

OPERATIONS RESEARCH AND SCHEDULING

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Abstract

In this manuscript, an overview is given of the activities done at the Operations Research and Scheduling (OR&S) research group of the faculty of Economics and Business Administration of Ghent University. Unlike the book published by [1] that gives a summary of all academic and professional activities done in the field of Project Management in collaboration with the OR&S group, the focus of the current manuscript lies on academic publications and the integration of these published results in teaching activities.

An overview is given of the publications from the very beginning till today, and some of the topics that have led to publications are discussed in somewhat more detail. Moreover, it is shown how the research results have been used in the classroom to actively involve students in our research activities.

1 Introduction

A university is an institution of higher education and research which grants academic degrees in a variety of subjects. It prepares young people for the outside world on the job market and a future career in a variety of business and/or research environments. The Operations Research and Scheduling (OR&S) group is a research group that is active at the Faculty of Economics and Business Administration at Ghent University and carries out research in collaboration with various companies, colleagues from international research groups and Vlerick Business School.

The faculty of Economics and Business Administration of Ghent University (Belgium) boasts a dynamic team of about 270 employees offering theoretically founded, high-quality and socially relevant education, research and scientific services to approximately 2,500 full-time students as well as to the community in the fields of economics, business economics and business engineering (www.feb.ugent.be).

Vlerick Business School is a leading international business school and offers fully-accredited, world-class education programmes combining a healthy mix of theoretical knowledge and practical insight. It is a leading academic institution with a strong tradition of innovative and independent research, and is consistently ranked among the top business schools in Europe and the world (www.vlerick.com).

All work presented in this article is done at one of these two institutions, often in collaboration, seldom in separation, in order to illustrate the link between research and teaching on the one hand and between teaching and practice on the other hand. Making these connections is crucial to get the students involved in the themes of the courses and better prepares them for their future career.

Figure 1 graphically illustrates the three connections that comprise the topic of this article. The connection between research and teaching is mainly made in the Business Engineering programme at Ghent University and MBA teaching at Vlerick Business School. The connection between teaching activities and the practical business world is mainly made by OR-AS, a company providing free versions of two commercial software tools and a business game to the students. Finally, EVM-Europe is an organisation that aims at connecting the research activities to the business world by organising a yearly event where “research meets practice”.

The purpose of this paper is to give a full summary of all research work done at the OR&S research group. Although it is recognised that a lot of excellent research on the Project Management theme is done at various institutions in the world, no other reference than the OR&S references will be given. Hence, this article is not intended to give a literature overview nor a summary of state-of-the-art research, but instead to present a flashback of the last decade(s) on the work done at the OR&S group. Therefore, the target audience of this article consists of colleagues and friends, students and researchers who have collaborated with us through the years. Most of all, this article acts as a summary for students who want to join our group, as a regular student during a group work in one of the courses at the Business Engineering programme, for a master thesis, as a PhD student, or in any other collaborative way.

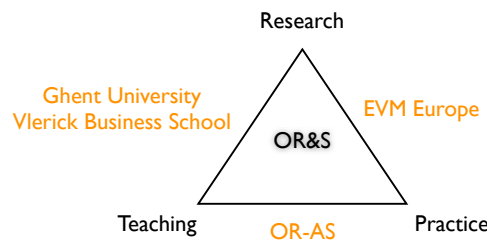


Figure 1: Connecting research and teaching with the business world (practice) at OR&S

The outline of this article is as follows. Section 2 gives an overview of the research papers written at the OR&S group till today. All papers will be ranked by year and a short summary of the process resulting in the publication outcome will be given. In section 3, the same papers will be classified into different topics, from Project Management and Scheduling to Personnel Scheduling and Project Control. Section 4 discusses the relevance of research for our teaching activities, both at the university and business school and the way the research is embedded in the teaching curriculum. It also shows how research can be a driver to let students get involved in the professional business world. Section 5 gives an overall conclusion of the themes discussed in this article.

