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Practices in timetabling in higher education institutions: a systematic review

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Abstract The study of differences between timetabling research presented in conferences like PATAT or published in Annals of OR and commercial timetabling software used in Higher Education Institutions (HEIs) is essential for the discussion about innovation in both higher education and in commerce. In the field of planning and scheduling, a lot of developments are made and it is important to recognise that these developments are of influence on HEIs through their use of timetabling software. A main objective of the work presented here is to provide up-to-date information about timetabling in HEIs and see to what extent they adopt and implement timetabling developments. This is crucial because of budgets of institutions being strictly limited and remaining resources like rooms having to be shared more and more. Developments in HEIs have caused planning processes in higher education to deal with more limitations than ever, while at the same time the demand towards flexibility and availability is increasing. This paper gives the results of a systematic literature review in which differences and similarities in theory and practice of timetabling in higher education are described and discussed. We looked at state-of-the-art timetabling research for HEIs, at innovations in the field of timetabling and at changing requirements in Higher Education. The aim of this paper is to motivate the discussion about both the differences and similarities and bring timetabling application development closer to educational requirements.

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1 Introduction

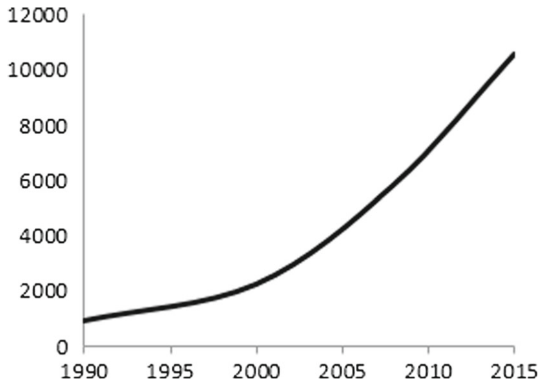
Nowadays, a paradigm shift is occurring in the field of education logistics. Instead of a continuous growth because of increasing numbers of students, higher education institutions, referred to as universities and colleges of higher education, have to deal with an onset shift of centralizing and diminishing resources like classrooms and housing due to budget cuts. In most national systems, those budgets are tied to national expenditures, which are based on public policy (Douglass 2010).

The traditional and more conventional view on education is gradually transforming into a student-central, hands-on learning platform where practices of rote learning are being less applied (Jonassen and Land 2012). Moreover, people are more likely now than before to study at more than one HEI or participate in courses offered for distance education. Tools like e-learning and MOOCs emerge from educational technology and help to opt for those choices. Therefore, most HEIs tend to offer learning programs and courses which enable students to develop a new set of skills they can use to adapt to the demands of the changing world. Instead of following a fixed curriculum scheme, a modular approach is often chosen in which various specialization options are offered. Where, at the one hand, students demand more flexibility from various facets in educational logistics, a trend of diminishing resources on the other hand is clearly visible. This pushes timetabling practices to the limit.

The combination of the receding availability of shared resources and increasing demands, causes HEIs to adapt their timetabling practices in order to maintain quality of studiability, suitable timetables for support staff and the degree of efficiency, whilst maintaining the educational quality levels. Studies have shown these problems in the field of timetabling to cause dissatisfaction amongst students, staff and organization. It is not just the possibilities that increase but also the expectations are much higher (Zusman 2005).

When searching scientific literature databases, one can notice that writings about timetabling practices in higher education are being published in increasing numbers in the last decade (2005–2015). Those writings include publications in the field of timetabling in higher education, practices and tools, timetabling algorithms, and more. Figure 1 reflects this trend when Google Scholar is accessed with searching terms “(Timetabling OR Timetable) AND Higher education”.

Fig. 1 Number of papers found on the subject of timetabling in higher education



The increasing amount of literature suggests that more research is being conducted in the broader field of education logistics. Conducted research in timetabling in HEIs has advanced rapidly in which practices and theories have been developed and elaborated increasingly (Kingston 2007). However, a lot of papers discuss situational topics based on environmental characteristics (McCollum and Ireland 2006), making it essential to identify and differentiate between those characteristics and developments for giving a state-of-the-art overview of timetabling in HEIs. Conducting this research enables us to investigate gaps between theory and practices of methods and processes used in this research domain. The goal of this paper is to look at notable differences in approaches described in recent literature and real-life implementations.

2 Research methodology

The increase in the output of research publications in the field of timetabling in HEIs has led to the fact that it is more difficult to keep track of what work has been established on the various aspects in this field. In order to find out what is state-of-the-art in both the research and in practice, we researched timetabling by identifying evidence, trends and conclusions in relevant studies. Within framing this research, the relations between the components of the problem have to be established and displayed. Figure 2 shows those relations.

The research plan consists of two main subjects: developments in timetabling and evolving characteristics of HEIs. However, this paper does not discuss actual software used in higher education, which is undoubtedly interesting in order to further support this paper but not in the scope.

An up-to-date overview of timetabling in HEIs consists of listing developments in timetabling in combination with the operational and structural characteristics and devel-

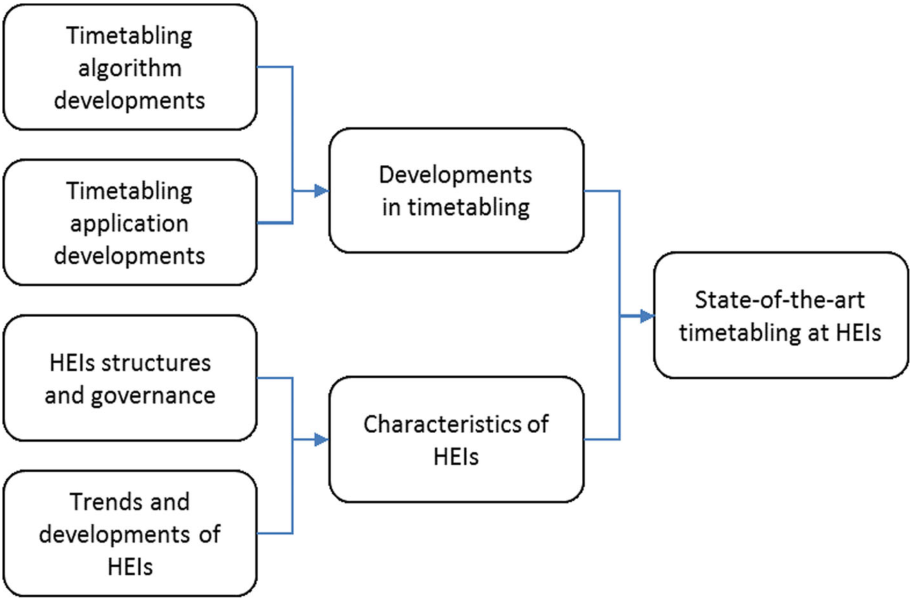


Fig. 2 Research plan to come to a comparison of both timetabling and higher education developments

