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Mathematical assessment for first-year STEM students: Development, experience, and outlook at the University of Innsbruck

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Mathematical competencies are essential for a successful transition into STEM studies. This article aims to exemplify how an assessment for an early diagnosis of mathematical deficits in such fields can be developed, implemented, and evaluated. Specifically, research questions regarding the relationship between performance on the developed assessment and academic success, measured by ECTS credits achieved per semester and dropout, are addressed. For this purpose, data from 301 first-year STEM students who voluntarily participated in the mathematics bridging course at the University of Innsbruck are analysed by means of linear and logistic regression. The analysis shows that an increase in the assessment solving frequency is associated with a significant increase in ECTS credits achieved per semester as well as a significant decrease in the risk of dropping out. Regarding these findings, further ideas and possible applications for the mathematical assessment are presented.

Keywords: Assessment, mathematics, university, success, dropout prevention.

Introduction and research questions

The term *mathematics problem* (Howson, 1995) is used to describe a phenomenon that has been causing concern at universities for several decades. It expresses the worry over first-year students' weak mathematics prerequisites, which prohibit them from effectively completing their postsecondary STEM (Science, Technology, Engineering, Mathematics) courses (Johnson & O'Keeffe, 2016). Even though the phenomenon has been known for a long time, it has lost none of its relevance. In Germany, for example, the university dropout rates in mathematics are 51%, in computer science 45%, and in physics 41% (Lumpe 2019).

In this regard, mathematical bridging courses may be a useful tool for easing the transition from a secondary to a postsecondary study by reducing knowledge gaps and providing possibilities for early social connections (Gordon & Nicholas, 2013). However, a lack of mathematical diagnosis tools in these courses is criticized in the German literature (Biehler et al., 2013). Thus, an attempt to develop an assessment as a diagnostic tool for bridging course participants at the University of Innsbruck is presented.

Of course, it is of great interest whether a connection between the developed assessment and later academic success in STEM studies emerges. Therefore, the following research questions are addressed in this article:

1. Is there a relationship between performance on the developed mathematical assessment and dropout in STEM studies?
2. Is there a relationship between performance on the developed mathematical assessment and the average number of achieved ECTS (European Credit Transfer and Accumulation System) credits in STEM studies?

Theoretical background and relevant concepts

Especially in STEM subjects, prior mathematical knowledge is crucial for a successful trajectory at universities (Gordon & Nicholas, 2013; Johnson & O’Keeffe, 2016; Lee et al., 2008; Müller et al., 2018). In this regard, the study entry phase is most essential to address such mathematical knowledge gaps and to prevent possible dropouts (Johnson & O’Keeffe, 2016). However, dropout rates remain high in STEM fields (Lumpe, 2019; Tieben, 2019).

To address this issue transparently, the cosh group in Baden-Württemberg published the minimum requirements catalogue for mathematics, which summarizes in a theoretical manner which mathematical skills are required to successfully pursue a STEM subject (cosh, 2014). Empirically, Neumann et al. (2017) conducted a Delphi study to investigate which mathematical competencies are necessary from a college and university perspective to successfully complete STEM degrees.

Another reaction to mathematical knowledge gaps among first-year STEM students are mathematical bridging courses. Despite conflicting results about their efficacy (Gerdes et al., 2021; Gordon & Nicholas, 2013; Johnson & O’Keeffe, 2016; De Paola & Scoppa, 2014), they are very common in German-speaking countries (Biehler et al., 2013). One of the reasons for these contradictory research results may lay in the chosen sample: While it is common in the U.S. to oblige students to take a mathematics bridging course due to insufficient performance, participation is usually voluntary in German-speaking countries. The resulting (self-)selection bias in the sample makes it difficult to attribute measured academic success or failure causally to bridging course participation (Gerdes et al. 2021). To reduce this confounder in our project, academic success is not examined in relation to bridging course attendance, but as a function of the diagnostic assessment used in the bridging course. Academic success is measured in terms of dropouts and the average number of ECTS credits achieved per semester – two of many ways to quantify academic success (Sorge et al. 2016).

