Final Report Summary - CAP-SCHED (Competitive Advantage for Process-intensive industries by SCheduling with Heuristics-EnhanceD simulation & optimisation)

The CAP-SCHED project: European added-value and relevance to SMEs

The chemical industry in the European Union accounts for around 30% of the world's total chemical production. The industry covers a vast range of products, such as fuels, paints, perfumes and cosmetics, pharmaceutical and medical products, fertilisers, plastics, soaps and detergents and a number of different process types, such as continuous and semi-continuous processes used in speciality chemical production, agro-food processing, high volume or batch processes, etc.

In terms of its economic importance to Europe, the industry comprises more than 23,000 enterprises, 95% of which are SMEs. Moreover, the industry employs close to 2 million people, that is, around 7% of the overall EU manufacturing industry workforce. A further 3 million employees work in sectors which directly use outputs of the chemical industry in their own processes and products.

The competitiveness of this industry is therefore vital to Europe's economy. Furthermore, it is clear that the structure of the chemical industry means that SMEs are central to the industrial and economic success of the majority of its sub-sectors.

Challenges addressed by the CAP-SCHED project

A key economic challenge facing Europe's chemical industry - no matter the sector of activity - is how to improve the cost-efficiency and profitability of manufacturing supply chains. These are complex in terms of their industrial and commercial structures. Furthermore, the supply of both raw and processed materials are often subject to rapid, hard-to-predict changes.

As prime examples, transport infrastructure is becoming increasingly congested, which injects erratic delays in delivery schedules; fuel and labour costs are rising; downstream supply lines are lengthening; customers are demanding shorter lead times; and environmental and safety controls on the distribution of chemicals are steadily tightening. In addition to these factors, the quality and physical properties of the raw materials used in processing can vary significantly from one delivery to the next.

Therefore, finding new ways to optimise processing despite fluctuations in the supply chain, so as to achieve cost reductions and to increase profit margin, is of particular interest.

A major challenge facing industrial processes, is to achieve optimised flow scheduling (that is, short-term planning of operations to achieve outputs as economically as possible) under tight time constraints. The human scheduler is often overwhelmed by the immense complexity, and the lack of time available to solve, the optimisation problem. However, poorly optimised flow scheduling solutions can lead to millions of Euros of lost profit, as well as unnecessary negative impacts on
Achieving a consistently optimised solution: An innovative approach by CAP-SCHED

The result targeted by the project is to drastically reduce the need for the human operator to engage in multiple 'trial and error' simulations in order to get to a consistently optimised solution.

The innovative approach which CAP-SCHED has developed to achieve this result, will use artificial intelligence techniques combined with numerical problem-solving methods.

The CAP-SCHED solution aims to assist the human operator - in complex, difficult or unusual operating circumstances and in the fastest possible time - to converge to an optimised flow scheduling solution which delivers the best possible advantages from economic, industrial competitiveness, and environmental impact standpoints.

Project context and objectives:

The innovation focus in CAP-SCHED has been to develop an intelligent scheduling solution for use in process-intensive industries.

CAP-SCHED allows the process (human) operator to interactively set various parameter values according to his/her intimate knowledge of the process, and to be assisted at the same time by automated, algorithmic constraint-solving capabilities which use domain-specific knowledge (heuristics) to optimise the remaining parameters within given operating constraints.

The essential objectives of the CAP-SCHED solution are to improve efficiency gains - through faster development and distribution of schedules - and to boost effectiveness - by higher throughput, reduced operating costs, and lower inventories - in the supply chain network for industries where getting from the raw material to the finished product is heavily process-dependent.

The concept underlying the work of the 'Research for SMEs' project CAP-SCHED, called for progressively rendering results, at each stage of development, to be capable of generic application to process flow scheduling (PFS) problems which share the same or similar characteristics, across a broad basket of otherwise unrelated process industries in terms of the business areas they address.

PFS applications include: continuous or semi-continuous processes (such as crude oil refining, and numerous chemical transformation processes such as plastics and synthetic rubber production); and batch processes (such as paints, pharmaceutical products).

On commencement of the CAP-SCHED project in 2008, the fundamental idea was that a panoply of PFS problems, encompassing a wide range of levels of complexity, could be addressed using a generic heuristic decomposition scheme.