opments of HEIs. Developments in timetabling encompass research in timetabling domains, with trends and developments of timetabling algorithm developments and timetabling software application developments. Characteristics of HEIs emerge by describing HEIs governance and structures, together with trends and developments of HEIs. The combination of both the characteristics of HEIs and developments in timetabling is a synthesis as a view on state-of-the-art timetabling within HEIs and in which gaps between theory and practice can be identified.

3 Developments in timetabling

This chapter describes developments in solving timetabling optimisation problems. First, the timetabling problem is explained in further details to give a clear understanding of a lacking general solution for timetabling. The second part outlines the advancements of automated timetabling throughout the years.

3.1 The timetabling problem

The constantly moving research field of timetabling has caused rapid developments in theory and practice. Wren (1995) defined timetabling as: "The allocation of given resources to specific objects being placed in space time, in such way as to satisfy as nearly as possible a set of desirable objectives, subjected to constraints." The presence of knowledge for creating timetabling software has led to new insights, like improved methodologies and more comprehensive models (McCollum and Ireland 2006). Also, increased effectiveness of the timetabling process is notable. Appropriate resources are to a greater extent linked to needs of users as well as staff and student. Moreover, those developments encouraged new approaches for space utilisation strategies and interactive timetabling (Burke et al. 2000). Timetabling applications are nowadays capable of applying new techniques and solution algorithms. Techniques and algorithms are taking more and various factors into account like performance issues, constraint requirements and student/personnel interests.

However, the variety of constraints, the diversity of the problem and specific requirements have caused finding an effective and general solution in timetabling to become more difficult (Jat and Yang 2009). There are different kinds of scheduling problems now, and timetabling is stated to be a common problem in this area. The timetabling problem is a so-called NP-hard and NP-complete optimisation problem, depending on the constraints (Even 1975). Feasible, efficient or fast solutions are all synonyms for polynomial time. Yet, none of these apply to the field of timetabling, which means that most of the timetabling challenges are not solvable within a realistic time frame. For these kinds of problems, computational heuristics are often taken into account as a solving strategy, resulting in a non-optimal but hopefully feasible solution (Hidalgo-Herrero et al. 2013). Despite the amount of literature and research dedicated to this problem, a gap still exists between reality and models used, or, in other words, between theory and practice. This is discussed by McCollum and Ireland (2006), who identified that it is extremely difficult to find a generally applicable model whereas different institutions recognise different constraints. Many studies that attempt to propose a model use specific datasets for proving their solution or model (Wren 1995; Schaerf 1999), which to a certain extent excludes generalisability. However, in order to propose an institution-wide timetable a comprehensive formulation of the problem has to be made in which the problem is relevant to real world practices. McCollum and Ireland (2006) emphasises that solutions for this problem must address a wider range of these practices rather than fine-tuning algorithms or meta-heuristics on particular datasets used.

3.2 Research in timetabling domains

Timetabling covers a variety of areas in which a significant amount of research has been conducted. Those broad domains encompass planning and scheduling of educational-, transport-, employee-, sports- and healthcare settings. Within educational timetabling, school timetabling and university timetabling for courses and examination are most studied. However, research in the area of school timetabling has not advanced as rapidly as university examination and course timetabling (Nurmi and Kyngäs 2008). This is due to the fact that studies are done in specific schools, in isolation (Santos et al. 2012), in contrast to university examination and course timetabling where more methods are compared for a set of problems or constraints instead of a study for a single institution.

A significant amount of surveys on educational timetables has been conducted in the past decade. This includes literature presented at conferences dedicated to timetabling practices, like the international conference on the Practice and Theory of Automated Timetabling (PATAT) and the Multidisciplinary International Scheduling Conference: Theory and Application (MISTA), both alternatingly held every 2 years. One of the areas of the research covers methodologies for specific domains of timetabling. Those methodologies aim to solve, and rather optimise, timetabling problems. The constructions of the solutions depend on how the timetabling problem is defined. The definition describes constraints variances and requirements and thus may alter from institution to institution. In recent studies, researchers use standardised formulations of those problems. Bellio et al. (2016) describe the most used variants in the domain of education timetabling. The problem is translated to a specific benchmark set and methodologies. Solutions and models are evaluated on those sets. Hence, researchers aim to evaluate their solution on multiple datasets in order to test for generalisation rather than specification, which is in line with what McCollum advocates. Recent timetabling competitions foster the emergence of standardized benchmark data sets that also aim to provide a ‘real-world’ application.

3.3 Trends and developments

A notable amount of developments regarding timetabling methods and algorithms can be found in studies, surveys and literature. This paragraph outlines those developments in order to classify them.

3.3.1 Timetabling algorithms developments

In this section, trends in solutions over time to solve timetabling problems are discussed. These solutions are differentiated among various fields of optimisation algorithms (Sörensen and Glover 2013). A chronology of metaheuristics is given based on literature and this is further elaborated on. However, these fields are not mutually exclusive. A notable amount of metaheuristics algorithms combines ideas from different fields, called hyper-heuristics. The aim is to provide different ways of finding solutions for the timetabling problem. The chronology consists of a trichotomy, which is about grouping and declaring similar events occurred in various periods of time.