2 The papers

2.1 The past

Before 2000: The years before the 21st century were the years where I was introduced to the world of Operations Research and Project Management. It was a journey through the literature searching for a problem that is complex and challenging. The literature on project scheduling was full of these problems. After a few years of searching and developing new algorithms, a first publication on the discrete time/cost trade-off problem (DTCTP) using the branch-and-bound technique based on the Fulkerson labeling algorithm was published in [2]. More than a decade later, the algorithm is still very relevant since it is used to calculate optimal solutions for time/cost trade-off files developed in ProTrack and the Project Scheduling Game (see section 4).

2001: In the early years of the 21st, the project scheduling literature was mainly developing solution methods for the so-called resource-constrained project scheduling problem (RCPSP). In this problem, a set of activities of a project needs to be scheduled within the limited availability of resources such that the total time is minimised. Instead of focusing on this classic and challenging optimisation problem, I chose to put all my research effort on an extension of this problem type by adding activity cash flows. Rather than minimising the total project duration, the objective was to maximise the net present. This problem is known as the resource-constrained project scheduling problem with discounted cash-flows (RCPSP-DC). The relevance of optimising cash flows in project planning and scheduling was inspired by the knowledge from literature that financial optimisation in project management is highly beneficial for big capital intensive projects with a long duration. In later years (cf. supra) various other extensions of the classic RCPSP have been investigated by the OR&S members.

The RCPSP-DC has been optimally solved by the branch-and-bound procedure of [3] and has been published in the flagship journal *Management Science*. From that moment, various extensions of the cash-flow models have been added to the classic RCPSP-DC leading to a variety of project scheduling algorithms. In [4], the activity cash flows were linearly dependent on the start or finish time of the activity, i.e. when activities are scheduled later in time, their cash flows could linearly decrease. Inspired by the principle of just-in-time manufacturing, an extension to penalties for earliness and lateness of activities has led to the resource-constrained project scheduling problem with weighted earliness/tardiness penalty costs (RCPSP-WET) as published in [5].

2002: In 2002, an extension of the DTCTP problem has been investigated by [6] using so-called time-switch constraints that specify work and rest times to project activities.

2003: The number of solution procedures and algorithms developed at the OR&S group increased the need for a well-designed set of project data to test the quality of the solution methods. This has led to the development of a project data generator, known as RanGen (random network generator). A first version of this generator is published in [7].

Meanwhile, various algorithms have been developed for extensions of the RCPSP-DC, such as the optimisation of progress payments in projects published by [8] and a case study with real project data from a water purification company in Belgium as shown in [9]. In that year, a first Dutch article on the RCPSP-DC has been published in [10].

2004: 2004 was a bad year for science since we were not able to publish a single article. I guess we were just working hard on article revisions and/or preparing new articles to be published in 2005 and later.

2005: In 2005, two extensions on the DTCTP have been developed. A first extension presents new computational results with time switch constraints [11] while a second one is the development of a student game, known as the Project Scheduling Game (PSG) with time/cost trade-offs [12].

2005 was also the year in which the first algorithm had been developed for the basic problem type (RCPSP), resulting in a bi-population meta-heuristic solution method developed by [13]. Many other algorithms have followed in later years.

As a side track, an introduction article has been written on supply chain management in the Management Jaarboek [14].

2006: 2006 was a turning point for OR&S thanks to the growing number of publications and the variety of research topics.

Thanks to the development of two new solution methods for the RCPSP, a scatter search method [15] and an electromagnetic solution approach [16], we were able to deliver the currently best known solutions in the literature.

Extending the knowledge and available procedures of resource constrained project scheduling problems were at full speed. In [17], the recursive method for maximising the net present value used in the RCPSP-DC was published. Other extensions to the resource- constrained project scheduling problem with work continuity constraints (RCPSP-WC) [18] and the resource-constrained project scheduling problem with quality dependent time slots (RCPSP-QTS) [19] were presented and published.