Ultimately, close, insightful dialogue with industry has led to a refinement of the initial approach, leading to two related yet distinct CAP-SCHED prototype scheduling solutions. Importantly, this has also led to an amplification of industrial relevance and market opportunity.

Project results:

Progressing beyond the state-of-the-art
Short-term production planning comprises the detailed scheduling of the production resources used in the transformation of input material into:

(a) intermediate products - which may require storage, assembly with other sub-process outputs, or be directly passed from one sub-process unit to the next; and
(b) end-products.

Although software packages are available on the market to provide assistance with scheduling, their usefulness in achieving schedule optimisation is severely hampered. This is largely due to their inability to support anything other than an approach dependent on successive approximation 'by trial and error' simulation of scheduling scenarios, by the human operator, in an attempt to find an adequate PFS solution.

Such approaches have consistently proven to be too limited in achieving optimisation of scheduling, since the human scheduler is often overwhelmed by the sheer combinatorial complexity of the scheduling problem, in view of characteristics of raw materials or intermediate products which enter the process flow, and which are both continuously changing, and can change rapidly. Compounding these issues, in batch process industries where the loading of available production resources is strongly affected by the sequence of jobs, both lot-sizing and detailed scheduling needs to be performed simultaneously.

For the present, the enormous complexities involved in continuous and batch PFS remain a major cause of process inefficiencies, with knock-on effects on the costs of operations.

An appreciation of the current state-of-the-art

Features and challenges of the process industry:

In the process industry, it is possible to distinguish continuous and batch type processes. Plants producing only a limited variety of products in high volumes, typically use special-purpose equipment allowing a continuous flow of materials in large campaigns.

Alternatively, some plants produce a large number of products in small quantities, using multi-purpose equipment operated in batch mode. In this case, there is a well-defined start-up time, well defined follow-up steps characterised by specific recipes (heating, adding other components and letting them react), and a well-defined end where the final products are obtained. Batch production involves an integer number of batches, where a batch is the smallest quantity to be produced. Several successive batches of the same product make a campaign.

Scheduling problems in the process industry include the following challenges:

- multi-product / multi-mode reactors;
- sequence-dependent setup times and costs;
- combined divergent, convergent and cyclic flows;
- multi-stage production using shared intermediates;
- multiple raw-material components and non-linear blending;
- limited intermediate storage, dedicated or variable tanks;
- unit maintenance decisions (e.g. opportunistic based on flow conditions, or predictive).

The following approaches are variously found as part of process planning and scheduling software tool modules on the market today, which themselves are part of larger, integrated packages which aim to support overall supply chain management and business optimisation (e.g. such as those commercialised by Aspen Technology Inc., JDA Software, and Oracle). In the list
following, approaches 1, 2, and 3 tend to be the most commonly implemented modules:

1. constraint programming (CP)
2. exact and deterministic methods using MILP and MINLP techniques
3. simulation-based approaches
4. meta-heuristics (such as evolutionary algorithms, Tabu search).

Problems which have an impact on scheduling may arise concurrently. Such scenarios lead to rapidly increasing combinatorial problem complexity, and make it difficult to obtain even a feasible (not to mention an optimal) solution in a practical amount of time.

CAP-SCHED relative to commercially-available planning and scheduling software packages

As regards currently available integrated scheduling software tools, although they may claim to include heuristics, this generally refers to simply recording, in a reference database, results achieved through a ‘by trial and error’ simulation regime carried out by the human operator, and which have led to acceptably effective scheduling solutions. Usually however, there is no automated assistance provided to the operator - which therefore still places a heavy reliance on the capabilities of the human operator to conduct ‘trial and error’ simulations, so as to identify and implement a timely solution. In the few instances where automation is claimed, the only automation found consists of coding and applying the operators practices in the form of priority rules, but this has nothing to do with constraint solving or optimisation.

This is in direct contrast to the CAP-SCHED solution, which synergistically combines and coordinates the human operator applying his/her experience and knowledge of the process, and algorithm-enabled approaches such as those listed in 1 to 4 previously, as a means to identify a globally optimised scheduling solution in the face of multiple, concurrent, unplanned events.

Importantly, no scheduling software tools are known to be on the market today which offer such advanced capabilities and functionality.