Up to 1995 Welsh and Powell (1967) represented graph colouring strategies for solving timetabling problems. They built the foundation for more sophisticated research on graph heuristics in timetabling (Merlot et al. 2002). Graph colouring timetabling heuristics are helpful methods in which the construct is evaluated on and being improved. Linear and integer programming techniques are mathematical based algorithms and assign integral values to variables. Variations of this technique were, and still are, widely used to solve combinatory optimisation problems. Constraint based techniques originate from research on artificial intelligence (Brailsford et al. 1999). These techniques encompass constraint logic programming and constraint satisfaction techniques. However, such techniques are generally computer extensive by means of an exponential amount of variables. In more recent literature, constraint based techniques are integrated with different heuristics and techniques in order to keep up with other state-of-the-art techniques.

1995–2010 In the late 90 s of last century, methodological approaches for solving timetabling problems were in general being classified into two categories of meta-heuristics: a population-based approach and a single-based approach (Burke et al. 2004). Starting with many candidate solutions, a population-based approach aims to find the best solution in the search space. The solutions are refined in a parallel optimisation environment. A single-based approach works with a single solution and then tries to improve for a better result. The constraints are satisfied in an iterative manner.

Tabu search falls under local search methodologies and is based on steepest descent search, as it tends to explore the search space by not re-interpreting recent moves. There are several relevant papers that carried out a valuable investigation of Tabu search techniques (Di Gaspero and Schaerf 2000; Petrovic and Bykov 2002). The investigations are based on (1) diversification of the neighbourhood whereby the search is extended to find more local optima and (2) intensification of steps made in Tabu search algorithms to find faster solutions.

Simulated annealing (SA) is another local search technique. This technique aims to search for a wider area of search space in which worse steps are accepted and allows for a more extensive search for the optimal solution. SA encompasses a certain amount of variants (Burke et al. 2004; Dowsland 1996), but is often combined with hill climbing techniques (Qu et al. 2009) and constraint programming (Brailsford et al. 1999). In line with local search based techniques, a recent trend recognises the definition of more different neighbourhoods. Structures like variable neighbourhood search (Burke et al. 2010) and large-scale neighbourhood (Meyers and Orlin 2006) search are associated with such techniques.

In the subdivision of population based algorithms, evolutionary algorithms encompass a major set of population based techniques. Genetic algorithms are most common and studied among the evolutionary algorithms. Corne et al. (1994) conducted a research on the use of genetic algorithms in education timetabling and provided a survey on this. Such algorithms are based on best individual solution in the population space and each best solution provides the basis for a new evolutionary cycle (Colorni et al. 1992). A survey of Qu et al. (2009) discusses different kinds of applications of genetic algorithms and how these algorithms are modelled. Memetic algorithms (Burke et al. 1995) is seen as an addition of genetic algorithms. Memetic algorithms are mostly supported by local search methods and have the ability to explore a region of population based method with local search techniques. It is, however, challenging to find the right balance between exploitation of local search and exploration by means of population based methods of the search space. Alkan and Ozcan (2003) elaborated in their study on the use of memetic algorithms in timetabling. They too acknowledge the need to keep a diversified population in order to maintain a right balance of the search space.

Another population based technique which is researched on in greater depths for the last decade is the glroup of ant algorithms (Dorigo and Blum 2005). These algorithms keep track of information gathered during a search, subsequently, and this information is used for generating new solutions in next stages (Qu et al. 2009).

Recent Both single-based and population based approaches have their drawbacks. The main drawback of a single-based approach is that the main focus lies on exploitation rather than exploration. This means that the search space is limited to one trend or solution for the current situation. Other solutions are not considered. On the other hand, population based algorithms often experience premature convergence because of the lack of concentration on current solutions in the search space. Local optima in this search space are made progressively similar to each other, causing a loss of diversity. Lately, most timetabling researchers have focused on local or single based solutions rather than populated based algorithms (Al-Betar and Khader 2012). A development that emanated from standard local and population based solution for timetabling problems is the application of hyper-heuristics. Hyper-heuristics, in contrast to meta-heuristics, search for solutions in the heuristic space instead of the "plain" solution space. In other words, hyper heuristics are a search method in which several heuristics are combined and adapted. The difference between metaheuristics and hyper-heuristics is that hyper-heuristics seek to find a generally applicable methodology instead of solving a particular problem instance.

Although other research in this area cannot be ignored, especially those based on systematic search, metaheuristic approaches proved that they are performing well on benchmark timetabling tests. Moreover, metaheuristics have become increasingly popular in automated timetabling practices by adapting dynamically to constraints and covering a wider variety of optimisation problems (Fig. 3).

Hyper-heuristics consist of search methodologies aimed to operate on a higher abstraction level than optimisation techniques and traditional search methodologies (Burke et al. 2003). One might say that this approach is one step further in comparison to meta-heuristics. Hyper-heuristics have the potential to give generalised solutions to timetabling as a whole. A numerous amount of studies pay attention to a hyper-heuristics approach (Burke et al. 2007; Kiefer et al. 2017) in which basic heuristics are combined with each other.

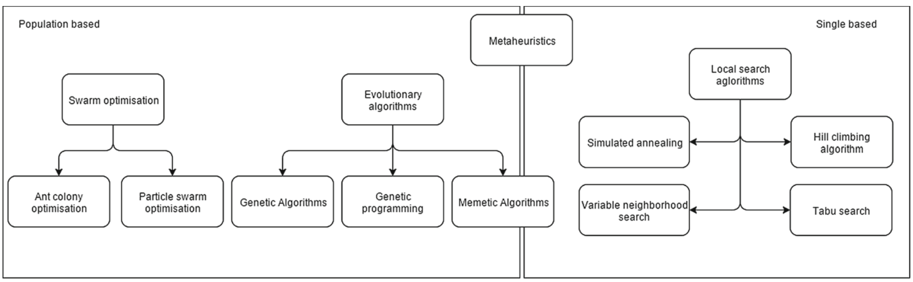


Fig. 3 An algorithm classification

3.3.2 Timetabling applications developments

Timetabling problems and methodologies can be complex, iterative and time consuming. Timetabling developers increasingly adopt a computer-based approach enabling institutions to automate tasks, finding (sub-)optimal solutions and work more efficiently. This section aims to outline and review relevant studies conducted throughout the last decades. The decision to distinct among decades is based on renowned surveys, conducted in the corresponding periods. It is also considered practical in both giving an overview and the possibility to describe developments in better detail. In this section timetabling applications are defined as the set of resources which function in a computerised environment to enhance timetabling practices.