The growing number of algorithms for the RCPSP and its extensions created a certain awareness that these algorithms only construct project schedules under various settings, while the real relevance in practice lies in the use of these schedules during project progress to control the performance of the projects and to take actions when project tend to run in trouble. A well-known technique to control projects is Earned Value Management (EVM), that soon became a new research topic at OR&S. In [20], three methods to measure the time performance of projects were classified and compared. This publication was enthusiastically read by professionals and has led to two articles written in Dutch [21, 22].

2006 was also the year in which we started a new research track, focusing on optimising the schedules of nurses. In [23], a scatter search solution method has been developed for this well-known nurse scheduling problem (NSP).

2006 was clearly the year of the change, focusing on extensions of the current work. It had an impact on all our future research activities.

2007: The RCPSP and its extensions were still on the research radar of OR&S. In [24], a decomposition based heuristic for the RCPSP has been published in the flagship Operations Research journal. The use of four heuristics for the DTCTP and its extensions have been published in [25]. Moreover, the relevance of the RCPSP-WC has been shown by [26] for the Westerschelde tunnel project at the Netherlands.

The research to project control and EVM started to lift off thanks to a simulation study written by [27] and an acceptance in an American professional journal "The Measurable News" [28].

The NSP has further been investigated, leading to the development of an electromagnetic search method [29] and a data generator to automatically create data for testing known as the NSP Library NSPLib [30].

Totally new to the OR&S group was the use of Operations Research techniques in a Management Accounting setting. The hard work during the summer in London and the simulation of accounting errors led to a publication in The Accounting Review [31] and soon another publication would follow.

As a side track, an introduction article on quality management was written in Dutch by [32].

2008: The study in Management Accounting and its robustness for errors led to a second publication in [33]. Similarly, the need for the automatic generation of project data led to a second version of RanGen in [34].

The RCPSP research has been extended to more realistic problem definitions. A search of the impact of activity assumptions on the resource use resulted in the publication in [35] while the presence of setup times and fast tracking was investigated by [36].

The research on project control was at full speed in 2008, leading to two publications in popular magazines [37, 38] and an award in Rome by the International Project Management Association [39].

A comparison of various crossovers used in meta-heuristic solution methods for the NSP was published in [40].

2009: The RCPSP-DC was still highly relevant for the research group, leading to a genetic algorithm solution method published in [41]. A new extension to the RCPSP, known as the resource-constrained project scheduling problem with multiple modes (RCPSP-MM) saw the light in OR&S, leading to the development of an artificial immune system method [42].

The research on project control resulted in another publication in the Measurable News [43] as well as a book chapter on static and dynamic drivers for forecasting accuracy during project control [44].

After a few publications on the NSP, it was about time to characterise the problem and its generated instances in [45]. Meanwhile, the impact of nurse characteristics on cyclic scheduling for the NSP was published in [46]. The experience built up during the last years on optimising very complex and challenging problems was illustrated on the production problem at Arcelor Mittal in [47].

2010: The RCPSP-DC has never been forgotten at OR&S, and this time a scatter search procedure to construct the currently best known solutions was developed by [48]. Likewise, the RCPSP-MM is solved by a genetic algorithm allowing activity splitting [49].

The research on project control gradually become more mature and 2010 was the year to link the EVM methods with Schedule Risk Analysis [50] in order to focus on an integrated project control approach. All the work on project control was summarised in the book “Measuring Time” [51] and promoted in [52].

The development of a branch-and-bound procedure for the NSP has been done by [53], and the experience in personnel scheduling was extended to the airline sector, using a scatter search algorithm [54].

Thanks to the success of the Business Engineering program at Ghent University and the need to illustrate the relevance of Operations Research to MBA students at Vlerick Business School, a student model to assign exams to students working in groups was developed and published in [55].