Illustrating the current, continued dependency on manual ‘by trial and error’ approaches, and bearing witness that there remains substantial scope for improving performance compared to commercial packages available today on the market, the product brochure for SAP APO (v4.0) states: ‘The heuristic does not necessarily generate a feasible plan; nevertheless, the benefit of using the heuristic approach is that it is robust and understandable by anyone willing to work the problem through the established rules.’

An appraisal of research and technology innovation in PFS optimisation

A review of published articles - in particular, one review (Mendez, 2006) published prior to the commencement of the CAP-SCHED project, and a second review (Gicquel, 2008) carried out directly by CAP-SCHED research performing partners - finds that:

(a) based on an analytical classification of the modelling approaches for each aspect of the batch processing problem: process topology, inventory policy, batch size, demand pattern, resource constraints, time representation - a general scheduling software tool that can address all types of batch processing cases remains elusive - in both the R&D community addressing this challenge, as well as in commercial software available to industry;
(b) a direct and systematic solution of large-scale industrial problems through mathematical programming is still an unresolved issue;
(c) hybrid optimisation procedures combining the strengths of different methodologies such as MIP formulation strengthening
and meta-heuristics, are a promising direction.

Indeed, concerning point (c), a previous (FP5) European research project named Large scale integrated supply chain optimisation software (LISCOS) has focused on the combination of mixed integer programming (MIP) and constraint programming (CP) methodologies which give rise to a new class of algorithms known as 'hybrid algorithms'. The project website can be found on URL: http://www.liscos.fc.ul.pt/

The general concept underlying LISCOS is also relevant to our CAP-SCHED solution - although the latter takes the concept significantly further, as detailed in the section following.

Advancing beyond the state-of-the-art

PFS solutions which use hybrid algorithms - as broached in the previous LISCOS project - are attractive via their promise to synergistically combine the most useful features of their component parts.

The innovative 'hybridisation' of user-oriented ('by trial and error') approaches with mathematical programming, resulting from the Research for SMEs CAP-SCHED project, represents a unique and significant step forward, with the capability to provide substantial financial and operating advantages to process-dependent industries

Specifically, the RTD effort applied to establishing the generic applicability of the CAP-SCHED solution to resolving PFS optimisation problems has led to the development of a framework which allows the use of the following three approaches, separately or in cooperation:

- a set of exact (MIP) optimisation modules;
- a metaheuristics module (Genetic algorithms and local search metaheuristics);
- a simulation module.

The above framework components have been used to develop and test a set of two CAP-SCHED prototypes which illustrate the ways in which these components can be combined, based on the characteristics of the industrial processes at hand.

Initial appraisal of the CAP-SCHED prototypes resulting from the RTD project, indicates that a significant step beyond the current state-of-the-art lies in the reduction of scheduling problem complexity as perceived by human schedulers. Immediate benefits compared to scheduling software currently used in industrial applications are:

(a) faster achievement of a practical scheduling solution; and
(b) improved confidence of having attained a feasible, globally-optimised PFS solution, able to satisfy a number of simultaneous (and sometimes competing) operating constraints, in a way that is meaningful to the work process.

This has therefore led to the development, implementation and preliminary, laboratory testing of the modules incorporating all three of the above-mentioned approaches, leading to a set of two CAP-SCHED prototypes which have been conceived for industries characterised by the following:

1. Continuous and semi-continuous multistage production processes - amenable to solution of PFS problems by heuristic decomposition methods and cooperation between optimisation and simulation.

Industrial applications include: crude oil refining; numerous chemical transformation processes such as plastics and synthetic rubber production.
2. Batch processes - that is, discrete-time, multi-product, multi-level, multi-resource processes, whose economic effectiveness may be dependent on resolving both lot-size and sequencing issues. Here, a combination of simulation, optimisation and metaheuristics approaches is required.
Specifically, a combined approach is relevant to maximising batch PFS effectiveness where process scheduling optimisation requires solving:
- lot-sizing issues: in this case, heuristic decomposition methods are applied in order to arrive at a set of sub-problems which are solved using MIP optimisation;
- sequencing issues: in this case, such issues are not amenable to PFS optimisation by heuristic decomposition methods, and are solved using a combination of MIP and metaheuristics algorithms.