Up to 1980 One of the first applications on a computer was developed by Gunzenhäuser and Junginger (1964). They tested an algorithm combined with simple heuristics on a mainframe computer. The resulting timetable was certainly not optimal and needed modification by hand. In 1980, Schmidt and Ströhlein (1980) provided an annotated bibliography in which early techniques and system implementations were discussed. Most of these systems were based on graph colouring and recursive exchange operations in which partial timetables were extended.

1981–1990 The application of computational timetabling was still not widely accepted in the mid 80's. Most education institutions did not have microcomputers available and the ruling thought about being scheduled by a machine caused resistance (Schmidt and Ströhlein 1980). Werra (1985) proposed graph-, network- and mathematical methods and how they could be used in timetabling programs of application. This study showed that certain requirements were not yet translated into constraints and included as ingredients in the various models. Ferland and Roy (1985) proposed a mathematical model to solve the timetabling problem in a university and implemented it on a microcomputer. The constraints, however, had to be relaxed because the computer was lacking memory space and computational power. Junginger (1986) described various software applications implemented and elaborated on the underlying approaches, which were mostly based on direct heuristics. This research concerned institutions in Germany, where the techniques and tools discussed were of a state-of-the-art nature in that time. Remarkably, literature in this area in the period of 1970–1985 consists mainly of case studies reporting on specific examples of computerised registration (Sabin and Winter 1986). This combination of case studies performed and the changing requirements of different institutions, made it difficult to produce standard computerised solutions. In the ensuing period of early 1985, a significant amount of institutions started to adopt the use of personal computers and were able to use bigger data entries (Molnar 1997).

1991–2000 A study of Bardadym (1995) pointed out various aspects of interactive timetabling for timetabling software. The study elucidated that timetabling software is capable of the following: database corrections, use of spreadsheets and DBMS, using timetabling editors and making use of an object-based interface. The use of those features, however, was mostly restricted to prove the timetables' correctness. The use of meta-heuristics and interactive timetabling were seen as the new wave of computer-aided timetabling. Schaerf (1999) illustrates this trend in a survey of automated timetabling in which the papers in the survey describe to a certain extent the implementation of timetabling software. The survey illustrated how at that time modern heuristics, like evolutionary algorithms, seemed to outperform the more traditional operational research methods. Institutions were now able to generate feasible timetables in an acceptable timeframe. There were still many cases in which the problem was computationally too hard. Schaerf (1999) argued the need for widely accepted benchmarks and a common formulation of the various timetabling problems. The absence of those elements caused algorithms and software application programs being incomparable among each other. A significant number of software applications developed within this period was either a commercial product, which meant it had lost the emphasis on developing the newest algorithms and focused merely on the GUI, or it had been designed for a specific institution (Froese et al. 1998; Carter and Laporte 1997).

2000–2015 State-of-the-art papers nowadays pay attention to problems and challenges featured in work over the last decades. More standardised benchmark datasets become available and researchers explore directions in which the timetabling problem is placed in a real-world problem context (Leung 2004), (McCollum et al. 2010). Standardisation of timetabling benchmarks however, leads to circumstances in which practical, real-world application is not maintainable most of the time due to specific circumstances in every individual institution. In other words, benchmark sets are mainly generated by means of a standard set of constraints or constraints based on specific HEI characteristics. In both cases testing algorithms against each other is not feasible because of the lacking generally applicability of real world problems (McCollum and Ireland 2006). De Causmaecker et al. (2002) discuss how the semantic web and components or formats like XML, can be used in timetabling applications. In a study of Chand (2004), the adaptation of relational databases and the modelling of timetabling data is reviewed. Ranson and Ahmadi (2006) reviewed the limitations of existing timetabling languages and standards and proposed a modern flexible language-independent timetabling model, which could be adopted in timetabling applications. There is an increasing number of models that are used in international timetabling competitions. Precisely these competitions gave rise to much research. Especially the international timetabling competitions (ITC) concern higher education, and have several tracks to apply to different institutions: Curriculum-Based Course Timetabling (CB CTT) and Post-Course Enrolment Timetabling (PE CTT). ITC3 were aimed at secondary schools, but are considered much richer in terms of constraints.

4 Characteristics of HEIs

HEIs are under a growing pressure to deliver a student-central academic climate in which timetabling practices are fuelled by individual preferences (Froese et al. 1998; Muklason et al. 2017). Literature covering timetabling developments alone is not sufficient for satisfying those demands. The operational process of timetabling is embedded in specific institutions and must therefore connect to structural preferences held by these institutions. This results in HEIs influencing the way timetabling applications are adopted by means of their characteristics. Defining these characteristics of HEIs, in turn, is interrelated with (cross-)national ideologies and legislations, which origins can be found in governmental influences and national systems of higher education (Clark 1986). In order to research the gap between theory and practice in greater depths, literature is reviewed concerning characteristics like knowledge levels, shared values and goals, organisational structure and current trends of governance in HEIs.

4.1 Governance of HEIs

Higher education encompasses a process of creating knowledge for enhancing employability and stimulating innovation where learning opportunities are made available through various institutions. HEIs are mostly integrated in a dynamic environment which is controlled and regulated by social, political, economic and institutional aspects (Scott 2001). This regulation is translated in governance and describes to a certain extent how an HEI is organised and managed. Investigating HE governance supports the search to identify characteristics of HEIs because governance is always present in an HEI (Marginson and Considine 2000). Governance embraces the determination of values inside HEIs, resource allocation and missions. The identity and formed culture of each HEI is shaped by legislations of HE governance. Nonetheless, the extensive notion of governance makes it difficult to categorise the structure of various systems in which HEIs are incorporated. Practices of HE systems and HE governance are also still predominantly shaped at a national level (Altbach 2015). A significant amount of research has been dedicated to national and cross-national analysis of HE systems and HEIs, explaining trends and characteristics (Agarwal 2006; Schofer and Meyer 2005).