2011: 2011 was yet another year to expand the focus and the research direction. Using Operations Research methods for manufacturing problems led to the development of meta- heuristics for the single machine scheduling problem [56] and the job shop scheduling problem [57], and their relevance was illustrated on a case study in a production company [58].

Despite this change in research direction, the good old traditional research topics had not disappeared.

[59] investigated the impact of resource scarceness for the RCPSP-MM and [60] developed a SAT procedure for this problem.

The research track on project control led to the development of two alternative control methods, known as top-down and bottom-up project control [61] and some findings on adding value to EVM were published in [62].

The NSP research track led to an evolutionary algorithm [63] and the impact of variable workload in the airline industry was investigated by [64].

2012: The research on project control was at a point that integrating the results in an integrated dynamic scheduling framework was the next logical step to take. This resulted in the book “Dynamic scheduling” published by [65] and an article in [66]. The need to make the connection between research and practice led to a study on project control with real data [67] as well as a presentation that shows the need of this connection in [68].

The research on the single machine scheduling problem was extended with release times and family setups [69] and some findings on the use of genetic algorithms were summarised in [70]. Moreover, a set of priority rule based solution methods for solving the job shop scheduling problem was published by [71].

2013: The research on project scheduling also led to publications, such as the development of a solution method for the so-called resource availability cost problem (RACP) [72].

The research on NSP and personnel scheduling in general was very successful in 2013, leading to an integrated nurse staffing and scheduling model [73], some interesting insights in nurse schedule constructions [74], the analysis of nursing organisational structures [75] and an artificial immune system for nurse re-rostering [76].

A comparison of solution strategies for both the RCPSP, RCPSP-DC and the NSP was described by [77] and finally, in the book “The Art of Project Management: A Story about Work and Passion” [1], an overview is given about the recent endeavours done in the past and the ideas that will be done in the future. It tells about the products and ideas in Project Management and gives a brief overview of the most important people who inspired the OR&S group for the work that has been done in the past. It does not look at the Project Management work from only a research and teaching point-of-view like it is done in this article, but also from a commercial point-of-view. It tells about work, and the passion that has led to the results of the hard work. It is not a scientific book. It is not a managerial book either. It is just a story ... about work and passion.

2.2 The future

Given all the work that is done in the past, I believe that the main focus for the future research should lie in further improving and integrating the three aspects of dynamic scheduling. An integrated baseline scheduling/risk analysis/project control system should lead to better models and a higher interest in Project Management. This research will be done in the near future and is funded by Ghent University through concerted research action funding.

Concerted research actions (CRAs) are research projects with a duration of six years of which the scientific excellence can be demonstrated on the basis of objective data, more specifically on the basis of publications and other indicators that show the scientific quality of the research group OR&S. In 2011, the research proposal entitled “Searching for static and dynamic project drivers to predict and control the impact of management/contingency reserve on a project’s success” was awarded after a review process and a final presentation to the jury.

This research project started in 2012 in collaboration with the George Washington University (US), University College London (UK) and CERN (Switzerland) and the aim is to move the research in project management and dynamic scheduling towards a higher level. Preliminary research results will be spread on the PM Knowledge Center website [81] and at international conferences, such as the EVM Europe conference [78]. The research should lead to an integrated view on project management and control and to publications in high-quality international journals. Without any doubt, for OR&S, the best is yet to come.

3 The topics

In the previous sections, the publications of the OR&S research were presented in a chronological order showing the progress starting from a single person group and ending with a team of researchers investigating various business themes. The current section will review the OR&S research outcome and classify them in the different business themes and research topics.

