Developing a curriculum modeling approach

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Abstract

Modernization of educational standards calls for appropriate changes in the educational process of a higher educational institution. The main component of the educational process is the curriculum. The development of the curriculum is greatly affected by the university's teaching staff, and as a result, it is a key problem of the educational process management. The paper proposes to formalize the relations among academic disciplines, competences, and teaching staff. The proposed approach to curriculum formation is based on descriptive models of such concepts as "Discipline", "Competence", and "Specialization". Optimization models, developed on the basis of the proposed descriptive models, allowed the evaluated choice of disciplines and teachers providing the maximum competence stated in the main educational programmes, when forming the curriculum. Such solutions can improve the quality of graduates training and their competitiveness on the labour market.

1 Introduction

The education system of the leading universities in the European education area is based on the ESG (European Standards and Guidelines). Standards and Guidelines for Quality Assurance in the European Higher Education Area (ESG) were adopted by the Ministers of Education in 2005.

Revised ESG approved by the Ministerial Conference in Yerevan, Armenia, on 14-15 May 2015 [Standards19] includes a summary list of standards and guidelines for quality assurance in higher education. European quality assurance standards in higher education consist of three parts.

The first part "Standards and guidelines for internal quality assurance" discusses the requirements for educational institutions, provided by the participants of educational relations (students, teachers). The second part "Standards and guidelines for external quality assurance" discusses the procedures of external quality assurance for the effectiveness of the internal quality assurance (e.g. accreditation programmes). The third part "Standards and guidelines for external quality assurance agencies" addresses the requirements for external agencies

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that carry out the procedures of external quality assurance from part 2. All three parts are closely interrelated and form the basis for European quality assurance structures.

ESG applies to all higher educational institutions and quality assurance agencies in Europe, regardless of their structure, function, size and the country of residence. One of the main tasks of European universities is to promote self-realization, disclosure and development of personal potential, creation and assimilation of their freedom and responsibility for life choices.

In Russia, with the adoption of amendments to the Law on Education in 2009, the development of Federal State Educational Standards of Higher Education (SFES HE) started. The transition to the third generation educational standards in Russia is the result of the analysis performed on the European educational standards. The transition to three levels of education (bachelor, master, postgraduate) leads to fundamental changes both in the structure and the content of educational standards.

Since December 2017, FSES 3++ have been introduced, taking into account professional standards. Moreover, the approximate main educational programmes (AMEP), used as guidelines for the discipline heads in higher educational institutions, have been developed. To implement each FSES HE, educational institution should develop a main educational programme (MEP), including a curriculum, a calendar study schedule, educational programmes for subjects, courses, disciplines (modules), other components, as well as assessment and resource materials. An opportunity arises to adjust the educational programme to the student preferences and the requirements of the labour market existing in a certain region.

The main element of the educational process in Europe and Russia is the curriculum, whose development is carried out given many requirements defined in the regulatory documents are met [Standards19] and [Federal-Standards19]. In terms of mathematical modelling, some of these requirements are not clear. As a result, the task of curriculum development is reduced to a class of poorly formalized tasks. All this leads to a variety of ways for curriculum development, the choice of a specific solution depending on subjective factors and, when trying to formalize them, on the applied models and algorithms. Existing investigations on the subject under study include only the formalization of the relationship between disciplines and competences [Fionova16], [Sibikina12], [Viriansky12], [Sedelmaier16], [Perez17], without the relationship between disciplines and teachers.

2 The concept of curriculum development

There are no strict standards for curriculum development in European higher education. Instead, there is a long list of subjects (modules), some of which are compulsory, and the rest the student can choose individually.

Let us highlight the main components in the educational programmes of European universities:

- Compulsory subjects (minimum core);
- Electives;
- Major (special) subjects.

The study of compulsory subjects is aimed at creating the foundation for the desired specialization acquisition. The compulsory subjects are studied for 1 or 2 years, depending on a programme and a student. As for electives, students can choose which they wish to attend. The student is supposed to choose at least three electives, but not more than five. The main purpose of the electives is to help students decide on their future specialization. The electives are taken concurrently with the compulsory subjects. After obtaining fundamental knowledge and skills, as well as getting to know a set of specializations in a particular field, the student proceeds to an in-depth study of the disciplines due to the chosen specialization.

The curriculum in Russia, despite the variability of the approximate curricula in AMEP, is reduced to the following components:

1. Module 1:

   Basic part:

   - compulsory subjects (humanities and special subjects);
   - fundamental special subjects formed by the head of the MEP.

   Variable part:

   - fundamental special subjects formed by the head of the MEP.