Rising competitive pressures, demographic and economic developments, as effects of globalisation and internationalisation, stimulated HE governance to reform. A study conducted by Dobbins et al. (2011), proposed three ideal-type models of HE governance in which contemporary policy developments are reflected in (1) the state-centred model; HEIs are seen as state operated institutions. The state is heavily influencing internal matters like HEIs-business relations, quality assurance and efficiency. Education and research must contribute to industrial and technological competitiveness. (2) HEIs as a self-governing community, is a model based on strong state-university partnership, that is governed by assumptions of corporatism and collective agreement. (3) A market-oriented nature. HEIs are seen as economic enterprises in local or global markets (Olssen and Peters 2005) and offer academic services to students. The aim is to bolster the choice of students in order to enhance the quality and diversity of services offered. It is argued that those types are hybridised with each other in various countries.

4.2 Structures of HEIs

In the early 1960's, most European countries placed emphasis on diversification of HE systems. Structures like binary (two)-type and multi-type were more likely to emerge. Those systems had to function as multipurpose, specialised HE. However, some countries continued to use a unitary system in which, for example, universities were the only kind of institutional type (Clark 1986). In the late 1970's, HE systems were increasingly paying attention to informal structural aspects like quality assurance, student excellence, job prosperity of graduates and the reputation of the institution. In the ensuing period, as of the late 1980's, the different kinds of institutional types of HE and diversification in programmes were no longer that relevant (Deem et al. 2007). However, the occurrence of multi-type structures was likely to persist in various countries (Boer et al. 2007; Ahola and Mesikammen 2003). A study conducted by Teichler (2006) discussed why a vast amount of changes in structural developments in HE systems were notable: this has been explained by a number of conceptual frameworks. First, the expansion and diversification of HE systems led to a more diverse need of students. Second, he described an "academic drift" of institutions in order to stabilise themselves and increase status. Finally, he identified a cyclical trend caused by reoccurring events like dropouts, for example. As a result of this cyclical trend, diversification among HEIs is reduced, or different HE types are subjected to segmentation. Around the late 1990's, the tendency arose to make HE systems more similar across Europe. The Bologna process, proposed in 1999, tends to harmonise HE systems throughout Europe in order to ensure compatible degree structures, equal academic qualifications and enhancing the attractiveness of foreign students to study across Europe (Altbach and Knight 2007). Those developments have to foster a structural convergence of HE systems in Europe, making a more generalised view of characteristics in HEIs, which are embedded in HE systems, more admissible. While various aspects proposed in the Bologna process have already been implemented, there is still not a wide framework on a structural level for HE systems which makes up for exceptions.

4.3 Nationalism and globalisation of higher education

Altbach (2015) elaborates in his study on the commodification of HE. He identifies a trend in which HE is increasingly seen as a commodity, which can be purchased by a consumer in order to build a “skill set”. This skill set can be used in the marketplace. Commodification of HE implicates the marketing of knowledge products like advanced training and bolstering of a highly skilled workforce. Two aspects which are interrelated with this are globalisation and internationalisation. Internationalisation of HEIs is mainly focused on fostering global learning experience, attracting overseas students and delivering national programmes abroad. This approach allows for situations in which the time and place dimension is less dependent, whereas the focus on mobility is more important in the learning process. Countries from all over the world move towards the internationalisation of HE. They are opening their doors for foreign universities and programmes, are regulating foreign providers, are marketing national educational products and countries in Europe are harmonising their divergent HE systems as an implication of the Bologna process. Internationalisation and globalisation are intertwined (Teichler 2004). Globalisation of HE stimulates the use of more advanced information and communication technology, the emergence of a world-wide knowledge network, as well as other influences beyond the control of HEIs (Philip et al. 2009). In more recent literature, HEIs are adapting newer IT practices to an ever greater extent (De Wit 2011). Through the use of the internet, programs can easily be offered at foreign universities. As ICT becomes more sophisticated, distant learning or blended learning is becoming more wide spread, in combination with traditional learning. Blended learning is defined as the combination of traditional face-to-face education and technology mediated instruction (Porter et al. 2014). A significant amount of research has been dedicated to the adoption and implementation of blended learning practices. Through the adoption of blended learning, students from different courses can participate in particular blended learning classes. It thus addresses some logistic changes that strengthen the need for a more flexible timetabling process. Another distant learning aspect is the rising topic on Massive Online Open Courses (MOOCs). They can be seen as scalable offerings of online courses which extend existing online learning approaches (Yuan and Powell 2013). MOOCs can give the possibility for freeing resources for HEIs in order to reduce costs and enhance space optimisation strategies, because participants are not bound to any location. Conclusions based on recent literature reflect that the emergence of MOOCs also accounts for structural changes and challenges in HEIs. Such kind of challenges in the field of timetabling in which questions like time-zone- and (fraudulent-free) examination planning arise. In conclusion, MOOCs influence to a certain extent the allocation of resources, which encompasses timetabling practices.

4.4 Competition in higher education

More and more external influences shape the policy, goals and characteristics of HEIs. The emergence of global rankings among HEIs is seen as a powerful stimulus for competitive thrive. HEIs are being constantly compared in a national and international context (Jacob 2015). Even more in the setting of national competition: this global referencing caused that the institutional identity of the individual HEIs is becoming less important than the national identity of HEIs (Teichler 2004). This is in accordance with a later study of Teichler (2006), when he states that most institutions aim to stabilise themselves and tend to attain a higher status by comparing themselves to the most successful HEIs based on rankings. Comparison in this manner causes many institutions to make changes in policy and strategy, which is driven by the norm, promoted by rankings. Students associate these global rankings with education quality and opportunities for a career. So, it is evident that students play a key role in these policy decisions.

The student-as-consumer model has become increasingly prevalent. Many HEIs have begun to adopt customer-based models for students (Clayson and Haley 2005; Cook-Sather et al. 2014). Emergence of marketing plans, marketing promotions by institutions and assessing students' experiences as effectiveness of HE, are examples of such models. Seeing students as customers of HE requires societal needs and norms. Moreover, expectations of the labour market also influence the student-customer-based model, because it is indirectly related to the societal needs incorporated by students.