3.1 Dynamic scheduling

The term dynamic scheduling is used to refer to an integrative project control approach using three main dimensions which can be briefly outlined along the following lines:

- Baseline scheduling is necessary to construct a timetable that provides a start and finish date for each project activity, taking activity relations, resource constraints and other project characteristics into account, and aiming to reach a certain scheduling objective.
- Risk analysis is crucial to analyse the strengths and weaknesses of the project baseline schedule in order to obtain information about the schedule sensitivity and the impact of potential changes that undoubtedly occur during project progress.
- Project control is essential to measure the (time and cost) performance of a project during its progress and to use the information obtained during the scheduling and risk analysis steps to monitor and update the project and to take corrective actions in case of problems.

An overview of recent studies is given in the book by [65] and the link to professional organisations and products for dynamic scheduling can be found in [1]. In the following subsections, the three main dimensions of dynamic scheduling will be discussed. The use and importance of data generation to carry out research is also mentioned.

Data generation: In order to carry out research and to be able to test the new algorithms, project data has to be available. Testing new algorithms or other novel ideas is done using a well considered and balanced view between theoretical fictitious project data and empirical real project data. Using fictitious project data allows the researchers to have full control on the project parameters in order to obtain and present general results that are applicable to a wide variety of projects. Afterwards, these general results can be translated into practical guidelines and rules-of-thumb that differ from project to project, company to company and sector to sector.

Therefore, data generators have been developed at OR&S, resulting in two versions of RanGen, published in [7, 34]. The validation of results on empirical project data is done in case studies, as briefly discussed in section 3.5. The data generators can be downloaded from www.projectmanagement.ugent.be. Some of the data sets used in research studies on risk analysis and project control can be downloaded from www.or-as.be/measuringtime.

Baseline scheduling: Constructing schedules for projects has been the topic since the first paper published in 1998 and will be a never-ending topic of research in the future. Resource-constrained project scheduling algorithms with time, net present value, work continuity of quality objectives as well as with extensions to setup times, to multiple modes and time/cost trade-offs have been investigated at the OR&S research group. The RCPSP has been investigated under different optimisation objectives and/or activity extensions as summarised along the following lines:

- RCPSP: Minimising the total duration of the project with limited resources is done in [13, 15, 16, 24, 35, 77].
- RCPSP-DC: Maximising the net present value using discounted cash flows and various cash flow models is done in [3, 4, 8, 9, 10, 17, 36, 41, 48, 77].
- RCPSP-WET: Minimising the weighted earliness/tardiness penalty costs is done in [5].

- RCPSP-WC: The minimisation of the idle time of resources using so-call work continuity constraints has been investigated in [18, 26].
- RCPSP-QTS: Optimising the timing of activities by incorporating quality dependent time slots has been presented in [19].
- RACP: The resource availability cost problem determines the optimal level of resources by minimising their cost, and has been investigated by [72].
- RCPSP-MM: Extending the RCPSP to multiple activity/duration options for activities extends the problem to the RCPSP-MM and is analysed by [42, 49, 59, 60].

While the RCPSP mainly focuses on the use of limited renewable resources, the use of non-renewable resources is also an important research topic in project scheduling. The importance of time/cost trade-off optimisation has led to the well-known discrete time/cost trade-off problem (DTCTP). This problem has been investigated by [2], and has been extended to time-switch constraints [6, 11], other objectives [25] and used in a business game [12].

Schedule Risk Analysis: Analysing risk in projects is one of the three important dimensions of dynamic scheduling [65] and is crucial for appreciating the value of the baseline schedule and for knowing the expected impact of changes in the schedule on the project objectives. Therefore, research on the use and relevance of schedule risk metrics has been carried out resulting in publications in [50, 61, 67, 66] and in a book on project control using Schedule Risk Analysis (SRA) [51, 52].

Project Control: Controlling the time and cost objectives of projects in progress is done by Earned Value Management (EVM) and its extension to Earned Schedule (ES) systems. Earned Value Management is a methodology used to measure and communicate the real physical progress of a project and to integrate the three critical elements of project management (scope, time and cost management). It takes into account the work completed, the time taken and the costs incurred to complete the project and it helps to evaluate and control project risks by measuring project progress in monetary terms.

