Preface

Some Early Opinions on Technology

There is practically no chance communications space satellites will be used to provide better telephone, telegraph, television, or radio service inside the United States

T. Craven, FCC Commissioner, 1961

There is not the slightest indication that nuclear energy will ever be obtainable. It would mean that the atom would have to be shattered at will.

Albert Einstein, 1932

Heavier-than-air flying machines are impossible.

Lord Kelvin, 1895

We will never make a 32 bit operating system.

Bill Gates, 1983

Such startling announcements as these should be deprecated as being unworthy of science and mischievous to its true progress.

William Siemens, on Edison's light bulb, 1880

The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine.

Ernest Rutherford, shortly after splitting the atom for the first time, 1917

Everything that can be invented has been invented.

Charles H. Duell, Commissioner of the US Patent Office, 1899

Content and Scope

Optimization is the determination of the values of the independent variables in a function such that the dependent variable attains a maximum over a suitably defined area of validity (c.f. the boundary conditions). We consider the case in which the independent variables are many but the dependent variable is limited to one; multi-criterion decision making will only be touched upon.

This book, for the first time, combines mathematical methods and a wide range of real-life case studies of industrial use of these methods. Both the methods and the problems to which they are applied as examples and case studies are useful in real situations that occur in profit making industrial businesses from fields such as chemistry, power generation, oil exploration and refining, manufacturing, retail and others.

The case studies focus on real projects that actually happened and that resulted in positive business for the industrial corporation. They are problems that other companies also have and thus have a degree of generality. The thrust is on take-home lessons that industry managers can use to improve their production via optimization methods.

Industrial production is characterized by very large investments in technical facilities and regular returns over decades. Improving yield or similar characteristics in a production facility is a major goal of the owners in order to leverage their investment. The current approach to do this is mostly via engineering solutions that are costly, time consuming and approximate.

Mathematics has entered the industrial stage in the 1980s with methods such as linear programming to revolutionize the area of industrial optimization. Neural networks, simulation and direct modeling joined and an arsenal of methods now exists to help engineers improve plants; both existing and new. The dot-com revolution in the late 1990s slowed this trend of knowledge transfer and it is safe to say that the industry is essentially stuck with these early methods. Mathematics has evolved since then and accumulated much expertise in optimization that remains hardly used. Also, modern computing power has exploded with the affordable parallel computer so that methods that were once doomed to the dusty shelf can now actually be used.

These two effects combine to harbor a possible revolution in industrial uses for mathematical methods. These uses center around the problem of optimization as almost every industrial problem concerns maximizing some goal function (usually efficiency or yield). We want to help start this revolution by a coordinated presentation of methods, uses and successful examples.

The methods are necessarily heuristic, i.e. non-exact, as industrial problems are typically very large and complex indeed. Also, industrial problems are defined by imprecise, sometimes even faulty data that must be absorbed by a model. They are always non-linear and have many independent variables. So we must focus on heuristic methods that have these characteristics.

This book is practical

This book is intended to be used to solve real problems in a handbook manner. It should be used to look for potential yet untapped. It should be used to see possibilities where there were none before. The impossible should move towards the realm of the possible. The use, therefore, will mainly be in the sphere of application by persons employed in the industry.

The book may also be used as instructional material in courses on either optimization methods or applied mathematics. It may also be used as instructional material in MBA courses for industrial managers.

Many readers will get their first introduction as to what mathematics can really and practically do for the industry instead of general commonplaces. Many will find out what problems exist where they previously thought none existed. Many will discover that presumed impossibilities have been solved elsewhere. In total, I believe that you, the reader, will benefit by being empowered to solve real problems.

These solutions will save the corporations money, they will employ people, they will reduce pollution into the environment. They will have impact. It will show people also that very theoretical sciences have real uses.

It should be emphasized that this book focuses on applications. Practical problems must be understood at a reasonable level before a solution is possible. Also all applications have several non-technical aspects such as legal, compliance and managerial ramifications in addition to the obvious financial dimension. Every solution must be implemented by people and the interactions with them is the principal cause for failure in industrial applications. The right change management including the motivation of all concerned is an essential element that will also be addressed. Thus, this book presents cases as they can really function in real life.