The student-teacher partnership collaboration is increasingly elaborated on in the last decade. This collaboration defines, and tries to understand, the role of both student and teacher in student learning (Cook-Sather et al. 2014). Within this partnership, insights with reference to this relation student-teacher are collected. Collaborations also aim to study and design teaching and learning together. Hence, this trend makes up for certain changes in structures and planning processes, like timetabling, in HEIs. To foster such developments in a more demand driven education structure, a flexible process of planning is essential. In this sense, the partnership must be harmonised in order to support a flexible environment between students and the HEIs. Direct implications are smaller-scale education, a shorter learning circle and more teacher FTEs per amount of students (State_government 2015).

5 Conclusions and discussion

Information technology became more sophisticated in the last decades. Timetabling software applications adapted and were made able to generate and optimise more suitable timetables in an automated setting for higher education institutions. Research on literature identified that applications of renowned vendors gradually adapted the use of spreadsheets, a database management system, timetabling editors, web-based tools and a more enhanced graphical user interface. So, timetabling software applications are using—and are therefore capable—of utilising modern (state-of-the-art) techniques.

The other component encompasses the working mechanism within, the solving method, the algorithm that is used in order to create a working timetable. The timetabling problem is very challenging and one needs to explore many possible combinations to find a list of acceptable solutions. Since it is impractical to enumerate all combinations, one will choose an approach that computes a subset, or a smaller part, of the solution space. These approaches are defined as heuristics, which are solving strategies that are used for hard optimisation problems. A particular set of algorithms, named heuristic algorithms, proved themselves effective to generate the best sub-optimal solution. Such algorithms can give an approximation that is considered as a solution which is acceptable. Heuristic algorithms, therefore, seem to outperform traditional methods and such algorithms are even combined in order to strengthen each other. The most recent developments are to be found in the field of hyper-heuristics. Such solution strategies aim to generate timetables by means of selecting the right algorithms in turn. However, commercial timetabling products seem to lack focus on the actual implementation of such solving methods in timetabling applications.

It has become clear that timetabling software applications are provided with most modern tools, technologies and techniques (Qu et al. 2009). However, a study conducted by Pillay

(2014) discussed that there still exists a gap between academia and industry. While academia tend to develop intelligent and profound methods to solve timetabling problems, industry appears to develop and design an easy to use interactive tool that aims to meet the needs of teaching and administration staff. Once industry has a productive timetabling application, they stop implementing the latest research on timetabling in their software. Most timetabling applications nowadays may have a nicer user interface than, say, 20 years ago, but still use timetabling algorithms that stem from the beginning of their software production, somewhere in the late 80 or 90 s from last century. This might be related to the fact that insufficient effort on the side of application development has been undertaken to translate real world situations into the constraints that have been identified in the format for the benchmark sets. Bridging this gap between the latest timetabling research and the implemented algorithms in timetabling applications can produce robust, efficient and to a certain extent general, timetabling applications in which the most modern heuristic approaches for timetabling problems are combined with the benefits of an easy to use timetabling application.

We analysed that there are a lot of changes and developments going on in the fields of both higher education and timetabling software applications. Both government and society are setting demands for HEIs, and in turn those HEIs demand more effectiveness and efficiency from equipment, students, teachers and staff. Timetabling in HEIs, consequently, has to deal with ever decreasing resources, proportionally to the increase of students, and is still expected to focus on delivering a feasible set of timetabling solutions. Defining the characteristics of HEIs gave insights on why timetabling problems are getting increasingly more complex and why the need for more flexible timetabling solutions exists. Timetabling software applications adapted in HEIs that should bolster those solutions are becoming more sophisticated and advanced, more user-friendly and reusable. However, a fundamental change is still not visible. Renowned timetabling applications lack state-of-the-art timetabling solving methods, like hyper-heuristic algorithms, which is being heavily researched on in literature lately. This research provided and acknowledges those flaws (Fig. 4). Software applications tend to focus on GUI rather than underlying algorithms

Successful implementations can align software engineering with algorithmic strength borrowed from research in the PATAT or MISTA community as well as in the metaheuristic and constraint processing communities. But such a state-of-the-art system that can timetable a complete university is rare, especially when satisfaction of the users is measured.

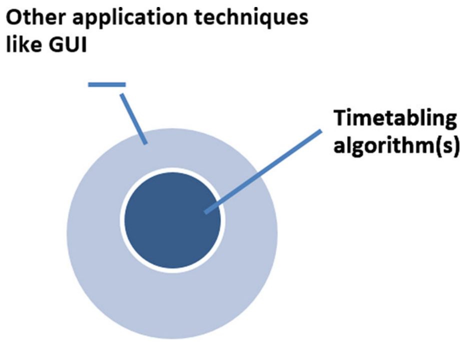


Fig. 4 Software applications focus on GUI rather than on underlying algorithms

6 Future research

Research models should be enhanced with additional literature and situational methods in order to do a more profound claim on gap analysis. Studies conducted by Barry McCollum and Ireland (2006) and Pillay (2014) identified these gaps and it would be valuable to investigate in further detail whether some have been tightened.

References

Agarwal, P. (2006). *Higher education in India: The need for change*. Working Papers id: 576, eSocialSciences. http://deas.repec.org/p/ess/wpaper/d576.html.

Ahola, S., & Mesikammen, J. (2003). Finnish higher education policy and the ongoing Bologna process. *Higher Education in Europe*, *28*(2), 217–227.

Al-Betar, M. A., & Khader, A. T. (2012). A harmony search algorithm for university course timetabling. *Annals of Operations Research*, *194*(1), 3–31.

Alkan, A., & Ozcan, E. (2003). *Memetic algorithms for timetabling.* Paper presented at the evolutionary computation, 2003. The 2003 congress on CEC'03.

Altbach, P. (2015). Knowledge and education as international commodities. *International Higher Education*, *28*, 1–3.

Altbach, P. G., & Knight, J. (2007). The internationalization of higher education: Motivations and realities. *Journal of Studies in International Education*, *11*(3–4), 290–305.