ECTS credits are the “currency” of higher education in Europe and are obtained by taking classes or passing tests. For a regular bachelor's and master's degree, 30 ECTS credits are scheduled per semester conforming to the Austrian University Act 120/2002 (2002).

A less explicit concept is that of dropout, since there isn’t a uniform definition for this term (Grau-Valldosera & Minguillón, 2014; Heublein, 2014; Tieben, 2020). In this regard, it must be clarified whether a transfer to another institution, a temporary termination of the degree program, or a switch to another STEM study also qualifies as a dropout. For our project, dropout is defined as any interruption of the considered STEM degree program at the University of Innsbruck.

Context and development of the diagnostic assessment

The University of Innsbruck is the largest educational and research institution in western Austria. The Austrian school system attempts to ensure subject-related study readiness by using a centralized mathematics final examination (BMBWF, 2019). Although all final-year pupils have been obliged to attend this centralized mathematics examination since 2015/16, the University of Innsbruck has nevertheless decided to offer mathematics bridging courses for STEM students during their study entry phase.

Based on the already mentioned work by Cosh (2014) and Neumann et al. (2017), an assessment for first-year STEM students was developed in the context of 13 bachelor theses at the University of Innsbruck. The students were supervised by a mathematician together with a mathematics education researcher and received expert's feedback from Department III/6f of the Federal Ministry of Education, Science and Research, which is responsible for creating the tasks for the Austrian centralized mathematics examination. The assessment was piloted as part of the mathematics bridging course during winter semester 2019/20. The final product consists of 129 closed-ended tasks, each of which corresponds to a single mathematical competency that is assumed to be relevant for STEM studies. The individual competencies can be assigned to the areas of *general mathematical skills*, such as logical thinking, *numbers and functions*, *equations and inequalities*, *coordinate systems and vectors*, *geometry and trigonometry*, *differential calculus*, *integral calculus* and *statistics and probability*.

The assessment with automatic feedback (correct/wrong with suggested solution) was digitized using the package *R/exams* (Zeileis et al., 2022) and exported to the online learning platform *OpenOLAT*. In this way, the tasks were made available to the participants at the beginning of the mathematics bridging course at the University of Innsbruck, i.e. before any instruction. Based on the results of this diagnostic assessment, students had the opportunity to reflect on and assess their own mathematical competence level in order to subsequently participate in practical or theoretical workshops on specific mathematical content areas (e.g. numbers and functions). Additionally to this initial assessment, the course was accompanied by formative self-reflection through written learning diaries.

For analytical purposes, the developed assessment was subjected to a Rasch item analysis based on provided data by 301 bridging course participants. Unidimensional Rasch analysis yields a WLE (Weighted-Likelihood-Estimates) reliability of 0.916 and an EAP (Expected A Posteriori) reliability of 0.907 for the assessment, which is considered very good for performance tests (Gäde et al., 2020).

Sample, available data and method

To examine whether and how performance in the developed assessment affects dropout and ECTS credits achieved per semester, data was collected from 301 STEM students, who participated voluntarily whether in the 2020/21 or in the 2021/22 mathematics bridging course at the University of Innsbruck. All participants were first-semester students in the specified degree programs¹. Data regarding the solving frequency in the assessment, earned ECTS credits per semester until 30.04.2022, study, dropout, age, gender, country, last school grade in mathematics², self-efficacy score, and self-concept score were obtained. The two latter scores were collected using validated 5-point Likert scales with 4 and 6 items, respectively.

¹ *Science*: Bachelor's program atmospheric sciences, biology, chemistry or physics

Technology: Bachelor's program computer science

Engineering: Bachelor's program civil and environmental engineering

Mathematics: Bachelor's program mathematics

² 1 means *very good*, 5 means *insufficient*.

