Simply the best

New trends in optimization to maximize productivity

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source: ThyssenKrupp

In April 2008, around 50 leading experts from industry and academia gathered to discuss the future trends of optimization in production management and manufacturing execution systems (MES). Presentations were made by 16 speakers focusing on the optimization of MES in the process industries. Among the topics covered were applications of mathematical optimization in industry and the experience and evaluation of modeling tools and optimization software.

Every year the German Operations Research society (GOR) organizes joint workshops with industry. In April 2008, ABB hosted the 80^{th} such workshop entitled "Optimization in Manufacturing Execution Systems."[1] The main message of the workshop was that optimization is a fast growing area with an increasing number of applications in the process industries. Production companies and automation system vendors alike are under increasing pressure to raise production yield and run plants at maximum productivity.

What is meant by "optimization"?

A traveling salesman planning his route between 20 customers at 20 different sites provides a classic example of an optimization problem. Planning a route would be easy enough, but planning the best route would be a different matter. Optimization experts could be consulted, but only if a clear definition of "best" could be established. Would the "best" route be the fastest route or the shortest route? Or would it be the route that allowed the salesman to stay in his favorite hotel?

The decision hinges on the saleman's[2] definition of "best" and on what aspects of his route he would "optimize" for. Daily life is full of such optimization challenges: What is the quickest way of traveling between Frankfurt and Berlin? Which method will be most productive over a particular timeframe? How can the salesman spend more time with his family? One way to solve these challenges is through a process of continuous improvement. This involves finding a solution, which is then subjected to a series of refinements to provide a better solution. This technique is often used to refine production processes with the aim of increasing productivity.

Continuous improvement is good – it will find a better solution – but optimization would be better. Optimization finds the best solution! In its mathematical sense, "optimization" is the process of finding the best of all possible solutions. Therefore, the set of all possible solutions can be represented by a formal model describing the aim of the exercise (the objective), the decision variables and the constraints.

Interest in mathematical optimization has intensified in recent decades as computers have become more powerful and sophisticated new algorithms have been developed.

Mathematical optimization means finding the minimum or maximum of the objective function by choosing the values for a set of decision variables, while satisfying the constraints. For any specified objective, there may be local and global optima 1. In mathematical optimization, it is not enough simply to move closer to the optimal point, as done in process improvement. In mathematical optimization, the aim is to find the best solution point globally.

The optimization world

Mathematical optimization is a well-defined technology based upon a formal representation of the optimization problem. In order to solve a real-world problem using mathematical optimization, three key steps are necessary 2.

1) Problem identification
2) Modeling, ie, expressing the problem in mathematical terms
3) The development of appropriate algorithms to solve the problem

For industrial applications, once established, the solution to the problem will be implemented in the production environment. Optimization solutions are part of the MES layer (for more details see "The automation pyramid" factbox on page 16 of this issue) that sits on top of the automation system and also communicates with enterprise resources planning systems. Successful implementation requires real-time capabilities, online configurability, connectivity and reliability 3a.

Optimization problems

Production planning and scheduling is an area in which there are many applications for optimization 3b. In

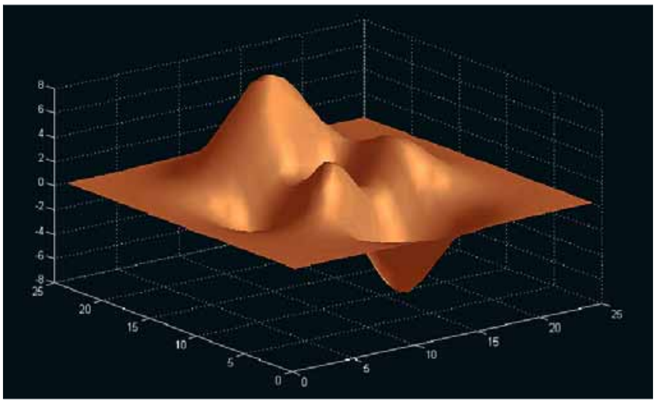
Footnotes

1) The workshop was jointly organized and hosted by Dr. Guido Sand, Scientist at ABB Corporate Research, and Prof. Josef Kallrath, head of the GOR working group. For the set of presentation slides contact guido.sand@de.abb.com.