Batch process industries concerned by either or both of the above issues typically involve: several types of final products, including the processing of intermediate products, and where each final product requires to be processed on several successive machines (resources) involving choice, at each production level, among several alternative resources.

Industrial applications include inter alia: agro-food and biotechnology industries (including enzyme production and biofuels); steel production; tyre manufacturing; textiles; glass-making; paper production; and engineered-to-order discrete batch product manufacturing.

The extent to which the effectiveness of various batch process industries is affected either separately by a sequencing or a lot-sizing issue, or by both in combination, remains to be established.

Assimilating a better understanding of the nature of scheduling issues which influence the economic effectiveness of batch industries is therefore of significant importance. Doing so will help determine the scope for value-engineering of the CAP-SCHED batch scheduling optimisation solution. Specifically, regarding whether the prototype should itself be further segmented into two specific modular solutions, one for lot-size-dependent batch process industries, the other for sequencing-dependent batch process scheduling.

The fundamental difference between the two prototypes comes from the fact that the first one addresses scheduling in continuous process industries (with potential components having semi-continuous behaviour) whereas the second addresses discrete type industries. An easy way to distinguish the two types of problems is through their mathematical formulation: all decisions in discrete processes are elements in finite sets, but the variety of situations create combinatorial optimisation problems. In continuous processes, the space of decision variables is infinite, but is delimited by a set of well defined constraints.

The CAP-SCHED system is different from existing solutions in the fact that it aims at handling large scheduling problems which are not tractable by a single technological approach. The CAP-SCHED strategy can be characterised by the following two aspects:

- It is one of 'divide and conquer' - meaning that a large problem is subdivided in sub-problems handled by 'local agents'.
- It typically combines different technological approaches: one of them is mathematical programming, the other one being either simulation (led by a human planner) or metaheuristics

This approach has shown itself to be very effective for large problems tested in the use cases. To our knowledge, no comparable 'off the shelf' solution is available.

The general architecture is the following:

- The system consists of a platform where a number of software optimisation agents reside and can be called to solve different
sub-problems; these can be traditional MIP solvers or metaheuristic algorithm.

- A simulation engine is available to human planners as a service.
- A central agent handles the problem formulation, its distribution among local solvers, and the solution process through iterative decomposition / coordination.
- The human planner interacts with the system through the simulation service and the central coordination agent.

In terms of data organisation: this will be dependent on the IT infrastructure of each site, but it is assumed that the permanent and variable data associated with the given process and scheduling problem will reside in a central database.

Potential impact:

Impact

Relevance to impacts cited in the FP7-SME-2011 work programme

Approach of the project in realising impact potential for the participating SMEs

The development of supply chain and process management tools is no longer a core RTD activity of enterprises in process-intensive industries. This places a crucial emphasis on promoting collaboration between all those involved in the value-chain, from those for whom business profitability depends on suitably optimised production processes, to those who develop the methods and tools used in the planning, scheduling, and control of processes. Compounding the issue, a paradigm shift has emerged in the acceptance criteria of technologically sophisticated, end-user organisations. Whereas criteria were before based on compliance of process management tools to desired functionality, issues of optimised operational performance now play a dominant role in acceptability.

This emphasises the need for effective networking - among the SMEs who supply tool components for supply chain and process management, as well as within sector-specific value-chains so as to comprehend, appreciate & assimilate high-level end-user requirements.

Furthermore, a major risk factor expressed by process industries in depending on SMEs as third-party sources for process planning and management components, is that SMEs are often perceived as insufficiently realistic regarding the market applicability of the methods and tools they are developing.

The expectation of end-user companies is that SMEs should anticipate risks and provide pro-active assistance with risk management in integration of new management technology, with a view to helping clients to achieve an acceptable RoI on their procurement investments in supply chain and process management tools. This should include performance benchmarking before approaching industrial clients, and include advice on work process and technical change management.

Therefore, the invaluable opportunity inherent in the approach adopted by the core group of SMEs who have developed CAP-SCHED, is the ability to embed themselves in their industrial end-user exemplar process participants' pursuit of improvements to process optimisation. This approach amplifies the impact of innovation as a key business process for their future growth and prosperity.