To answer the first research question, a logistic regression model was fitted whose output variable is *dropout* (1 = no dropout, 0 = dropout) and whose primary input variable is the solving frequency in the assessment (between 0 and 100%). Beside earned ECTS credits per semester, all other mentioned variables served as control variables, whereby non-relevant control variables were removed using backward selection and the AIC (Akaike Information Criterion). The remaining model has the following form:

$$Dropout \sim Assessment\ solving\ frequency + Study + Age + Self\text{-}efficacy$$

To answer the second research question, a linear regression model was fitted whose output variable is *ECTS credits per semester* and whose primary input variable is the solving frequency in the assessment (between 0 and 100%). Irrelevant control variables were again removed using backward selection and the AIC. In this case, *dropout* is coded as 1 if the student dropped out, and 0 if the student didn't drop out. The remaining model has the following form:

$$ECTS\ credits\ per\ semester \sim Assessment\ solving\ frequency + Study + Age + Grade + Self\text{-}efficacy + Dropout$$

A significance level of 5% is used for the presentation and interpretation of the results.

Results

Figure 1 and Table 1 illustrate the relevant results regarding the first research question.

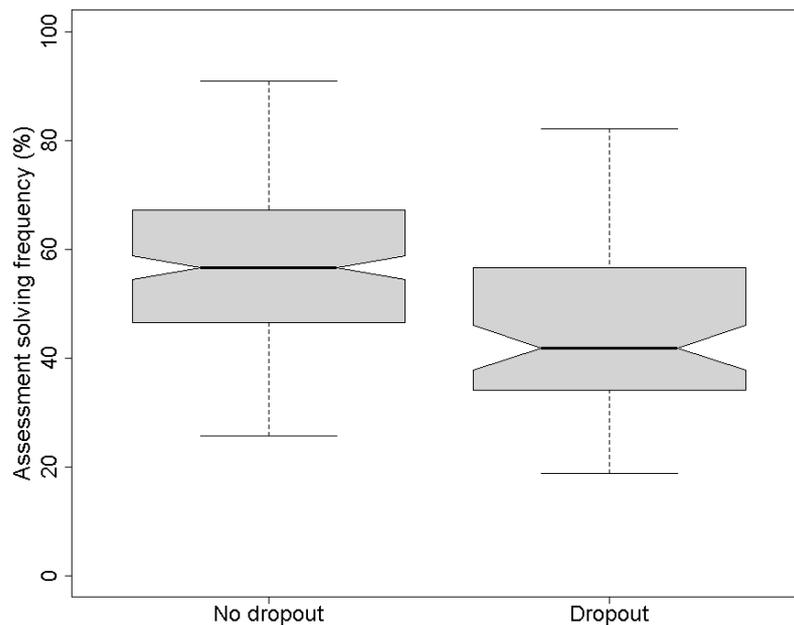


Figure 1: Solving frequency in the developed assessment by dropout, displayed as boxplots

Table 1: Logistic regression estimates of significant input variables, including odds ratios and p-values

	Estimate with 95% confidence interval	Odds ratio with 95% confidence interval	p-value

Intercept	-6.89 (-12.6 to -1.19)	/	0.018
Assessment solving frequency (%)	0.07 (0.04 to 0.09)	1.07 (1.04 to 1.1)	< 0.001

The base category in Table 1 refers to a first-year student who studies atmospheric sciences, is 0 years old, has an assessment solving frequency of 0% and reached a self-efficacy score of 0. For the assessment solving frequency, the calculated estimate amounts to 0.07 and is highly significant. The corresponding odds ratio of 1.07 means that each one-unit increase in the solving frequency increases the odds of not dropping out by 7%. All other mentioned input variables do not yield significant results and are thus not reported in Table 1.

Similarly, the significant linear regression results for the second research question are presented in Table 2.

