Results Report

Summary

Modular education is becoming increasingly relevant in secondary educational systems across Europe, including Austria. These educational systems are characterized by increasing degrees of freedom to let students express their preferences and choose their own subjects, paving the way for individualized timetables. However, the resulting scheduling problem is highly complex, creating practical implementation hurdles. The main goal of the project "Course scheduling in modular educational systems" was to investigate AI-based combinatorial optimization approaches for the problem of finding the best possible timetable taking into consideration the elections and preferences of students. For this, a novel problem formulation based on mathematical programming (Integer Linear Programming) was designed, effectively adding this new problem to the existing literature and opening it for researchers in the combinatorial optimization community. Through the collaboration with the Austrian market leader Untis, a company with HQ in Lower Austria, a new and open dataset with practical instances was published according to the principles of open data. One of the main challenges of the new problem formulation is that exact methods like branch-and-bound are not suitable for practical use, as their computational complexity only allows for solving instances of small size. We therefore designed metaheuristics to address the trade-off between solution quality and performance, and focused on neighborhood based approaches: Simulated Annealing (SA) and Adaptive Large Neighborhood Search (ALNS). Additionally, we combined them with a especially crafted heuristic that solved the problem of assigning courses to students before the actual timetable was generated. The results showed that SA was able to generate competitive solutions for most of the instances analyzed, and that ALNS combined with Upper Confidence Bound (UCB) destroy operator selection only works well with instances of moderate size. In summary, the project provided a practical approach for solving the modular high-school timetabling problem resulting in several peer-reviewed publications, and showing that high-quality solutions can be obtained in practice by means of metaheuristic approaches. These results are expected to be used in Lower Austria based commercial software solutions to increase the impact of the project across European regions and countries and to advance the scientific understanding of the high-school timetabling problem as a whole.

Research Question and Research design

Background and objectives: Description of the context and relevance of the research project, as well as a presentation of the research objectives and questions.

Across several European systems, especially Austria, Germany and Finland, high schools are moving toward flexible, course-based curricula that let students tailor subjects to their interests. While this boosts engagement, it also makes constructing feasible timetables significantly harder and calls for computational support to manage constraints such as student collisions, prerequisite structures, and workload limits. At the same time, the literature lacks a general, adaptable framework that can accommodate regional and national differences in how course timetabling is formulated and constrained, creating a gap between research prototypes and deployable solutions for diverse school systems.

The project aimed to close this gap by designing and developing novel optimization algorithms for key variants of the course timetabling problem, combining academic advances with the industry partner's practical know-how. Rather than creating individual solutions for each context, the researchers analyzed similarities and differences across systems to synthesize broadly applicable techniques, with a regional focus on Austria, Germany, Finland, and Switzerland to maximize transferability and comparability. Given the NP-hard nature of the problem, the work emphasized heuristic and metaheuristic strategies capable of computing near-optimal solutions efficiently. Performance was validated through quantitative comparisons, including against theoretical solutions from mixed-integer models and state-of-the-art academic baselines, and through qualitative assessments with the industry partner, ensuring both scientific rigor and real-world relevance. Additionally, results were positioned relative to standardized benchmarks established by the international timetabling community to contextualize improvements and foster dissemination.

Research design, methodological implementation, and process: Description of the chosen research design, the methods for data collection and analysis, and a concise description of the project implementation process.

The project followed an applied, co-design research strategy that tightly integrates industry know-how, algorithmic innovation, and feedback from schools in iterative build–measure–learn cycles to develop and refine timetabling algorithms. Quantitative and qualitative strands run in parallel: prototype performance is measured against rigorous computational baselines while users and stakeholders evaluate usability, interpretability, and fit to institutional processes.

Problem data were collected via structured descriptions for each regional use case, elicited through stakeholder interviews and publicly available requirements to capture constraints, policies, and objectives at system level. For experimentation and benchmarking, anonymized datasets were compiled with the industry partner which reflect real scheduling complexity and enable repeatable tests. Analysis emphasizes: (i) quantitative assessments, including comparisons to theoretical solutions derived from mixed-integer formulations and to state-of-the-art academic methods; and (ii) qualitative evaluations to assess solution quality, practicality, and change-management implications in schools. Results are also positioned against standardized benchmarks from the timetabling community to contextualize performance and generality.

The work proceeded in staged work packages: WP2 formalized and contrasted regional problem formulations and mapped commonalities/differences to the literature to define requirements and evaluation criteria. WP3 conducted an extensive literature review, designed tailored optimization strategies, built data conversion tools, and developed algorithmic prototypes for the most promising approaches. WP4 established the validation testbed, executed comprehensive quantitative trials, and ran qualitative assessments with the industry partner to iterate toward deployable solutions. WP5 disseminated findings to scientific and general audiences, including preparing conference/journal outputs and public-facing materials to maximize outreach and impact. Tooling, licenses, and IPR were managed to enable reproducibility of scientific results (e.g., releasing code and data for published findings when appropriate) while allowing the industrial partner to integrate production-ready code under a closed license. Risks were mitigated by the industry partner's extensive domain expertise and broad school network, which helped ensure sufficient input for algorithm development and validation.