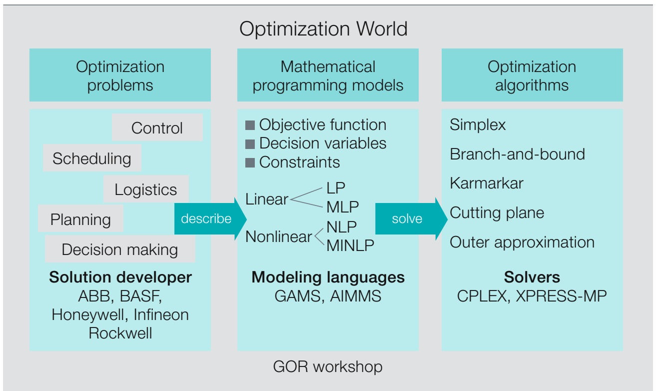
2) The "traveling salesman problem" is a classical problem in mathematical optimization.

3) The solution developers, modeling languages and solvers named here were presented at the workshop. There are others which are not named here.

1 Optimization objective as a function of two variables



2 The key elements of mathematical optimization[3]



planning and scheduling, the task is to allocate scarce resources to tasks over a specified period of time. In the production environment, resources comprise energy, raw materials, process equipment and manpower. Mathematical optimization can be used to determine the best use of these resources under given production constraints. For example, energy consumption and cost can be minimized by optimizing the energy efficiency of equipment and shifting energy-intensive operations to periods of low consumption when cheaper electricity tariffs are available 3c.

Although many industrial problems have been analyzed and improved solutions have been developed, in many areas the best solution has not yet been found and the optimization potential remains untapped. Problems that are often addressed manually include the following:

- Production scheduling (in terms of both volume and product type)
- Machine scheduling for each batch of products
- Capacity allocation (manpower and resource planning)

Interest in mathematical optimization has intensified in recent decades as computers have become more powerful and sophisticated new algorithms have been developed.

Modeling the optimization problem

When expressing an optimization problem in mathematical terms, the first step is to define the problem clearly. Is the aim to maximize throughput or to minimize energy consumption? Or are both variables important? Once the objective has been clarified (not always an easy task), the next step is to identify the decision variables, the choices that can be made. For example, can an energy-intensive production process be shifted to take advantage of cheaper electricity tariffs? What equipment is available and which machines would be best suited to the task in hand? Can raw material be purchased from different suppliers? When these questions have been answered, the constraints of the problem can be defined.

With each problem that needs to be solved comes a different set of considerations. A process might rely on the use of limited resources, such as raw materials, processing capacity, or even storage capacity for the final product. All processes are limited by bottlenecks, but it is not always easy to identify where these bottlenecks are.

3 Table of speakers participating in the meeting

	Topic	Speaker	Affiliation
a	Requirements on sustainable MES solutions and technologies in process industry of process industries	Ansgar Münnemann	BASF, Germany
b	Overview of planning and scheduling for enterprise-wide optimization	Ignacio Grossmann	Carnegie Mellon University, USA
c	On the relevance of optimization for the growing requirements on energy efficiency with cases studies	Bazmi Husain	ABB, Sweden
d	Manufacturing – Is there a role for algebraic modeling systems?	Jan-Henrik Jagla	GAMS, Germany
e	Optimizing manufacturing processes and planning with AIMMS	Frans de Rooij	AIMMS, Netherlands
f	Integrated manufacturing planning, batching, and scheduling, with ILOG plant PowerOps	Julien Briton	ILOG, France
g	Solving hard production planning and scheduling problems using Xpress-MP	Oliver Bastert	Fair Isaac, Germany
h	Production Optimization – requirements for sustainable Success	Alexander Horch	ABB, Germany
i	Oil & gas supply chain optimization	Marco Fahl	Honeywell, Germany
j	Advanced process control and optimization in the modern industry	Eduardo Gallestey	ABB, Switzerland
k	Unattended operation of water supply and optimization of pump schedules	Jan Poland	ABB, Switzerland
l	Chance constrained model predictive control for building energy management	Manfred Morari	ETH Zürich, Switzerland
m	Non-anticipative scheduling in semiconductor manufacturing systems involving setups	Hermann Gold	Infineon Technologies, Germany
n	The challenge of increasing complexity in production optimization	Iiro Harjunkoski	ABB, Germany
o	Integration of manufacturing optimization according to ISA 95	Thomas Schulz	Rockwell Automation, Germany
p	Uncertainty-conscious production scheduling	Sebastian Engell	TU Dortmund, Germany