Table 2: Linear regression estimates of significant input variables, including p-values

	Estimate with 95% confidence interval	p-value
Assessment solving frequency (%)	0.18 (0.1 to 0.25)	< 0.001
Study = Bachelor's program computer science	8.92 (1.98 to 15.87)	0.012
Grade = 2	-3.25 (-5.63 to -0.87)	0.008
Grade = 3	-3.41 (-6.43 to -0.39)	0.028
Grade = 4	-9.34 (-13.79 to -4.9)	< 0.001
Dropout = yes	-10.71 (-13.1 to -8.32)	< 0.001

The fitted linear regression model shows an adjusted R-squared value of 0.53. The base category refers to a first-year student who studies atmospheric sciences, is 0 years old, whose last school grade was 1, has a solving frequency of 0% at the assessment and reached a self-efficacy score of 0 and did not drop out of the degree program. The model does not provide significant results for the intercept, age, and self-efficacy score. The significant results listed in Table 2 provide, *ceteris paribus*, the following findings: The bachelor's program in computer science has a significant positive effect on the outcome variable. Enrolment in this degree program is accompanied by an increase in the average ECTS credits of 8.92. Moreover, people with poorer last mathematics grades achieve fewer ECTS credits per semester. Also, individuals who drop out of their studies achieve on average 10.71 fewer ECTS credits per semester than those who do not drop out. The interesting result for the research question, however, is that an increase in the assessment solving frequency by one percentage point is

accompanied by a highly significant increase in the average number of earned ECTS credits per semester of 0.18. This means that an increment of about 5.5 percentage points in the assessment solving frequency is associated with an estimated increase of 1 ECTS credit per semester.

Discussion and outlook

The results show that the developed mathematics assessment offers the possibility to identify students at risk of dropping out at an early stage. Referring to the current use of the assessment in the mathematics bridging course at the University of Innsbruck, this is a pleasing result in many respects. On one hand, it is an effective diagnostic tool for this type of course, as requested by Biehler et al. (2013). On the other hand, the timing of the assessment at the beginning of the semester seems appropriate, because competence gaps should be addressed as early as possible to prevent dropouts (Johnson & O’Keeffe, 2016). In combination with the mathematical workshops and formative elements offered during the bridging course, we believe that the assessment provides good opportunities to catch up.

However, it should be noted that the sampled students participated voluntarily in the mathematics bridging course at the University of Innsbruck and could therefore be subject to a self-selection bias, as stated by Gerdes et al. (2021). This self-selection bias is, among other things, responsible for the divergent results on the benefits of mathematical bridging courses, as explained in the theoretical background. The chosen research design considers this possible obstacle by estimating the effect of the diagnostic assessment within the sample and not in comparison to another, possibly non-comparable group of students. However, it would of course be valuable to repeat the conducted analysis also for non-participants of the mathematics bridging course. To this end, first randomization attempts of the assessment were made. Randomization in this context means that used numbers, the order of answer options and partly also the answer options themselves are created randomly for each task in the assessment. Therefore, a different and individual version of the assessment including automated feedback is generated in each session. In this form, the assessment could be conducted several times for formative self-monitoring. Additionally, it would be possible to develop a recommendation system, which recommends specific mathematical exercises or materials based on the assessment results. In combination with such an automated recommendation system, the assessment could be made accessible university-wide via *OpenOLAT* – also for students who do not participate in the mathematics bridging course.

Moreover, another option is to use the assessment as a compulsory entrance test for first-year STEM students. People who do not achieve a certain solving frequency would be obliged to attend a mathematics bridging course or other remedial activities.

Limitations

Beside the self-selection bias, the data collection process itself is another limitation. Due to the partially online instruction during the COVID-19 pandemic, it is not possible for the authors to ensure that all students followed the instructions while solving the assessment (e.g., individual work, no use of technology).

Furthermore, it is impossible to make sure that a dropout in the current research design was not merely a temporary interruption or a transfer to another institution. The same applies to the definition of first-year students: Individuals enrolled in the declared STEM program in their first semester at the University of Innsbruck were defined as such. Whether these students have already completed another degree program or have previously studied at another university is beyond our knowledge.

Finally, only short- to medium-term academic success measured by ECTS credits and dropout is considered in this study: The period under consideration for the 2020/21 cohort is three semesters, for the 2021/22 cohort one semester.

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