Various methods in EVM/ES exist to measure the performance of projects in progress and to forecast the final duration and cost given partial progress data. The accuracy of EVM/ES methods to forecast the project duration of projects in progress is investigated by [20, 21, 22, 27, 28, 37, 38, 39, 43, 44, 62]. This knowledge is used in various project control studies published in articles [61, 67, 66] and a book [51, 52].

3.2 Personnel scheduling

Data generation: The need for data in research has been previously explained in section 3.1. Similarly to project data, a data generator for nurse scheduling problem instances has been developed by [30]. This so-called NSPLib problem set can be downloaded from www.projectmanagement.ugent.be. The data was characterised using complexity metrics described in [45].

Nurse scheduling: The Nurse scheduling problem (NSP) is the problem of determining a work schedule for nurses that is both fair and efficient and has been investigated widely in literature. At OR&S, various algorithms have been developed and published in [23, 29, 40, 46, 53, 63, 73, 74, 75, 76, 77].

Crew scheduling: Although most personnel scheduling algorithms at OR&S have been developed for nurses, extensions have been made to the crew scheduling problem (CSP) in airline companies, published in [54, 64].

3.3 Machine scheduling

Single and parallel machine scheduling is an Operations Research discipline that the OR&S research group has investigated using meta-heuristic search procedures.

Single machine scheduling: Single machine scheduling (SMS) is the process of assigning a group of jobs to a single machine. The jobs are arranged so that one or many performance measures may be optimised. In the papers written by [56, 69, 70], various algorithms for this challenging scheduling problem have been developed, mainly focusing on the maximum lateness objective.

Job shop scheduling: The job shop scheduling problem (JSP) is an optimisation problem in which jobs are assigned to multiple identical machines while trying to minimise the total duration of the production schedule. This problem is related to the RCPSP discussed earlier and is extremely hard and challenging to solve. OR&S research is published in the papers written by [57, 58, 71].

3.4 Management accounting

The relevance of Operations Research techniques using simulation studies and a controlled design and generation of data was illustrated in a study on the impact of errors in management accounting systems, published in [31, 33].

3.5 Case studies

Although not the primary focus of academic research, many of the results have also been validated on real data, in a real business settings or at least in a controlled setting using empirical data. These case studies show the relevance of the research efforts done at OR&S and are an ideal tool to popularise our results to a broader audience.

- Water production: The relevance of optimising cash flows using the net present value was illustrated on a case study of the Vlaamse Maatschappij voor Watervoorziening published by [9].
- Westerschelde tunnel: The use of work continuity constraints in a tunnel construction project to optimise the idle time of a freezing machine is shown in [26].
- Project control: The alternative control methods were developed and tested in previous research papers and were validated on real project data from 8 Belgian companies in [67].
- Steel production: The optimisation of a steel production schedule at Arcelor Mittal by using heuristic solution methods is shown in [47].
- Exam modeling: The assignment of case studies to students who have to solve this case in groups is used at Vlerick Business School and is described in [55].
- Nurse scheduling: The optimisation of nurse schedules at the University hospital in Ghent (Belgium) is discussed by [46, 75].
- Crew scheduling: The use of algorithms to assign pilots to airplanes has been illustrated by [54, 64] for Brussels Airlines.
- Vulkoprin: The relevance of the job shop scheduling problem to optimise the production of a Belgian manufacturing company producing industrial wheels and castors in rubber is demonstrated by [58].

4 No teaching without research

The primary goal of research is to publish in high quality international journals and to present the research results on well-known and recognised conferences across the world. However, at OR&S, a secondary goal is to make a link between the research results and their use in teaching for our Business Engineers at the Faculty of Business Administration of Ghent University as well as for the MBA students and participants on commercial trainings at Vlerick Business School. Although it is hard to specify which paper has exactly contributed to the teaching sessions, a summary of the most important connections between the research results and use in the classroom is given.