- special subjects;

2. Module 2:
   Basic part:
   - compulsory practical training.

   Variable part:
   - additional and special practical training.

3. Module 3:
   Basic part:
   - state Final Certification.

4. Module 4:
   Variable part:
   - electives.

   To formalize curriculum development, the following elements will be introduced:
   - disciplines;
   - competences;
   - teaching staff.

It is impossible to specify directly what competencies are acquired as a result of studying a particular discipline, and there are no formalized procedures to determine the specialization of the teaching staff in curriculum disciplines. The study [Kaneva17] introduces a formalized representation of "Competence" through the tuple, whose elements are a set of descriptors and a set of terms. Therefore, each element introduced to formalize curriculum development can be represented in the descriptor space as such:

$$W = \left\langle S^W, D^W, T^W \right\rangle,$$

where W is the designation of the selected element, S^W is the formulation of the selected element in a natural language, D^W a set of descriptors, T^W is a set of terms.

The algorithm of finding semantic similarity between two elements proposed in [Kaneva17] and [Zykina20] allows us to calculate the degree of interrelation between disciplines and competences through the obtained parameters $k_{ij} \in [0,1]$, which will be referred to as the coefficients of the i-th competence closure with the j-th discipline. The algorithm also allows us to obtain the degree of interrelation between disciplines and teaching staff through the parameters $h^s_{pj} \in [0,1]$ (the coefficient of the p-th teacher specialization in the s-th type of educational activity on the j-th discipline). The introduction of these coefficients allows us to form a set of disciplines for each competence, providing the maximum competence, and to obtain a set of teachers with the maximum specialization for each discipline.

3 Mathematical model "Discipline - competence"

Let us introduce the following notations:

$I^u = \{i^u_1, i^u_2, ..., i^u_{m_u}\}$ – is a set of indices for universal competences.

$I^o = \{i^o_1, i^o_2, ..., i^o_{m_o}\}$ – is a set of indices for general professional competences.

$I^p = \{i^p_1, i^p_2, ..., i^p_{m_p}\}$ – is a set of indices for professional competences.

i – is the number (index) of competence $i = \overline{1,m}, m = m_u + m_o + m_p$.

j – is the number of discipline $j = \overline{1,n}$.

$k_{ij} \in [0,1]$ – is the coefficient of the i-th competence closure with the j-th discipline.

$J^f = \{j^f_1, j^f_2, ..., j^f_{n_f}\}$ – is a set of indices for the fundamental disciplines (they must be included in the curriculum, i.e. the disciplines from the approximate educational programme).

$J_\alpha^i = \{j_1^i, j_2^i, ..., j_{n_i}^i\}, i = \overline{1,m}$ – is a set of indices for disciplines, each providing the$i$-th competence closure no less than the value $\alpha \in [0,1]$.

$J_\alpha^u = \bigcup_{i\in I^u} J_\alpha^i \backslash J^f$ – is a set of indices for disciplines involved in universal competences closure.

$J_\alpha^o = \bigcup_{i\in I^o} J_\alpha^i \backslash J^f$ – is a set of indices for disciplines involved in general professional competences closure.

$J_\alpha^p = \bigcup_{i\in I^p} J_\alpha^i \backslash J^f$ – is a set of indices for disciplines involved in professional competences closure.

Let us introduce a formalized representation of the curriculum structural part through the tuple $k_c =< s, b >$, $c = \overline{1,6}$, $s =< 1, 2, 3, 4 >$, $b =< 1, 2 >$.

$k_1 =< 1, 1 >$ –is a compulsory part of module 1 (discipline);

$k_2 =< 1, 2 >$ – is a part of module 1 formed by the participants of an educational process (discipline);

$k_3 =< 2, 1 >$ – is a compulsory part of module 2 (practical training);

$k_4 =< 2, 2 >$ – is a part of module 2 formed by the participants of an educational process (practical training);

$k_5 =< 3, 1 >$ – is a compulsory part of module 2 (state final certification);

$k_6 =< 4, 1 >$ – is a part of module 4, formed by the participants of an educational process (electives).

$J_\alpha^{k_1} = J_\alpha^u \bigcup J^f \bigcup J_\alpha^o$ – is a set of indices for disciplines that can be used to form the compulsory part of module 1;

$J_\alpha^{k_2} = J_\alpha^o \bigcup J_\alpha^p$ – is a set of indices for disciplines that can be used in the part of module 1 formed by the participants of an educational process.

$J_\alpha^{k_3}$ – is a set of indices for disciplines that can be used to form the compulsory part of module 2.

$J_\alpha^{k_4}$ – is a set of indices for disciplines that can be used in the part of module 2 formed by the participants of an educational process.