Core results and Impacts

Results and Analysis: Presentation of the main findings, supported by visualizations (tables, graphs, or charts). Interpretation and discussion of the results in relation to the original research questions and objectives.

The first project main result is concerned with the analysis of modular educational systems across Europe. After conducting extensive interviews with experts from educational systems in Austria, Germany, the Netherlands, Switzerland and Finland, a novel methodological approach was developed to quantify the degree of modularity of the educational systems studied. Due to the nature of the federal German educational system, results were reported for individual German federal states as well. The results show the highest degree of modularity in Finland, closely followed by Switzerland and some specific German federal states. While the modularity of the Austrian educational system was found to be rather low in comparison with the other regions investigated, the potential for modular education in Austria was assessed to be high. A selection of results is shown in Figure 1, where we visualized the modularity for educational systems using radar charts.

In the next phase of the project, ILP optimal solutions were obtained when feasible and compared to Untis, the KHE solver, and a special heuristic based on Large Neighborhood Search with iterative resource refinement. This heuristic was designed to start with a simplified solution obtained by temporally removing the modular constrains from the problem formulation and applying two especially tailored neighborhoods (time-based and resource-based) combined with the ILP solver Gurobi. The results are shown in Table 1, where it can be seen that the KHE+heuristic procedure obtains very competitive solutions (marked in bold) compared to the ones obtained by Untis. The numbers shown in the table correspond to the objective values obtained by the best solutions found (divided into hard and soft constraint scores).

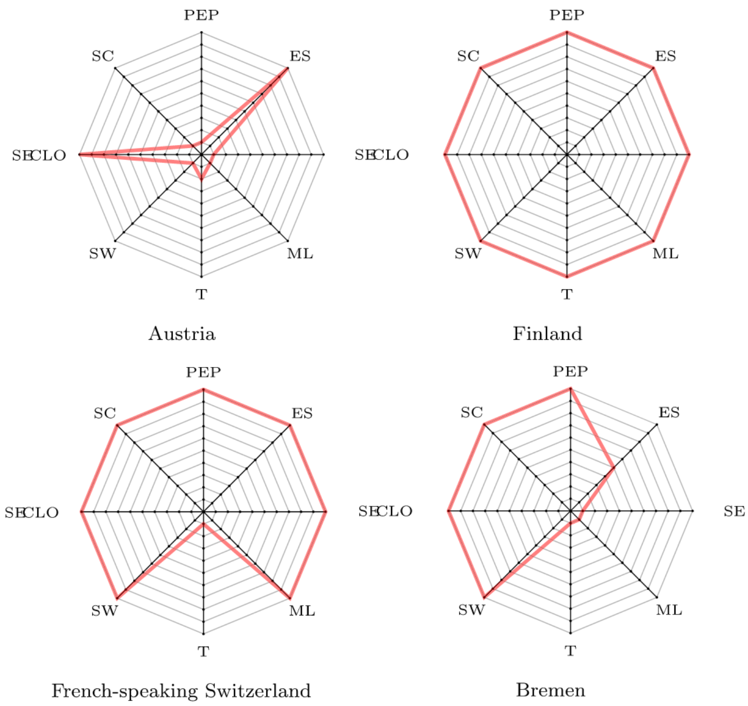

Figure 1. Selection of the educational systems studied and their degree of modularity.

