A Three-Phase Framework for Course Planning and Timetabling in Upper Secondary Schools with Self-Directed Learning

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1 Introduction

Educational systems show a growing trend towards more individualized learning paths. Particularly in upper secondary education, students can often select elective subjects according to their interests and academic goals instead of following strictly predefined curricula. At the same time, pedagogical concepts increasingly incorporate flexible learning formats alongside traditional classroom teaching. One example is the introduction of self-directed learning sessions (SDL sessions), in which students work independently on subject-specific tasks while teachers provide guidance. The setting considered in this work originates from a research project conducted in collaboration with a small network of upper secondary schools in Germany that integrate SDL sessions into their instructional concept. In these schools, SDL sessions allow students to complete part of their required subject hours through supervised independent learning in addition to regular teacher-led classroom instruction. The combination of individualized course selection and SDL sessions introduces additional combinatorial challenges for timetable planning, which are difficult to handle with existing timetabling software systems and therefore motivate the development of new planning approaches.

2 Problem Description and Related Work

In upper secondary schools in Germany, students can choose from a set of advanced and basic courses when composing their individual curriculum. Advanced courses require a higher weekly workload than basic courses, and each student usually selects two or three advanced courses (depending on the federal state) in addition to several basic courses, resulting in a curriculum of roughly twelve subjects. For each subject, a required number of weekly hours must be fulfilled. In the schools considered in this study, these hours are delivered through a hybrid instructional concept that combines regular classroom lessons with the SDL sessions. Regular lessons follow the traditional format of teacher-led instruction for a group of students, while SDL sessions allow students to work independently on subject-related tasks under the supervision of a teacher. At the same time, the planning process must account for operational constraints such as class size limits, teacher availability, room capacities, and the required number of weekly teaching hours for each subject.

In the classical high school timetabling problem the set of lessons, including their teachers and classes, is fixed in advance and the curriculum is predefined. The task is to assign each lesson or event to a period and a room without creating resource conflicts [7]. Another line of research focuses on university course timetabling and distinguishes between Post-Enrolment Course Timetabling (PE-CTT) [5], where individual student enrollments are known prior to the timetabling process, and Curriculum-Based Course Timetabling (CB-CTT) [2], where predefined curricula represent groups of students that must attend the same set of courses. When course capacities are limited, students must additionally be assigned to specific course sections while avoiding timetable conflicts, a problem commonly referred to as student sectioning [6]. For upper secondary schools with elective systems, Kristiansen et al. introduced the Elective Course Planning Problem (ECPP), which assigns course classes to predefined timetable blocks while maximizing the number of satisfied course requests [4]. Hoshino and Fabris [3] investigate the optimization of student course preferences in school timetabling and consider the construction of compatible course bundles. Furthermore, Aslan et al. [1] investigate learning activity planning in personalized, demand-driven learning environments using a hyper-heuristic framework.

The problem studied in this paper lies between classical school timetabling and university course timetabling due to the elective course structure, while also incorporating student sectioning aspects and elements of personalized learning through flexible SDL sessions.

3 Solution Approach

To address the problem, the following three-phase planning framework is proposed in which the overall planning task is decomposed into separate planning stages:

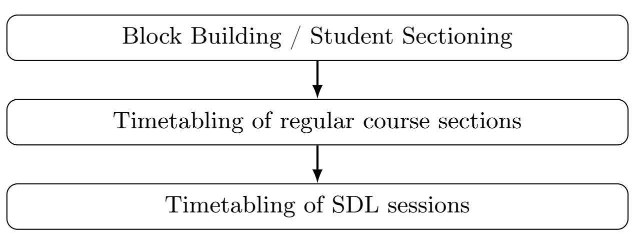

Fig. 1. Three-Phase Framework

Phase 1: Block Building / Student Sectioning In the first phase, a block structure is constructed based on student course selections. A block represents a scheduling unit used in the later timetabling phase and contains a set of course sections that can take place in parallel without creating conflicts for any student. This phase can be interpreted as a combination of course bundling and student sectioning and can be viewed as a conflict-grouping problem in which course sections that share students must not be assigned to the same block. The model determines both the assignment of students to course sections and the assignment of course sections to blocks. Constraints ensure that each student is assigned to a section of every selected course, section capacities are respected, and conflicting sections are placed in different blocks. The objective is to construct a compact block structure with as few blocks as possible, since each block must subsequently be scheduled in the timetable according to the weekly duration of the corresponding courses.

Phase 2: Timetabling of regular course sections In the second phase, the blocks determined in Phase 1 are scheduled within the weekly timetable. Each block is assigned to time slots as often as required to cover the portion of subject hours delivered through regular teacher-led lessons within the hybrid instructional concept, while the remaining hours are fulfilled through SDL sessions. Since the blocks already contain conflict-free course sections determined in Phase 1, the timetabling process operates on the level of blocks rather than individual courses. The model determines the assignment of blocks, teachers, and rooms to time slots. Constraints ensure that all required lesson hours are scheduled while preventing teacher and room conflicts and respecting teacher availability. Additional constraints can be used to enforce pedagogical and organizational requirements. The objective is to produce compact and practical timetables for both students and teachers while ensuring the feasibility of all scheduled lessons.

Phase 3: Timetabling of SDL sessions In the third phase, the timetable constructed for the regular course blocks is complemented by SDL sessions. In this step, it is determined which SDL sessions are offered and at which time slots they take place. Each session is supervised by a teacher and associated with a subject area that determines the subjects for which students can complete learning tasks during that session. The model determines the set of SDL sessions to be offered as well as their assignment to teachers and time slots. Constraints ensure sufficient SDL capacity for all subjects, fulfillment of the remaining subject-specific hour requirements of all students, and compatibility with teacher availability and the timetable generated in Phase 2. The objective of this phase is to ensure that all students can fulfill the remaining required subject hours not covered by regular classroom lessons. SDL sessions are therefore scheduled while remaining compatible with the previously constructed timetable and giving preference to time slots with the greatest potential to satisfy outstanding student demand.

The solution framework is implemented through three separate mathematical optimization models corresponding to the three planning phases. This decomposition reduces the size and complexity of the individual models and limits the combinatorial interactions between decisions occurring at different planning levels. In contrast, a fully integrated formulation would lead to a substantially larger and more complex model that is difficult to solve in practice. The phases are currently solved sequentially, with the output of each phase serving as input to the subsequent phase. While this decomposition may exclude some globally optimal solutions, it substantially improves tractability and enables the solution of practically relevant instances. To evaluate the computational performance of the approach, implementations based on the Gurobi solver as well as a CP-SAT solver were developed.

Initial computational experiments on representative real-world instances indicate that all three phases can be solved within acceptable computation times. Further computational studies are currently being conducted to systematically assess the performance, scalability, and solution quality of the proposed decomposition approach, including the potential benefits of feedback mechanisms between planning phases. The overall goal is to establish the framework as a practical decision-support tool for schools implementing flexible pedagogical concepts and enabling students to pursue more individualized learning paths.

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