Bardadym, V. A. (1995). Computer-aided school and university timetabling: The new wave. *Paper presented at the international conference on the practice and theory of automated timetabling*.

Bellio, R., Ceschia, S., Di Gaspero, L., Schaerf, A., & Urli, T. (2016). Feature-based tuning of simulated annealing applied to the curriculum-based course timetabling problem. *Computers & Operations Research*, *65*, 83–92.

Brailsford, S. C., Potts, C. N., & Smith, B. M. (1999). Constraint satisfaction problems: Algorithms and applications. *European Journal of Operations Research*, *119*(3), 557–581.

Burke, E., Bykov, Y., Newall, J., & Petrovic, S. (2004). A time-predefined local search approach to exam timetabling problems. *IIE Transactions*, *36*(6), 509–528.

Burke, E. K., Cowling, P., Silva, J. L., & McCollum, B. (2000). Three methods to automate the space allocation process in UK universities. *Paper presented at the proceedings of the international conference on the practice and theory of automated timetabling (PATAT 2000)*, Heidelberg.

Burke, E. K., Eckersley, A. J., McCollum, B., Petrovic, S., & Qu, R. (2010). Hybrid variable neighbourhood approaches to university exam timetabling. *European Journal of Operational Research*, *206*(1), 46–53.

Burke, E. K., Hart, E., Kendall, G., Newall, J., Ross, P., & Schulenburg, S. (2003). Hyperheuristics: An emerging direction in modern search technology. In: F. Glover & G. Kochenberger (Eds.), *Handbook of metaheuristics* (vol. 16, pp. 457–474). Dordrecht: Kluwer Academic Publishers.

Burke, E. K., McCollum, B., Meisels, A., Petrovic, S., & Qu, R. (2007). A graph-based hyper-heuristic for educational timetabling problems. *European Journal of Operational Research*, *176*(1), 177–192.

Burke, E. K., Newall, J. P., & Weare, R. F. (1995). A memetic algorithm for university exam timetabling. *Paper presented at the international conference on the practice and theory of automated timetabling*.

Carter, M. W., & Laporte, G. (1997). Recent developments in practical course timetabling. *Paper presented at the international conference on the practice and theory of automated timetabling*.

Chand, A. (2004). A constraint based generic model for representing complete university timetabling data. *Paper presented at the proceedings of the 5th international conference on the practice and theory of automated timetabling*.

Clark, B. R. (1986). *The higher education system: Academic organization in cross-national perspective*. Berkeley: University of California Press.

Clayson, D. E., & Haley, D. A. (2005). Marketing models in education: Students as customers, products, or partners. *Marketing Education Review*, *15*(1), 1–10.

Colorni, A., Dorigo, M., & Maniezzo, V. (1992). *A genetic algorithm to solve the timetable problem* (pp. 90–060). Milan, Italy TR: Politecnico di Milano.

Cook-Sather, A., Bovill, C., & Felten, P. (2014). *Engaging students as partners in learning and teaching: A guide for faculty*. Hoboken: Wiley.

Corne, D., Ross, P., & Fang, H.-L. (1994). Evolutionary timetabling: Practice, prospects and work in progress. *Paper presented at the in proceedings of the UK planning and scheduling SIG workshop*, Strathclyde.

De Boer, H. F., Enders, J., & Leisyte, L. (2007). Public sector reform in Dutch higher education: The organizational transformation of the university. *Public Administration*, *85*(1), 27–46.

De Causmaecker, P., Demeester, P., & Berghe, G. V. (2002). Using web standards for timetabling. *Paper presented at the proceedings of 4th international conference on the practice and theory of timetabling (patat 2002)*.

De Werra, D. (1985). An introduction to timetabling. *European Journal of Operational Research*, *19*(2), 151–162.

De Wit, H. (2011). Globalisation and internationalisation of higher education. *rusc*, *8*(2), 241–247.

Deem, R., Hillyard, S., & Reed, M. (2007). *Knowledge, higher education, and the new managerialism: The changing management of UK universities*. Oxford: Oxford University Press.

Di Gaspero, L., & Schaerf, A. (2000). Tabu search techniques for examination timetabling. *Paper presented at the proceedings of the international conference of the practice and theory of automated timetabling (PATAT 2000)*, Heidelberg.

Dobbins, M., Knill, C., & Vögtle, E. M. (2011). An analytical framework for the cross-country comparison of higher education governance. *Higher Education*, *62*(5), 665–683.

Dorigo, M., & Blum, C. (2005). Ant colony optimization theory: A survey. *Theoretical Computer Science*, *344*(2–3), 243–278.

Douglass, J. A. (2010). *Higher education budgets and the global recession: Tracking varied national responses and their consequences*. Retrieved from Berkely:

Dowsland, K. A. (1996). Simulated annealing solutions for multi-objective scheduling and timetabling. *Modern Heuristic Search Methods*. 155–166.

Even, S., Itai, A., & Shamir, A. (1975). On the complexity of time table and multi-commodity flow problems. *Paper presented at the 16th annual symposium on foundations of computer science, 1975*.

Ferland, J. A., & Roy, S. (1985). Timetabling problem for university as assignment of activities to resources. *Computers & Operations Research*, *12*(2), 207–218.

Froese, A. D., Gantz, B. S., & Henry, A. L. (1998). Teaching students to write literature reviews: A meta-analytic model. *Teaching of Psychology*, *25*(2), 102–105.

Gunzenhäuser, R., & Junginger, W. (1964). Über eine Methode zur Erstellung von Schulstundenplänen mit Hilfe einer Ziffernrechenanlage. *MTW*, *11*, 100.

Hidalgo-Herrero, M., Rabanal, P., Rodriguez, I., & Rubio, F. (2013). Comparing problem solving strategies for NP-hard optimization problems. *Fundamenta Informaticae*, *124*(1–2), 1–25.

Jacob, W. J. (2015). Globalization and higher education policy reform. In *Second international handbook on globalisation, education and policy research* (pp. 151–165). Springer.

Jat, S. N., & Yang, S. (2009). A guided search genetic algorithm for the university course timetabling problem. Schneider-Brunel.