When expressing an optimization problem in mathematical terms, the first step is to define the problem clearly.

Objective functions and their relationship with decision variables and constraints are expressed by mathematical equalities and inequalities[4]. The complete formulation is referred to as a "mathematical program," where the term program is used differently to the common notion[5]. Mathematical programs are of different types, depending on the nature of the formulation. If all equations, ie, the objective and all constraints, can be formulated using only linear terms with continuous variables, the optimization is referred to as linear programming. The formulation of a linear program (LP) is as follows:

Footnotes

[4] Equality is a proposition stating that two terms are equal ie, an equation. Inequality is a proposition stating the relative size, order, or difference of two objects ie, greater than (>),less than (<), or not equal to (≠).

[5] The term "mathematical program" does not refer to a computer program but is simply a synonym for a formal optimization model. Correspondingly, the term "mathematical programming" is a synonym for solving the mathematical program, ie, for mathematical optimization.

$$\text{maximize } c^T x \quad \text{subject to } Ax \leq b$$

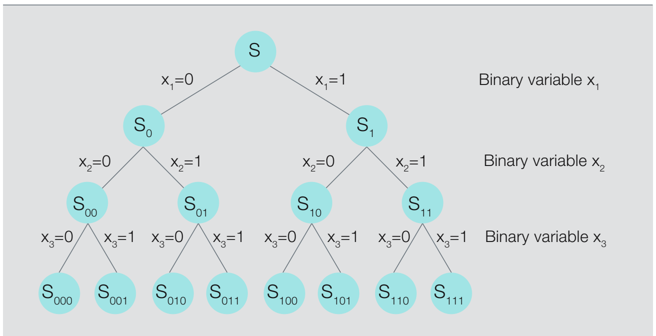
where x is a vector of variables, c and b are known parameter vectors and A is a matrix of known parameters. $c^T x$ is the objective function and $Ax \leq b$ represent the constraints[6].

If any equation comprises a nonlinear term, for example a product of two decision variables ($x_1 \cdot x_2$), then the problem is referred to as a nonlinear program (NLP).

In many cases, the decisions to be made are binary and answer yes/no questions: "Shall I visit customer x today: yes/no?" Also, many variables are integers (whole numbers): A carpenter can manufacture only a whole number of tables, never a fraction of a table. In this case, the problem would be a mixed-integer linear program (MILP) or a mixed-integer nonlinear program (MINLP).

Most modeling languages for mathematical programs were developed for operations research, but have found increasing use in engineering applications. Two dedicated modeling languages for optimization problems are GAMS and AIMMS. The roots of these modeling tools are in economic optimization 3d, but there is increasing interest in their use in engineering applications. Current software includes debugging, profiling and data analysis features 3e. The modeling systems provide interfaces to a number of standard solvers for the different types of mathematical programs.

5 Binary search tree for solving mixed-integer linear programs



Finding the optimal solution

Finding the optimal solution to a problem can be very difficult, particularly if there are large numbers of variables to be considered and if the problem is highly complex. Generally, even large LPs can be solved in a relatively short time because the best solution lies at the constraints or at intersections of the constraints. For example, the throughput of a process may be limited by an output-flow rate. This means that the maximum throughput will be exactly equal to the limiting output flow rate. Finding the solution to NLPs, however, can be more challenging, especially if the problem is non-convex[7] 4. In these cases, more complex algorithms must be applied or the problem must be divided into convex sub-problems.