Due to the wide scope of the book, it is impossible to present neither the methods nor the cases in full detail. We present what is necessary for understanding. To actually implement these methods, a more detailed study or prior knowledge is required. Many take-home lessons are however spelt out. The major aim of the book is to generate understanding and not technical facility.

This book is intended for practitioners

The intended readership has five groups:

1. *Industrial managers* - will learn what can be done with mathematical methods. They will find that a lot of their problems, many seemingly impossible, are already solved. These methods can then be handed to technical persons for implementation.
2. *Industrial scientists* - will use the book as a manual for their jobs. They will find methods that can be applied practically and have solve similar problems before.
3. *University students* - will learn that their theoretical subjects do have practical application in the context of diverse industries and will motivate them in their studies towards a practical end. As such it will also provide starting points for theses.
4. *University researchers* - will learn to what applications the methods that they research about have been put or respectively what methods have been used by others to solve problems they are investigating. As this is a trans-disciplinary

book, it should facilitate communication across the boundaries of the mathematics, computer science and engineering departments.
5. *Government funding bodies* - will learn that fundamental research does actually pay off in many particular cases.

A potential reader from these groups will be assumed to have completed a mathematics background training up to and including calculus (European high-school or US first year college level). All other mathematics will be covered as far as needed. The book contains no proofs or other technical material; it is practical.

A short summary

Before a problem can be solved, it and the tools must be understood. In fact, a correct, complete, detailed and clear description of the problem is (measured in total human effort) often times nearly half of the final solution. Thus, we will place substantial room in this book on understanding both the problems and the tools that are presented to solve them.

Indeed we place primary emphasis on understanding and only secondary emphasis on use. For the most part, ready-made packages exist to actually perform an analysis. For the remainder, experts exist that can carry it out. What cannot be denied however, is that a good amount of understanding must permeate the relationship between the problem-owner and the problem-solver; a relationship that often encompasses dozens of people for years.

Here is a brief list of the contents of the chapters

1. What is optimization?
2. What is an optimization problem?
3. What are the management challenges in an optimization project?
4. How can we deal with faulty and noisy empirical data?
5. How do we gain an understanding of our dataset?
6. How is a dataset converted into a mathematical model?
7. How is the optimization problem actually solved?
8. What are some challenges in implementing the optimal solution in industrial practice (change management)?

Most of the book was written by me. Any deficiencies are the result of my own limited mind and I ask for your patience with these. Any benefits are, of course, obtained by standing on the shoulders of giants and making small changes. Many case studies are co-authored by the management from the relevant industrial corporations. I heartily thank all co-authors for their participation! All the case studies were also written by me and the same comments apply to them. I also thank the co-authors very much for the trust and willingness to conduct the projects in the first place and also to publish them here.

Chapter 8 was entirely written by Andreas Ruff of Elkem Silicon Materials. He has many years of experience in implementing optimization projects' results in chemical corporations and has written a great practical account of the potential pitfalls and their solutions in change management.

Following this text, we provide first an alphabetical list of all co-authors and their affiliations and then a list of all case studies together with their main topics and educational illustrations.

Bremen, 2011 *Patrick Bangert*

Markus Ahorner
COO
m.ahorner@algorithmica-technologies.com
Section 4.8, p. 53; Section 4.9, p. 58
algorithmica technologies GmbH
Gustav-Heinemann-Strasse 101
28215 Bremen, Germany
www.algorithmica-technologies.com

Dr. Patrick Bangert
CEO
p.bangert@algorithmica-technologies.com
All sections
algorithmica technologies GmbH
Gustav-Heinemann-Strasse 101
28215 Bremen, Germany
www.algorithmica-technologies.com

Claus Borgböhmer
Director Project Management
claus.borgboehmer@de.sasol.com
Section 4.8, p. 53
Sasol Solvents Germany GmbH
Römerstrasse 733
47443 Moers, Germany
www.sasol.com