Jonassen, D., & Land, S. (2012). *Theoretical foundations of learning environments*. Abingdon: Routledge.

Junginger, W. (1986). Timetabling in Germany—a survey. *Interfaces*, *16*(4), 66–74.

Kiefer, A., Hartl, R. F., & Schnell, A. (2017). Adaptive large neighborhood search for the curriculum-based course timetabling problem. *Annals of Operations Research*, *252*(2), 255–282.

Kingston, J. H. (2007). The KTS high school timetabling system. *Paper presented at the proceedings of the international conference on the practice and theory of automated timetabling (PATAT 2006)*, Heidelberg.

Leung, J. Y. (2004). *Handbook of scheduling: Algorithms, models, and performance analysis*. Boca Raton: CRC Press.

Marginson, S., & Considine, M. (2000). *The enterprise university: Power, governance and reinvention in Australia*. Cambridge: Cambridge University Press.

McCollum, B., & Ireland, N. (2006). University timetabling: Bridging the gap between research and practice. *Paper presented at the proceedings of the international conference on the practice and theory of automated timetabling (PATAT 2006)*.

McCollum, B., Schaerf, A., Paechter, B., McMullan, P., Lewis, R., Parkes, A. J., et al. (2010). Setting the research agenda in automated timetabling: The second international timetabling competition. *INFORMS Journal on Computing*, *22*(1), 120–130.

Merlot, L. T., Boland, N., Hughes, B. D., & Stuckey, P. J. (2002). A hybrid algorithm for the examination timetabling problem. *Paper presented at the Proceedings of the international conference on the practice and theory of automated timetabling (PATAT 2002)*, Heidelberg.

Meyers, C., & Orlin, J. B. (2006). Very large-scale neighborhood search techniques in timetabling problems. *Paper presented at the international conference on the practice and theory of automated timetabling*.

Molnar, A. (1997). Computers in education: A brief history. *The Journal*, *24*(11), 63–68.

Muklason, A., Parkes, A. J., Özcan, E., McCollum, B., & McMullan, P. (2017). Fairness in examination timetabling: Student preferences and extended formulations. *Applied Soft Computing*, *55*, 302–318.

Nurmi, K., & Kyngäs, J. (2008). A conversion scheme for turning a curriculum-based timetabling problem into a school timetabling problem. *Paper presented at the Proceedings of the 7th international conference on the practice and theory of automated timetabling (PATAT 2008)*, Heidelberg.

Olssen, M., & Peters, M. A. (2005). Neoliberalism, higher education and the knowledge economy: From the free market to knowledge capitalism. *Journal of Education Policy*, *20*(3), 313–345.

Petrovic, S., & Bykov, Y. (2002). A multiobjective optimisation technique for exam timetabling based on trajectories. *Paper presented at the Proceedings of the international conference on the practice and theory of automated timetabling (PATAT 2002)*, Heidelberg.

Philip, G., Altbach, L., Reisberg, L., & Rumbley, E. (2009). Trends in global higher education: Tracking an academic revolution. *Paper presented at the a report prepared for the UNESCO 2009 world conference on higher education*.

Pillay, N. (2014). A survey of school timetabling research. *Annals of Operations Research*, *218*(1), 261–293.

Porter, W. W., Graham, C. R., Spring, K. A., & Welch, K. R. (2014). Blended learning in higher education: Institutional adoption and implementation. *Computers & Education*, *75*, 185–195.

Qu, R., Burke, E. K., McCollum, B., Merlot, L. T., & Lee, S. Y. (2009). A survey of search methodologies and automated system development for examination timetabling. *Journal of scheduling*, *12*(1), 55–89.

Ranson, D., & Ahmadi, S. (2006). An extensible modelling framework for timetabling problems. *Lecture notes in Computer Science*, *3867*, 383–393.

Sabin, G. C. W., & Winter, G. K. (1986). The impact of automated timetabling on universities-a case study. *Journal of the Operational Research Society*, *37*(7), 689–693.

Santos, H. G., Uchoa, E., Ochi, L. S., & Maculan, N. (2012). Strong bounds with cut and column generation for class-teacher timetabling. *Annals of Operations Research*, *194*, 399–412.

Schaerf, A. (1999). A survey of automated timetabling. *Artificial Intelligence Review*, *13*(2), 87–127.

Schmidt, G., & Ströhlein, T. (1980). Timetable construction-an annotated bibliography. *The Computer Journal*, *23*(4), 307–316.

Schofer, E., & Meyer, J. W. (2005). The worldwide expansion of higher education in the twentieth century. *American Sociological Review*, *70*(6), 898–920.

Scott, W. R. (2001). *Instituitions and organizations*. Thousande Oakes: Sage.

Sörensen, K., & Glover, F. W. (2013). Metaheuristics. In: S. I. Gass & M. C. Fu (Eds.), *Encyclopedia of operations research and management science* (pp. 960–970). New York: Springer.

State_government. (2015). Hoger onderwijs kleinschaliger, op maat en nog beter. Retrieved from https://www.rijksoverheid.nl/actueel/nieuws/2015/07/07/hoger-onderwijs-kleinschaliger-op-maat-en-nog-beter.

Teichler, U. (2004). The changing debate on internationalisation of higher education. *Higher Education*, *48*(1), 5–26.

Teichler, U. (2006). Changing structures of the higher education systems: The increasing complexity of underlying forces. *Higher Education Policy*, *19*(4), 447–461.

Welsh, D. J., & Powell, M. B. (1967). An upper bound for the chromatic number of a graph and its application to timetabling problems. *The Computer Journal*, *10*(1), 85–86.

Wren, A. (1995). Scheduling, timetabling and rostering—a special relationship? *Paper presented at the proceedings of the international conference on the practice and theory of automated timetabling (PATAT 1995)*, Heidelberg.

Yuan, L., Powell, S. & JISC, CETIS (2013). MOOCs and open education: Implications for higher education.

Zusman, A. (2005). Challenges facing higher education in the twenty-first century. *American higher education in the twenty-first century: Social, political, and economic challenges, 2*, 115–160.