Economic justification for the proposed project: the SME perspective

The business activities of the SME partners, their complementary current core client base, and geographic locations, mean that the CAP-SCHED prototypes will be exercised in a broad basket of industrial applications which are consistent with the
intentions of the market expansions of each SME:

- For Princeps: Strengthening its position as a supplier of simulation and optimisation solutions within the petrochemical industry, in addition to moving into biotechnology application sectors (with a particular interest in biofuel production).
- For ManOPT: By further promoting the company's position as a provider of expertise and solutions for manufacturing system optimisation through adding a truly innovative (and through the work of the project), industrially-verified approach to scheduling optimisation. Moreover, the work of Princeps in performance testing of the semi-continuous flow process CAP-SCHED prototype in the petrochemical industry, can be considered as providing leverage to ManOPT's intention to expand its business interests into pharmaceutical industry processes.
- For TTS: By providing an innovative and pragmatic extension which brings value-added benefits to deploying its 'SSP' production systems simulation methodology in the context of TTS's consulting services, in addition to adding scheduling simulation capabilities to the TTS software toolkit of modules used in high-fidelity modelling of new production facilities.

The work of both ManOPT in exercising CAP-SCHED in a batch process is expected to assist TTS with valuable leverage to address a new market sector and opportunity for its services and simulation software - namely, structural steel fabrication, where economic operators in this area remain inadequately equipped as regards deployment of advanced IT in process planning and optimisation.

Impact assessment on SME project partners

- The above scenario projects a net increase of +6 staff across the 3 SMEs by post-project year 5, directly related to requirements by the partners to support exploitation of the CAP-SCHED solution.
- 100% of IPR resulting from the CAP-SCHED project has been transferred to the core SMEs. No account is therefore necessary for reversion of royalties to research performing organisations.
- Achieving a level of net revenues such as that projected above by year 2, can be expected to fuel growth, leading to additional recruitment opportunities.
- Note that the underlying assumptions and figures used in the above projection will be subject to refinement during the course of the CAP2M-SCHED project.

Realising the exploitation potential at the level projected by the above figures, relies of course on promoting take-up of the CAP-SCHED scheduling solution to process industries.

The workshop and professional networking event which is part of WP 4 (see deliverable D4.2 month 15) is important as a means to demonstrate to industrial participants that CAP-SCHED has not just been developed by a single company, but that it is the result of a collaborative endeavour.

Moreover, discussion at such an event of the project's approach to achieving results - and the overt presence of managers from the companies having afforded access to scheduling optimisation exemplars so as to assess and tune performance of CAP-SCHED - can be considered as a key success factor. This is since discussions of this kind will lend significant credibility to the SMEs as capable of anticipating risks and providing pro-active assistance with risk management in integration of new management technology.

Impact assessment on end-user process industry project partners

Scheduling is the process of developing and maintaining optimal tactical and operational plans, down to the fine-grain level - usually daily - with the objective of maximising value (measured in terms of effect on profit margin) from the available envelope of options which affect the process. All of this must be done by taking into consideration a wide variety of constraints, including market conditions, manufacturing plant conditions, and supply, delivery and shipment logistics. In other
words, scheduling provides a critical link between corporate planning, and plant operations.

Viewed in this context, scheduling and the ability to obtain cost-effective process throughput and production output, directly reflects on management's agility in coping with the supply chain. It places an emphasis on cooperation between planning (over the long term), scheduling (over the short term), and process execution activities, and their links to operations, logistics, purchasing, and sales.

The industrial reality is that scheduling remains largely supported by disparate collections of spreadsheets and data, with decision-support tools whose capabilities are very limited. Management agility is therefore hard to achieve. And significantly, the ability to analyse multiple alternatives - particularly where unforeseen occur - is not part of the current work processes or best practice.

Although a number of solutions are available on the market to provide assistance with scheduling, their usefulness in achieving an acceptable solution to schedule optimisation is severely hampered by virtue of the simplistic approaches they offer to simulation.

Essentially, although many solutions provide quite acceptable long-term process planning capabilities, they fail to provide adequate support to the human operator in effectively coping with process characteristics which are both continuously changing, and can change rapidly.

An analysis of factors leading to annual operating losses (or, missed opportunity costs through ineffective process optimisation) are listed in the following table. The figures are drawn from a petrochemical industry exemplar site.