Pablo Cajaraville
Director Engineering and Sales
p.cajaraville@reinermicrotek.com
Section 6.6, p. 135
Reiner Microtek
Poligono Industrial Itziar, Parcela H-3
20820 Itziar-Deba, Spain
www.reinermicrotek.com

Roger Chevalier
Senior Research Engineer
roger.chevalier@edf.fr
Section 6.10, p. 152
EDF SA, R&D Division
6 quai Watier, BP49
78401 Chatou Cedex, France
www.edf.com

Jörg-A. Czernitzky
Power Plant Group Director Berlin
joerg-andreas.czernitzky@vattenfall.de
Section 7.10, p. 197
Vattenfall Europe Wärme AG
Puschkinallee 52
12435 Berlin, Germany
www.vattenfall.de

Prof. Dr. Adele Diederich
Professor of Psychology
a.diederich@jacobs-university.de
Section 7.6, p. 183
Jacobs University Bremen gGmbH
P.O. Box 750 561
28725 Bremen, Germany
www.jacobs-university.de

Björn Dormann
Research Director
b.dormann@desma.de
Section 6.6, p. 135
Klöckner Desma Schuhmaschinen GmbH
Desmastr. 3/5
28832 Achim, Germany
www.desma.de

Hans Dreischmeier
Director SAP
hans.dreischmeier@vestolit.de
Section 4.9, p. 58
Vestolit GmbH & Co. KG
Industriestrasse 3
45753 Marl, Germany
www.vestolit.de

Bernd Herzog
Quality Control Manager
bernd.herzog@hella.de
Section 4.11, p. 63
Hella Fahrzeugkomponenten GmbH
Dortmunder Strasse 5
28199 Bremen, Germany
www.hella.de

Dr. Philipp Imgrund
Director Biomaterial Technology
Director Power Technologies
philipp.imgrund@ifam.fraunhofer.de
Section 6.6, p. 135
Fraunhofer Institute for Manufacturing
and Advanced Materials IFAM
Wiener Strasse 12
28359 Bremen, Germany
www.ifam.fhg.de

Maik Köhler
Technical Expert
m.koehler@desma.de
Section 6.6, p. 135
Klöckner Desma Schuhmaschinen GmbH
Desmastr. 3/5
28832 Achim, Germany
www.desma.de

Lutz Kramer
Project Manager
Metal Injection Molding
lutz.kramer@ifam.fraunhofer.de
Section 6.6, p. 135
Fraunhofer Institute for Manufacturing
and Advanced Materials IFAM
Wiener Strasse 12
28359 Bremen, Germany
www.ifam.fhg.de

Guisheng Li
Institute Director
lgsh50@tom.com
Section 6.12, p. 157
Oil Production Technology Research Institute
Plant No. 5 of Petrochina Dagang Oilfield Company
Tianjin 300280, China
www.petrochina.com.cn

Bailiang Liu
Vice Director
liubailiang@petrochina.com.cn
Section 7.9, p. 194
PetroChina Dagang Oilfield Company
Tianjin 300280
China
www.petrochina.com.cn

Oscar Lopez
Senior Research Engineer
olopez@alfalan.es
Section 6.6, p. 135
MIM TECH ALFA, S.L.
Avenida Otaola, 4
20600 Eibar, Spain
www.alfalan.es

Torsten Mager
Director Technical Services
torsten.mager@kng.de
Section 5.6, p. 102
KNG Kraftwerks- und Netzgesellschaft mbH
Am Kühlturm 1
18147 Rostock, Germany
www.kraftwerk-rostock.de

Manfred Meise
CEO
manfred.meise@hella.de
Section 4.11, p. 63
Hella Fahrzeugkomponenten GmbH
Dortmunder Strasse 5
28199 Bremen, Germany
www.hella.de

Kurt Müller
Director Maintenance
kurt.mueller@vestolit.de
Section 4.9, p. 58
Vestolit GmbH & Co. KG
Industriestrasse 3
45753 Marl, Germany
www.vestolit.de