Background reading: The most obvious way to integrate research in teaching activities is to put the papers available to students such that they can use them as background or study material. In the course “Project Management”, the papers on the business game [12] and the illustrative consultancy projects [9, 26, 67] are optionally used as background material. In the course “Applied Operations Research”, the personnel scheduling paper [46] is used as supportive study material for students to construct their own personnel schedule.

Case studies: Some of the research results have been translated into case studies that are used in class exercises, such as the The Mutum-Paraná II bridge project case studies (A, B and C) published in [65]. One of the courses at Ghent University contains one big integrated group exercise, known as the (unpublished) St. Catherina hospital case and is the result of many of the nurse scheduling research discussed earlier.

Software: The use of software allows the student to actively learn the topics discussed in courses. Many of the dynamic scheduling algorithms discussed earlier have been implemented in the commercial software tool ProTrack [79]. This tool is freely available to Project Management students and is used to solve case studies, group works or for writing master theses.

Another IT tool is the Project Scheduling Game (PSG) [12] that is used in many classes at universities and business schools and is used as a group exercise of the Project Management course at Ghent University.

A more advanced software tool is P2 Engine [80] that is made available to PhD students and students working on a master thesis in Project Management. P2 Engine is a command line utility tool based on the LUA scripting language to generate gigabytes of project data. It generates project baseline scheduling data and risk analysis metrics as well as dynamic project progress data that can be used for testing and validating novel research ideas.

Both ProTrack and P2 Engine contain all the RanGen algorithms published in [7, 34] to generate a lot of project data.

Finally, by definition, the OR student model to assign case studies to students and student groups is used in the classroom when a big group has to be divided in smaller subgroups based on preferences [55].

Online learning: The themes and research discussed in section 3.1 on dynamic scheduling have been integrated in a free and online learning tool known as PM Knowledge Center (PMKC) [81] and is used by students following a Project Management course. In order to convince (young) students to get involved in the Project Management discipline, PMKC also contains press articles with links to interesting PM organisations and/or events.

Business interaction: Further interaction between students and professionals is stimulated by the ProTrack Facebook group [82], the OR-AS blog [83] and the yearly EVM Europe event [78]. Finally, the yearly University Contest that awards the best students following the course “Project Management” with a financial prize given by PMI Belgium is another way to get the young students involved in the PM profession

5 Conclusions

In this paper, an overview is given of the research activities and publications over the last 15 years done at the Operations Research and Scheduling (OR&S) research group of the Faculty of Economics and Business Administration of Ghent University, in collaboration with the work done at Vlerick Business School. A flashback on the past activities has been made in a chronological order and the work has been classified along the various topics that have been investigated at the OR&S group. A link with teaching activities has been made to show that research can be used as a supportive tool in teaching activities at universities and business schools. A short look forward into the (near) future has been made to show that future research is on its way. Figure 2 displays a classification of most of the OR&S publications along six different criteria as explained along the following lines:

- Topic (general): The main topics are Management Accounting (MA), Machine Scheduling (MS), Project Management (PM) and Personnel Scheduling (PS). The two remaining topics are Operations Research (OR) when specific OR methods are used but the topic does not belong to the previous four topics, and a rest class (Other) for various other topics.