<table>
<thead>
<tr>
<th>Cause of annual losses (thousands of EUR)</th>
<th>Value (Thousand EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Lost market opportunities</td>
<td>500</td>
</tr>
<tr>
<td>2) Difficulty to react to unforeseen events</td>
<td>400</td>
</tr>
<tr>
<td>3) Disruption due to incidents</td>
<td>400</td>
</tr>
<tr>
<td>4) Under utilisation of equipment capacity</td>
<td>300</td>
</tr>
<tr>
<td>5) Poor visibility on other parts of the organisation</td>
<td>300</td>
</tr>
<tr>
<td>6) High inventory levels</td>
<td>300</td>
</tr>
<tr>
<td>7) Demurrage costs</td>
<td>300</td>
</tr>
<tr>
<td>8) Quality give-away</td>
<td>200</td>
</tr>
<tr>
<td>9) Material and energy losses</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2900</strong></td>
</tr>
</tbody>
</table>

With the possible exception, of item 5) in the above list, CAP-SCHED is capable of affording improvements on all other items.

As a module within a larger simulation and optimisation solutions package, the estimated price component for CAP-SCHED for a large refinery is of the order of EUR 7000 per annum (lease price, and inclusive of maintenance charge). It can be readily calculated from above table that for a large refinery, payback on CAP-SCHED is achieved even if a mere 0.25 % of the value of losses can be overcome.

Of particular relevance is the figure for item 2) 'difficulty to react to unforeseen events': note that in this case, if approximately 2 % of the annual losses due to this factor alone can be recuperated, then once again, this will have provided sufficient payback for the annual cost of CAP-SCHED.
Impact of the CAP-SCHED unique selling proposition (USP)

The above analysis of end-user economic impact of deploying CAP-SCHED, and the noted difficulty of process operators to react in an effective and timely manner to unforeseen events, is particularly relevant to the market success of CAP-SCHED.

Specifically, recalling that today, process operators are faced with achieving optimisation largely by 'trial and error' methods, then the main advantage is that CAP-SCHED will give the process scheduler a quick idea of a good and feasible solution.

That is, the person tasked with process scheduling can reach a good and practical solution through accelerated interaction between simulation and optimisation, allowing him/her to go further, faster, and therefore to drastically improve management agility in identifying an appropriate scheduling solution within the time available.

Impact of externalities: ISA standards

In the process planning and scheduling applications' area, one standard of relevance to the CAP-SCHED solution already exists, with a second being developed. It is to be noted however that none are currently fully embraced by developers and end-users alike. For example, the SAP supply chain management solution does not yet fully implement the ISA standards. The standards in question are:

ISA95 (ISO/IEC62264) is a multi-part standard concerned with enterprise-control system integration, and more specifically, with ensuring the interoperability between production and planning activities.

Beyond the specific aspects of communication and the functional definition of production management, ISA95 provides a set of models for the space-time description of the production system. The main aim is to underpin developing a 'production architecture' approach which is capable of supporting the evolution of any company, ensuring a better alignment of its information systems with its operational requirements.

During the development work of the precursor CAP-SCHED project, end-user partner Genencor International has provided valuable guidance to the core SMEs in ensuring that CAP-SCHED is compliant with ISA95.

This has been achieved through involvement of the company's worldwide corporate information systems management team. The team's remit is to rationalise the IT solutions deployed throughout the company to ensure a consist, coherent integrated IT infrastructure and applications' environment which complies with relevant industry standards, and therefore promotes safeguard of investments in IT.

ISA106 'Procedural automation for continuous process operations' is a recently-formed committee. The objective is to develop a set of standards, recommended practices, and technical reports on the design and implementation of procedures for automating continuous process operations.

ISA106 may eventually impact the technology of the CAP-SCHED prototype A, aimed at semi-continuous process scheduling optimisation. It is the intention of Princeps to maintain a watch on the emerging outputs from this committee, so as to anticipate any required adjustments to the solution.

Project website:
http://www.princeps.com

Contact:
Hamid Chehade
Related information

| Result In Brief | Better scheduling for supply chains |

Reported by

PRINCEPS SARL
10, Rue Jean Jaures
92800 PUTEAUX
France

Subjects

Economic Aspects - Scientific Research

Last updated on 2013-06-17
Retrieved on 2019-07-18

Permalink: https://cordis.europa.eu/result/rcn/58324_en.html
© European Union, 2019