	N2-N107	N205	N5-N106	N7-N105	N2-N107
Gr 12	N6-N8	N6-N104	N201	N6-N104	N5-N106	N2-N107
Gr 13	N6-N4	N7-N105	N203	N7-N105	N3-N101	N2-N107
Gr 14	N4-N5 (2)	N2-N107	N203	N4-N102	N6-N104	N2-N107
Gr 15	N1-N4 (3)	N7-N105	N201	N5-N106	N4-N102	N2-N107
Gr 16	N6-N9	N3-N101	N204	N6-N104	N7-N105	N2-N107
Gr 17	N6-N7	N7-N105	N202	N3-N101	N4-N102	N2-N107
Gr 18	N6-N4	N4-N102	N206	N7-N105	N3-N101	N2-N107
Gr 19	N6-N7	N5-N106	N202	N6-N104	N7-N105	N2-N107
Gr 20	N6-N4	N7-N105	N207	N5-N106	N4-N102	N2-N107
Gr 21	N6-N8	N3-N101	N207	N3-N101	N7-N105	N2-N107
Gr 22	N4-N3	N7-N105	N207	N6-N104	N7-N105	N2-N107
Gr 23	N6-N8	N3-N101	N206	N6-N104	N5-N106	N2-N107
Gr 24	N6-N8	N3-N101	N203	N6-N104	N7-N105	N2-N107
Gr 25	N4-N3	N7-N105	N204	N6-N104	N5-N106	N2-N107
Gr 26	N6-N4	N3-N101	N206	N6-N104	N7-N105	N2-N107
Gr 27	N6-N9	N5-N106	N207	N6-N104	N3-N101	N2-N107
Gr 28	N6-N8	N2-N107	N204	N6-N104	N7-N105	N2-N107
Gr 29	N1-N4 (1)	N4-N102	N202	N5-N106	N4-N102	N2-N107
Gr 30	N6-N9	N7-N105	N206	N7-N105	N6-N104	N2-N107
Gr 31	N6-N7	N3-N101	N201	N4-N102	N3-N101	N2-N107
Gr 32	N6-N4	N5-N106	N204	N5-N106	N7-N105	N2-N107
Gr 33	N6-N7	N7-N105	N202	N3-N101	N5-N106	N2-N107
Gr 34	N6-N8	N6-N104	N207	N6-N104	N4-N102	N2-N107
Gr 35	N4-N5 (1)	N3-N101	N206	N5-N106	N7-N105	N2-N107
Gr 36	N4-N3	N4-N102	N205	N6-N104	N4-N102	N2-N107
Gr 37	N1-N4 (2)	N5-N106	N204	N7-N105	N3-N101	N2-N107
Gr 38	N4-N3	N4-N102	N207	N4-N102	N6-N104	N2-N107

Figure 4: Elements of the system to be studied for each question and each group - Part1.

Group	Generator (Q 3.1)	Generator (Q 3.2)	Node (Q 4)	Eq. machine (Q 4)	Generator (Q 5.1)	Generator (Q 5.2)	Line (Q 5.3)	Line (Q 5.4)	Node (Q 6)
Gr 1	M1	M2	N202	N12	M2	M3	N6-N8	N102-N202	N201
Gr 2	M2	M1	N201	N14	M1	M4	N3-N4	N101-N201	N202
Gr 3	M1	M2	N204	N12	M2	M5	N6-N7	N104-N203	N203
Gr 4	M2	M1	N201	N12	M1	M3	N6-N8	N2-N107	N204
Gr 5	M1	M2	N206	N14	M2	M4	N6-N7	N1-N2	N205
Gr 6	M2	M1	N201	N14	M1	M5	N6-N4	N101-N201	N206
Gr 7	M1	M2	N202	N12	M2	M3	N6-N9	N102-N202	N201
Gr 8	M2	M1	N201	N14	M1	M4	N6-N8	N103-N204	N201
Gr 9	M1	M2	N204	N12	M2	M5	N3-N4	N105-N205	N202
Gr 10	M2	M1	N202	N12	M1	M3	N1-N4(1)	N1-N2	N203
Gr 11	M1	M2	N206	N14	M2	M4	N6-N4	N103-N204	N204
Gr 12	M2	M1	N202	N14	M1	M5	N6-N7	N104-N203	N205
Gr 13	M1	M2	N206	N12	M2	M3	N1-N4(2)	N2-N107	N206
Gr 14	M2	M1	N204	N14	M1	M4	N6-N9	N105-N205	N202
Gr 15	M1	M2	N201	N12	M1	M5	N6-N8	N103-N204	N201
Gr 16	M1	M2	N206	N14	M1	M3	N6-N8	N104-N203	N202
Gr 17	M2	M1	N201	N12	M2	M4	N6-N9	N105-N205	N203
Gr 18	M1	M2	N204	N14	M1	M5	N3-N4	N101-N201	N204
Gr 19	M1	M2	N206	N14	M2	M3	N6-N8	N104-N203	N205
Gr 20	M2	M1	N201	N12	M1	M4	N6-N8	N104-N203	N206
Gr 21	M1	M2	N206	N14	M2	M5	N6-N9	N104-N203	N203
Gr 22	M2	M1	N201	N12	M1	M3	N6-N7	N104-N203	N201
Gr 23	M1	M2	N202	N14	M2	M4	N6-N8	N103-N204	N202
Gr 24	M2	M1	N201	N12	M1	M5	N6-N9	N105-N205	N203
Gr 25	M1	M2	N202	N14	M2	M3	N6-N7	N104-N203	N204
Gr 26	M2	M1	N201	N12	M1	M4	N3-N4	N102-N202	N205
Gr 27	M1	M2	N206	N14	M2	M5	N6-N7	N1-N2	N206
Gr 28	M2	M1	N204	N14	M1	M3	N6-N9	N101-N201	N204
Gr 29	M1	M2	N206	N14	M2	M4	N6-N8	N103-N204	N201
Gr 30	M2	M1	N201	N14	M1	M4	N3-N4	N101-N201	N202
Gr 31	M1	M2	N204	N12	M2	M5	N6-N7	N104-N203	N203
Gr 32	M2	M1	N201	N12	M1	M3	N6-N8	N2-N107	N204
Gr 33	M1	M2	N206	N14	M2	M4	N6-N7	N1-N2	N205
Gr 34	M2	M1	N201	N14	M1	M5	N6-N4	N101-N201	N206
Gr 35	M1	M2	N202	N12	M2	M3	N6-N9	N102-N202	N201
Gr 36	M2	M1	N201	N14	M1	M4	N6-N8	N103-N204	N201
Gr 37	M1	M2	N204	N12	M2	M5	N3-N4	N105-N205	N202
Gr 38	M2	M1	N202	N12	M1	M3	N1-N4(1)	N1-N2	N203

Figure 5: Elements of the system to be studied for each question and each group - Part2.