Instance	ILP	Untis	KHE	KHE + RR
GermanyRHPF1	(6462, 823618)	**(1111, 1103832)**	(2102, 53834)	(1135, 2106340)
GermanyHAMB1	(23189, 98974)	(2570, 74272)	(1141, 300468)	**(1038, 390228)**
GermanyNRWE1	(1830, 45453)	(158, 53794)	(949, 28910)	**(112, 23230)**
GermanyHAMB2	(2606, 667275)	**(489, 736409)**	(2077, 627306)	(514, 765511)
GermanyNRWE2	(11859, 717755)	**(3, 522239)**	(1856, 563526)	(685, 1152013)
GermanyRHPF2	(1838, 344274)	**(139, 578861)**	(1218, 279125)	(223, 675497)
GermanyRHPF3	(4641, 41015)	(698, 67950)	(1884, 14875)	**(421, 17535)**
GermanyNRWE3	(4138, 712339)	**(3, 595152)**	(1527, 725029)	(454, 1167449)
GermanyNRWE4	(18803, 481400)	**(481, 2108384)**	(2669, 407148)	(1398, 2126676)
GermanyRHPF4	(19993, 3345866)	**(469, 2861834)**	(3521, 1061372)	(3218, 140346)
GermanySAAR1	(2866, 902480)	**(148, 1216406)**	(1301, 688897)	(160, 894812)
GermanyRHPF5	(3750, 105501)	(875, 92920)	(1477, 1135343)	**(172, 1107317)**
GermanyRHPF6	(13668, 1729304)	**(688, 5249020)**	(2791, 1417831)	(1937, 3594917)
GermanyBAWU1	(2720, 895979)	(1269, 1404472)	(1793, 763273)	**(1126, 2737060)**
GermanyBAWU2	(12997, 1244282)	(2384, 1439922)	(3107, 1258268)	**(1759, 1742691)**
GermanyBAWU3	(1545, 648188)	**(466, 1153160)**	(2502, 628112)	(609, 1288909)
GermanyBAWU4	(4324, 1062721)	(1993, 1426330)	(2745, 726440)	**(657, 1674536)**
GermanyHESS1	(3347, 600172)	(1908, 1247660)	(2251, 619474)	**(919. 1383554)**

Table 1. Comparison of results between ILP, Untis, and the combination of KHE + heuristic.

In the next step, the SA and ALNS metaheuristics were benchmarked against Untis, this time with special focus on SA since it was early clear that ALNS would only be able to handle instances of smaller size. In order to ensure a fair comparison with Untis, it was necessary to perform an extensive weight analysis between the constraint weights used by Untis and those used in the XHSTT formulations of the problems. This resulted in adjustments to the problem instances, which were made publicly available as well. Table 2 shows the main results, where best values are shown in bold, and best known solutions are marked with an asterisk. This comparison shows that the

SA heuristic with the especially crafted neighborhood operators designed in the context of this project is highly competitive, finding best solutions to a significant share of the dataset, and otherwise finding comparatively good solutions with regards to the other methods. In summary, the results obtained by the SA heuristic showed that practical solutions to the modular high-school timetabling problem can be found in reasonable times, while its applicability to real-world context was jointly assessed with the industry partner to be highly relevant to school scheduling practices.

Instance	Greedy	Untis	KHE	SA
RHPF1	(12, 4257203)	(0, 143077)	(0, 58351)	**(0, 32084)***
HAMB1	(2673, 260553)	(2526, 149837)	(2522, 217491)	**(2416, 92759)***
NRWE1	(58, 230703)	**(11, 52737)***	(72, 32199)	(17, 28730)
HAMB2	(172, 558144)	(153, 199872)	**(76, 144615)***	(76, 202133)
NRWE2	(110, 1132059)	**(2, 253004)***	(3, 218381)	(110, 1132059)
RHPF2	(55, 834550)	**(7, 164752)***	(9, 192428)	(19, 391771)
RHPF3	(462, 121914)	(430, 99509)	(552, 73405)	**(418, 46009)***
NRWE3	(58, 686283)	(1, 270259)	**(1, 229200)***	(58, 686283)
NRWE4	(284, 2295201)	(247, 1127564)	(162, 984229)	**(132, 1340851)***
RHPF4	(662, 3731599)	(284, 1660320)	**(259, 1783553)***	(286, 1694688)
SAAR1	(101, 1368636)	(2, 781833)	**(1, 576094)***	(9, 642221)
RHPF5	(697, 562500)	(704, 120522)	**(372, 378415)***	(373, 374141)
RHPF6	(636, 4546697)	(1081, 4426289)	(358, 3904301)	**(312, 3479251)***
BAWU1	(697, 1730640)	(723, 1147938)	(510, 1165927)	**(499, 1143194)***
BAWU2	(617, 1887511)	(748, 803621)	**(546, 594847)***	(546, 666883)
BAWU3	(159, 470821)	(178, 361595)	(190, 303036)	**(141, 298004)***
BAWU4	(38, 688467)	(52, 719623)	**(2, 589747)***	(2, 600925)
HESS1	(372, 865276)	(973, 522952)	(235, 699490)	**(235, 699318)***

Table 2. Comparison between Greedy heuristic, Untis, KHE and SA.

Impact on Science: Discussion of the scientific implications of the findings; connectivity of the findings to international research activities.

The implications of the previously presented results are manifold for scientific understanding of the modular high-school timetabling problem. First of all, we provided a novel formulation for the problem which represents an original contribution to the existing literature. Up to date, no other problem formulations were considered jointly with modular constraints and the specific scheduling preferences already known and formalized in the XHSTT format. Additionally, the results stress the importance of especially tailored metaheuristic approaches to obtain high-quality solutions of practical importance in a reasonable amount of time. This is an explicit consequence of the No-Free-Lunch Theorems for Optimization, a well-known result that underlines the importance of including specific domain knowledge into metaheuristic algorithm design. The heuristics developed in this project (the greedy construction heuristic presented in Table 2 and the resource refining heuristic presented in Table 1) incorporate this practical knowledge into metaheuristic algorithms, therefore allowing to include problem knowledge relevant to the modular educational systems studied in this project.