$J_\alpha^{k_5}$ – is a set of indices for disciplines that can be used to form the compulsory part of module 3.

$J_\alpha^{k_6}$ – is a set of indices for disciplines that can be used in the part of module 4 formed by the participants of an educational process.

$\underline{V}^{k_1 \cup k_2}$ – is the lower limit of credits for module 1 of the curriculum.

$\overline{V}^{k_1 \cup k_2}$ – is the upper limit of credits for module 1 of the curriculum.

$\underline{V}^{k_3 \cup k_4}$ – is the lower limit of credits for module 2 of the curriculum.

$\overline{V}^{k_3 \cup k_4}$ – is the upper limit of credits for module 2 of the curriculum.

$\underline{V}^{k_5}$ – is the lower limit of credits for module 3 of the curriculum.

$\overline{V}^{k_5}$ – is the upper limit of credits for module 3 of the curriculum.

$\underline{V}^{k_6}$ – is the lower limit of credits for module 4 of the curriculum.

$\overline{V}^{k_6}$ – is the upper limit of credits for module 4 of the curriculum.

V –is the limit on the total number of the curriculum credits.

v_j – is the number of credits allocated to the j–th discipline.

$$x_{k_c j} = \begin{cases} 1, & \text{if the} j\text{-th discipline is included into} \\ & \text{the } k_c\text{-th part of the curriculum;} \\ 0, & \text{otherwise.} \end{cases}$$

The solution of the problem will be matrix X with dimension $| < s, b > | \times n$. Let us limit the number of credits for each module of the curriculum:

$$\underline{V}^{k_1 \cup k_2} \leq \sum_{j \in J_\alpha^{k_1 \cup k_2}} v_j x_{k_1 \cup k_2 j} \leq \overline{V}^{k_1 \cup k_2}$$

$$\underline{V}^{k_3 \cup k_4} \leq \sum_{j \in J_\alpha^{k_3 \cup k_4}} v_j x_{k_3 \cup k_{4_j}} \leq \overline{V}^{k_3 \cup k_4}$$

$$\underline{V}^{k_5} \leq \sum_{j \in J_\alpha^{k_5}} v_j x_{k_5 j} \leq \overline{V}^{k_5}$$

$$\underline{V}^{k_6} \leq \sum_{j \in J_\alpha^{k_6}} v_j x_{k_6 j} \leq \overline{V}^{k_6}$$

Let us limit the total number of credits for the curriculum:

$$\sum_{j\in J_\alpha^{k_1\cup k_2}} v_j x_{k_1\cup k_2 j} + \sum_{j\in J_\alpha^{k_3\cup k_4}} v_j x_{k_3\cup k_4 j} + \sum_{j\in J_\alpha^{k_5}} v_j x_{k_5 j} = V.$$

Let us limit the uniqueness of the j-th discipline appearance in the curriculum:

$$\sum_{c=1}^{6} x_{k_c j} \leq 1, j = \overline{1,n}.$$

It is necessary to maximize the coverage of each competence in the curriculum:

$$\sum_{j\in J_\alpha^i}\sum_{c=1}^{6} k_{ij} x_{k_c j} \to max, i = \overline{1,m}.$$