- **Topic (specific):** The topics are more specified in detail using abbreviations that have been used throughout this article. RCPSP-x is used to refer to an extension of the RCPSP, excluding the RCPSP-DC (that has a separate label). The abbreviation GEN is used to refer to data generation methods discussed in section 3.1 and MA to refer to Management Accounting publications (section 3.4).
- **Teaching:** The use of the publications in teaching activities can be done in various ways. The papers can be used in business games (BG), as background material (BM), study material (SM) or optional reading (O) or for master theses (MT). Other papers have indirectly (I) contributed to our activities or are simply not used (NU).
- **Solution method:** The methods used to solve problems can be classified as exact methods (Exact) that guarantee an optimal solutions or heuristic methods (Heur). Other studies make use of simulations (Sim) or generation of data (Gen). Case studies are also classified (Case) and a remaining portion (Other) did not use any OR technique.
- **Journal classification:** International peer-reviewed journal can consist of articles in web of science (A1) or other articles (A2). National peer-reviewed journals are classified in A3. The label A4 is used for journal articles that can not be classified in A1, A2 or A3. Book as authors are classified in B1 and book chapter as B2. P1 is used for a proceeding in a web of science journal (mainly Lectures Notes in Computer Science).
- **Year of publication:** A summary of section 2.1 is displayed in the last graph.

Obviously, this article will be updated yearly with the new publications and research outcomes in various ways.

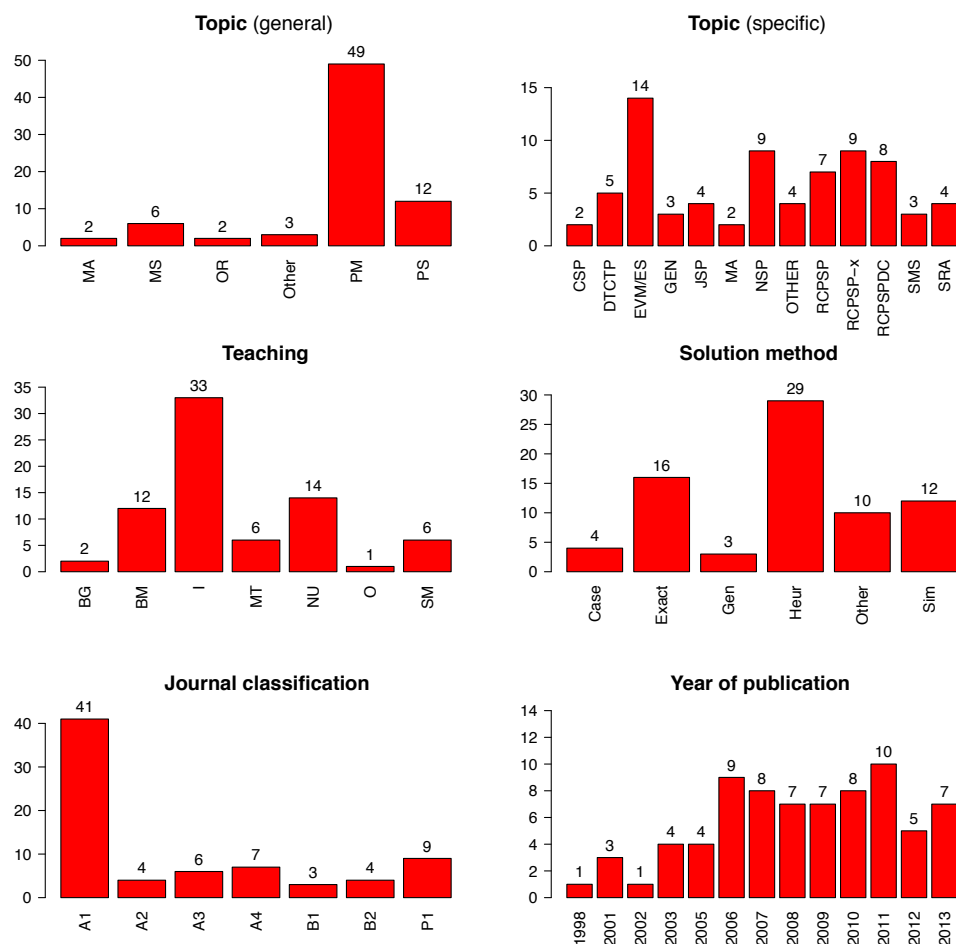


Figure 2: Classification of the OR&S publication portfolio

6 Acknowledgements

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