Applications: Description of possible practical applications of the research findings, including any successful examples or potential collaborations; optional: Recommendations for policy or practical measures.

The research findings obtained in this project can be integrated into commercial timetabling solvers to support modular education to the extent needed by the degree of modularity of the specific educational system at hand. Through the collaboration with the industry partner Untis, this is guaranteed to impact how modular education is implemented across European educational systems. Policy recommendations for the implementation of modular education are currently in active discussion with educational stakeholders like Bildungsdirektionen and the Ministry of Education in Austria and abroad to ensure that the benefits of modular education are experienced by students in their specific application domains.

Networking and Communication

Networking: Description of the collaborations and networks that have been established or continued through the project, including the institutions involved and the nature of the collaboration.

The collaborations carried out during the project duration were shaped on the one side by the industry partner Untis, which provided a rich network of schools, regional and national educational public institutions, and policy and decision makers. Specifically, this network is enriched by professional timetabling experts in Austria, Germany, Switzerland and the Netherlands whose expertise shape timetabling in other institutions as well. Through the project's results, these experts ensure that the application of the timetabling algorithms developed in this project produces tangible impact in secondary schools across Europe.

On the other side, the doctoral collaboration with Associate Prof. Dr. Nysret Musliu from TU Wien's Institute of Logic and Computation ensured that a high level of academic rigor was maintained throughout the project and that Dipl.-Ing. Krystallidis could carry out the research in this project as part of this doctoral dissertation, which is ongoing at the time of this writing.

Dissemination: Description of science dissemination activities in which the project and its results were presented to an interested public, including the institutions involved and the nature of the collaboration.

The dissemination activities of the project were focused on the following areas:

- Scientific dissemination: The project's results were published in the open access journal Heliyon (10.1016/j.heliyon.2024.e39694) and as a conference paper in the most important international scientific conference on the theory and practice of automated timetabling, PATAT 2024 held in Copenhagen, Denmark. Additionally, two papers which are directly related to the project activities are currently in peer-review for the journal Computers and Operations Research and the PATAT 2026 conference.
- Stakeholder involvement: The researchers participation on the Untis Salzburg seminar in 2024 and 2025 ensured a high degree of dissemination of the project results in the target group of practitioners and decision makers. The Untis Salzburg seminar is a fixed focal point of the German-speaking timetabling community (DACH region) and abroad that brings together both timetablers and public administrations to discuss challenges and opportunities of automated timetabling for educational systems. This seminar has been held each year since 1974 and provides discussion forum for timetabling, ensuring that the project results are known by the relevant stakeholders.
- Popular science: The project was featured on IMC Krems wide ranging social media channels to make the project's goals and contributions known to a wider audience. This included press releases, articles and posts on different social media platforms and channels.

Outlook

Further research: Presentation of possible further research activities based on the project results; perspectives for further investigations and long-term research priorities.

The main further research activities that originate in this project focus around the doctoral dissertation of project staff member Dipl.-Ing. Andreas Krystallidis, under the supervision of Associate Prof. Dr. Nysret Musliu and co-supervised by Prof. (FH) Dr. Rubén Ruiz Torrubiano. Specifically, this dissertation will integrate aspects of Instance Space Analysis and Reinforcement Learning into the problem formulation, aspects which could only be investigated on the surface level in the context of the project activities. Additionally, further collaboration between IMC Krems and Untis is planned to successfully bring the project results into commercial products and investigate the impact of the algorithms designed in the project for real-world timetabling purposes.

Contact

Contact information: Information about people and institutions for inquiries or further information.

Principal investigator: Prof. (FH) Dr. Rubén Ruiz Torrubiano. ruben.ruiz@imc.ac.at, +43 2732 802302

Project staff member: Dipl.Ing. Andreas Krystallidis, andreas.krystallidis@imc.ac.at (no longer employed at IMC Krems).

Project staff member: Prof. (FH) Dipl.-Ing. Dr. Deepak Dhungana, deepak.dhungana@imc.ac.at, +43 2732 802151

Research services IMC Krems: Dr. Florian Huber, florian.huber@imc.ac.at, +43 2732 802131.

Doctoral supervision TU Wien: Associate Prof. Dr. Nysret Musliu, nysret.musliu@tuwien.ac.at

Project staff member Untis: Dr. Lukas Matthias Wolf, lukas.m.wolf@untis.at, +43 2266 622410

Project staff member Untis: Dipl.-Ing. Peter Schmidt, peter.schmidt@untis.at, +43 2266 622410