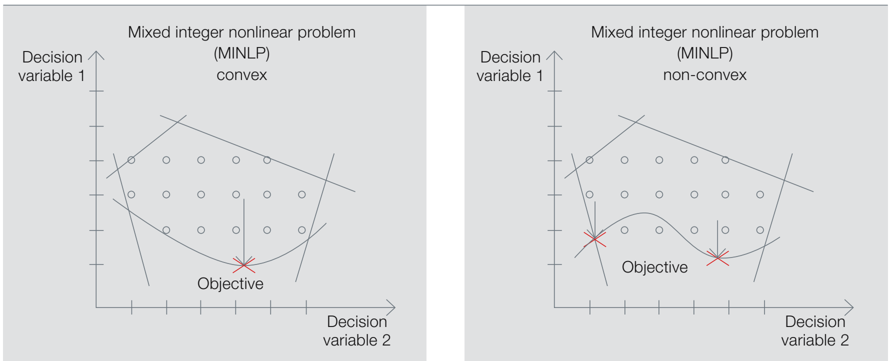
A standard method to solve mixed-integer problems (MILPs or MINLPs) is to apply branch-and-bound algorithms.

Discrete decisions can also complicate an optimization problem as the number of possible solutions grows exponentially with the number of choices to be made. The production sequence of three products, A, B and C, which are all manufactured by the same machine, can be produced 3! (factorial)= 1*2*3 = 6 different sequences (ie, ABC, ACB, BAC, BCA, CAB and CBA). Normally, to manufacture 100 different products, several machines would be needed. Manufacturing just twenty products on one machine would result in 20! different sequences – a number with 18 digits – and it is clear that not even a super computer could try all combinations within a reasonable time. If a computer was able to test one million combinations per second, it would need 77,000 years to try 20! combinations and find the best solution. This sequencing problem is very similar to the traveling salesman problem stated above: The number of possible traveling routes is also 20!

A standard method to solve mixed-integer problems (MILPs or MINLPs) is to apply branch-and-bound algorithms. Branch-and-bound algorithms can be used to solve a sequence of LPs or NLPs and are capable of finding an optimal solution by examining only a fraction of the possible solutions and eliminating whole branches of the search tree 5.

There are many solvers available, such as ILOG CPLEX, which can deal with very large optimization problems using multiple CPUs in parallel processes 3f. Xpress-MP Optimizer is noted for its ability to solve numerically difficult or unstable problems, which is often applied in the process industries 3g. Because these sophisticated algorithms are still very expensive, in the range of several thousand dollars each, optimization as a service that can be purchased on demand, may

4 Optimization problem types – convex and non-convex nonlinear programming problems



Footnotes

[6] As each equality constraint can equivalently be represented by two inequality constraints, the formulation covers both equality and inequality constraints.

[7] When the problem is described by a function that forms a non-convex curve on a graph.

become a popular option 3h. The US government already provides a website (NEOS) onto which optimization problems in GAMS or AMPL can be uploaded and solutions retrieved in real time. This may not be viable for all applications, but is a good way to test and verify problems before investing in expensive solvers[8].

Applications

Real-world optimization problems are usually hard to solve. The problem type is often nonlinear and/or contains binary variables. The performance of standard tools is often insufficient, necessitating the development of engineered solutions. Engineered mathematical programming uses carefully designed optimization models and intelligent solution strategies, often based on problem decomposition. When designing such a solution, the optimization core ie, formulating and implementing the problem, often contributes no more than 10 to 15 percent of the engineering effort. Problem understanding, idea development, discussion with customers, testing, documentation, marketing, and so on, constitutes the remaining effort. During the GOR workshop, this opinion was shared by speakers presenting optimization application solutions – both from inside and outside ABB. The applications introduced included supply chain management in liquefied natural gas plants 3i, economic process optimization and scheduling in minerals 3j, optimization of pump schedules in pump stations 3k, online optimization for building energy management 3l and batch scheduling in semiconductor plants 3m.