4 Mathematical model "Discipline - teaching staff"

Let us introduce the following notations:
p – is a teacher's number (index), $p = \overline{1,l}$.
d – is the number (index) of a teacher's qualification:
$d = 1$ – professor;
$d = 2$ – is an associate professor;
$d = 3$ – is a senior teacher;
$d = 4$ – is a teaching assistant.
$P^d = \{p_1^d, p_2^d, ..., p_{l_d}^d\}, d = \overline{1,4}$ – is a set of indices for teachers of the d-th qualification.
$P^{dn} = \{p_1^{dn}, p_2^{dn}, ..., p_{l_{dn}}^{dn}\}$ –is the set of teachers indices with a scientific degree Doctor of Sciences.
$P^{kn} = \{p_1^{kn}, p_2^{kn}, ..., p_{l_{kn}}^{kn}\}$ – a set of indices for teachers having a degree of candidate of sciences.
c^d – is the cost of full working hours for the teacher with the d-th qualification.
s – is the number of an education activity on a discipline:
$s = 1$ – is lectures;
$s = 2$ – is practical classes;
$s = 3$ – is laboratory classes;
$s = 4$ – is individual work;
$s = 5$ – is an examination;
$s = 6$ – is personal tuition on an examination;
$s = 7$ –is a pass-fail examination, $s = \overline{1,q}$.
$S^j = \{s_1^j, s_2^j, ..., s_{q_j}^j\}, j = \overline{1,n}$ – is a set of indices for education activities on the j-th discipline.
v_j^s – is the number of credits allocated to the s-th educational activity on the j-th discipline.
$D^s = \{d_1^s, d_2^s, ..., d_{t_s}^s\}, s = \overline{1,q}$ – is a set of indices for the qualification required to perform the s-th educational activity.
$h_{pj}^s \in [0,1]$ – is the coefficient of the p-th teacher's specialization in the s-th educational activity on the j-th discipline. If $h_{pj}^1 = 1$, then the p-th teacher is the leading one on the j-th discipline. This coefficient depends on the teacher's qualifications, further education courses, publications, personal ratings, etc.
$P_\beta^{sj} = \{p_1^{sj}, p_2^{sj}, ..., p_{l_j}^{sj}\}, j = \overline{1,n}, s = \overline{1,q}$ – is a set of indices for the teachers whose specialization in the s-th educational activity on the j-th discipline is no less than $\beta \in [0,1]$.
$P^s = \bigcup_{d\in D^s} P^d$ – is a set of indices for the teachers eligible to perform the s-th educational activity.
$P_j = P^d \cap P_\beta^{sj} \cap (P^{kn} \cup P^{dn})$ – is the set of teacher indices, which academic degree in the $j-th$ discipline.
wr_{sj} – is working hours allocated for the s-th educational activity on the j-th discipline
a_s – is the number of groups in the same study year involved in the s-th educational activity.

$$y_{ps}^j = \begin{cases} 1, & \text{if the } p\text{-th teacher performs the } s\text{-th} \\ & \text{educational activity on the } j\text{-th discipline;} \\ 0, & \text{otherwise.} \end{cases}$$

It is required to maximize the teaching staff's specialization in each discipline:

$$\sum_{s=1}^{q} \sum_{p \in P^d \cap P_\beta^{sj}} h_{pj}^s h_{pj}^s \to max, j = \overline{1,n}.$$

However, the total cost of disciplines in the curriculum should be minimal. This requires minimizing the cost of each discipline:

$$\sum_{s \in S^j} \sum_{d \in D^s} \sum_{p \in P^d \cap P_\beta^{sj}} y_{sp}^j wr_{sj} c_d \to min, j = \overline{1,n}.$$

Based on the analysis of the requirements outlined in the educational standards, a limit will be imposed on the share of the teaching staff with an academic degree:

$$\sum_{j=1}^{n} \sum_{s \in S^j} \sum_{d \in D^s} \sum_{p \in P^d} \cap P_\beta^{sj} \cap (p^{kn} \cup p^{dn}) wr_{sj} y_{sp}^j \geq \gamma, j = \overline{1,m}.$$

The conditions are also set on the number of members of the teaching staff for each educational activity on the discipline:

$$\sum_{p \in P^s} y_{ps}^j = 1, s = 1, j = \overline{1,m}.$$

$$1 \leq \sum_{p \in P^s} y_{ps}^j \leq a^s, s = 2, j = \overline{1,m}.$$

$$1 \leq \sum_{p \in P^s} y_{ps}^j \leq a^s, s = 3, j = \overline{1,m}.$$

$$1 \leq \sum_{p \in P^s} y_{ps}^j \leq a^s, s = 4, j = \overline{1,m}.$$

Constraint means that only one teacher can deliver lectures. Constraints mean that laboratory, practical and independent classes can be delivered by several teachers, but the number of these teachers should not exceed the number of the groups in the same study year involved in the s-th educational activity.

5 Mathematical models analysis

The use of the algorithm for finding semantic similarity between two elements [Zykina20] allows one to formalize the calculation of the degree of interrelation between disciplines and competences and the degree of interrelation between disciplines and teachers. As a result, the constructed models "Disciplines – competences", "Disciplines – teaching staff" are deprived of subjectivism and uncertainty.

Numerical studies of the constructed models are possible using the intlinprog function in MatLab [Ketkov05]. This function allows you to solve problems of integer, mixed and Boolean programming.

The solution of the model "Disciplines – Competences" is vector x, which defines a set of disciplines that provide the maximum of competences. The solution of the model "Disciplines – teaching staff" is vector y, which defines a set of teachers with maximum specialization.

6 Conclusion

The approach proposed for modeling is of practical importance: there is an opportunity to automate the laborious process of forming a curriculum that meets the formal requirements.

Novelty and advantages of the proposed approach lie in the fact that if it is possible to choose a set of disciplines and teaching staff, one can construct an optimal curriculum according to the given criteria.

It seems promising to use the proposed models for building curricula for individual training trajectories.

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