In the following, three very successful ABB optimization solutions, published previously and discussed at the GOR workshop, are shown in the context of mathematical optimization.

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Copper plant scheduling and optimization

In copper production, the ore is purified in several consecutive stages. During this process, it is transferred between stages in ladles using cranes. Large copper plants have parallel processing lines for the stages that would otherwise create bottlenecks and these must be synchronized to prevent overloading. This is a complex problem because the length of the purification stages differ depending on the quality of the ore.

The productivity of a copper plant is chiefly determined by the scheduling of the batches through the plant. ABB has developed an optimization solution to determine the optimum schedule for this process [1] 6. The task was to determine a production schedule that maximized the plant's throughput, by determining the optimal material quantity and detailed timing for each batch of copper production. The overall schedule was constrained by equipment availability for each stage of purification, as well as by processing and transportation times. The problem was formulated as an MILP and the solution used ILOG CPLEX to generate the schedule and the optimal recipe definition for each batch. The objective was to minimize the makespan[9] tm of all products p on all machines m:

$$\min\ tm$$
$$\textit{subject to}$$
$$tm \geq tf_{pm}\ \forall p, m$$

Where tf is the finishing time of a product p on machine m. The optimization solution showed the plant's potential to increase throughput by up to 20,000 tons of copper concentrate per year.

Energy efficient hot rolling

In a hot rolling mill, steel slabs are heated to several hundred °C and rolled into thin sheets. An important decision variable is the speed at which each slab is rolled.

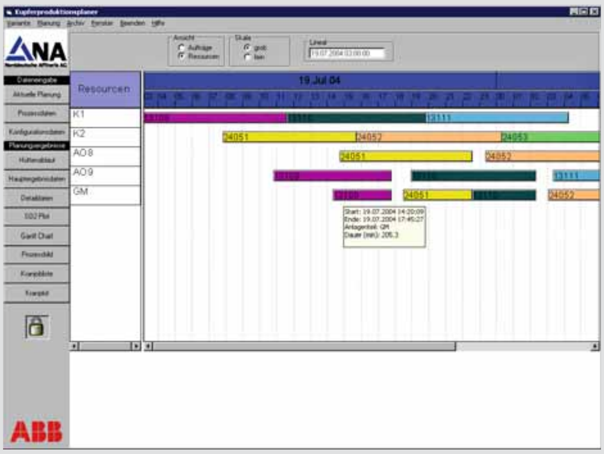
Minimizing energy consumption is one optimization objective the opera-

Footnotes

8) For further information visit NEOS website: http://www-neos.mcs.anl.gov/(December, 2008).

9) Makespan is the total production duration, ie, until the last product has finished on the last machine.

6 Copper production and Gantt chart of the optimal schedule



7 Hot rolling mill optimization solution faceplate [2]

Structure of a rolling optimization set-up

Objective
Minimization of total rolling POWER/ENERGY, or,
Maximization of PRODUCTION SPEED, or,
Minimization of deviation from target powers (LOAD SHARING), or,
Minimization of deviation from target widths (GROOVE UTILIZATION), or,
Minimization of deviation from target areas (GROOVE UTILIZATION)

Parameter Bounds
… < Roll gap < …,
… < Motor speed < …,
… < Interpass tension < …,
… < Width < …,
… < Area < …,
… < Production speed < …,
… < Billet temperature < …,

Variables
Roll gaps, motor speeds

tor may pursue, while at the same time meeting upper and lower speed limits for bar width, area, speed, interpass tension, roll gap and motor speed. In short, the question is: what is the best production speed for a hot rolling mill if the system is limited by available motor power and torque?

ADM™ (Adaptive Dimension Models) is an ABB software tool that formulates solutions to the optimization problem as a nonlinear program[10] [2]. In addition to minimizing energy consumption, the user interface allows the operator to choose between alternative optimization objectives, such as maximizing throughput, minimizing deviations from target power, width or areas 7.

ABB's ADMTM software tool formulates solutions to the optimization problem as a nonlinear program.

Minimizing trim loss in paper cutting

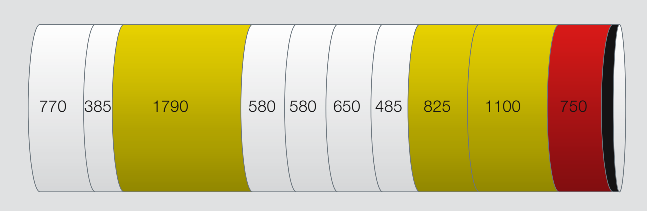
Paper mills produce so-called jumbo paper reels, 10 meters wide, which are cut down after production to meet customer specifications. Qtrim[11], a re-trimming solution developed at ABB, takes an existing cutting plan for a jumbo reel and re-plans it according to the requirements [3]. The quality-based trim loss problem asks the following: What is the best way to cut rolls to customer-specified dimensions while also meeting the customer's quality requirements? The objective can be expressed in mathematical terms as follows:

$$\max \sum_{r,j} c_{rj} \cdot xd_{rj}$$

where index r indicates the rolls and index j indicates discrete slices, corresponding to a position on a jumbo reel. The cost coefficient c_{rj} is the value of a roll r at a given position j. The binary variable xd_{rj} indicates if roll r is allocated to slice j ($xd_{rj}=1$) or not ($xd_{rj}=0$).

The output of the optimization is a cutting plan that minimizes the quality

8 Optimized trim set of a jumbo reel (Quality A = white, B = yellow, C = Red) [3]



losses. By implementing the best quality considerations in the cutting process, profit margins can be improved by up to 15 percent 8.

Complexity and uncertainty

In the processing industries, there are already numerous optimization solutions to improve productivity. However, there still remain some unresolved issues that were discussed at the workshop. One is the ever-increasing complexity of problems 3n. The reasons for this are manifold, but many problems that were previously solved manually should now be optimized mathematically. Also, separate problems concerning the same production process can be combined. For example, a production process can be optimized for both throughput and energy consumption. More and more information can be measured, stored and used for optimization, which increases the number of decision variables and constraints. With an increase in complexity comes the problem of performance. Solutions to problems should be available in seconds or minutes.

A further open issue is the fact that optimization software solutions have to be integrated into the existing landscape of IT systems and cannot be used independently 3o. They require information from other systems, from the control, business-planning and logistic systems. There are a number of useful industrial standards for integration. For instance, the ISA-95 standard describes the necessary standards for interfacing between these systems.

Lastly, most optimization solutions assume that the input parameters are correct. The decisions must be made based on information that is available before the optimization algorithm is run. In the real production environment, the correct parameter values are often not known. A batch may take on average 10 minutes to produce but can in some instances be finished after eight minutes, in others after 12. Dealing with these uncertainties is a key challenge for real-world applications of these solutions 3p. Evolutionary algorithms, in combination with traditional solution algorithms, show potential to deal with these types of problems.

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Footnotes

[10] http://www.abb.com/metals → Profile mills → Profile mill products → ADM

[11] http://www.abb.com/cpm → CPM for the Pulp and Paper Industry → Quality Based Re-Trim Optimization

References

[1] **Harjunkoski, I., Beykirch, G., Zuber, M., Weidemann, H. J.** The process "copper": copper plant scheduling and optimization. *ABB Review* 4/2005, 51–54.

[2] **Daneryd, A., Olsson, M.G., Lindkvist, R.** Energy efficient rolling: on-line minimization of energy consumption in the hot rolling of long products. *ABB Review* 2/2007, 49–52.

[3] **Harjunkoski, I., Säynevirta, S.** The cutting edge: cutting the inefficiency out of paper re-trimming. *ABB Review* 4/2006, 53–58.