Kaline Pagnan Furlan
Research Assistant
Metal Injection Molding
kaline.pagnan.furlan@ifam.fraunhofer.de
Section 6.6, p. 135
Fraunhofer Institute for Manufacturing
and Advanced Materials IFAM
Wiener Strasse 12
28359 Bremen, Germany
www.ifam.fhg.de

Yingjun Qu
Institute Director
jyj_cq@petrochina.com.cn
Section 6.12, p. 157
Oil Production Technology Research Institute
Plant No. 6 of Petrochina Changqing Oilfield Company
718600 Shanxi, China
www.petrochina.com.cn

Pedro Rodriguez
Director R&D
prodriguez@alfalan.es
Section 6.6, p. 135
MIM TECH ALFA, S.L.
Avenida Otaola, 4
20600 Eibar, Spain
www.alfalan.es

Andreas Ruff
Technical Marketing Manager
andreas.ruff@elkem.no
Chapter 8, p. 201
Elkem Silicon Materials
Hochstadenstrasse 33
50674 Kln
www.elkem.no

Dr. Natalie Salk
CEO
PolyMIM GmbH
Am Gefach

natalie.salk@polymim.com
Section 6.6, p. 135
55566 Bad Sobernheim
www.polymim.com

Prof. Chaodong Tan
Professor
tantcd@126.com
Section 6.12, p. 157; Section 7.9, p. 194
China University of Petroleum
Beijing 102249
China
www.upc.edu.cn

Jörg Volkert
Project Manager
Metal Injection Molding
joerg.volkert@ifam.fraunhofer.de
Section 6.6, p. 135
Fraunhofer Institute for Manufacturing
and Advanced Materials IFAM
Wiener Strasse 12
28359 Bremen, Germany
www.ifam.fhg.de

Xuefeng Yan
Director of Production Technology
yxf_993@126.com
Section 6.12, p. 157
Beijing Yadan Petroleum Technology Co., Ltd.
No. 37 Changqian Road, Changping
Beijing 102200, China
www.yadantech.com

Jie Zhang
Vice CEO
nyboc@sina.com
Section 7.9, p. 194
Yadan Petroleum Technology Co Ltd
No. 37 Changqian Road, Changping
Beijing 102200, China
www.yadantech.com

Timo Zitt
Director Dormagen Combined-Cycle Plant
timo.zitt@rwe.com
Section 7.11, p. 199
RWE Power AG
Chempark, Geb. A789
41538 Dormagen
www.rwe.com

The following is a list of all case studies provided in the book. For each study, we provide its location in the text and its title. The summary indicates what the case deals with and what the result was. The "lessons" are the mathematical optimization concepts that this case particularly illustrates.

Self-Benchmarking in Maintenance of a Chemical Plant
Section 4.8, p. 53
Summary: In addition to the common practice of benchmarking, we suggest to compare the plant to itself in the past to make a self-benchmark.
Lessons: The right pre-processing of raw data from the ERP system can already bear useful information without further mathematical analysis.

Financial Data Analysis for Contract Planning
Section 4.9, p. 58

Summary: Based on past financial data, we create a detailed projection into the future in several categories and so provide decision support for budgeting.
Lessons: Discovering basic statistical features of data first, allows the transformation of ERP data into a mathematical framework capable of making reliable projections.

Early Warning System for Importance of Production Alarms
Section 4.11, p. 63
Summary: Production alarms are analyzed in terms of their abnormality. Thus we only react to those alarms that indicate qualitative change in operations.
Lessons: Comparison of statistical distributions based on statistical testing allows us to distinguish normal from abnormal events.

Optical Digit Recognition
Section 5.4, p. 92
Summary: Images of hand-written digits are shown to the computer in an effort for it to learn the difference between them without us providing this information (unsupervised learning).
Lessons: It is possible to cluster data into categories without providing any information at all apart from the raw data but it pays to pre-process this data and to be careful about the number of categories specified.

Turbine Diagnosis in a Power Plant
Section 5.5, p. 96
Summary: Operational data from many turbines are analyzed to determine which turbine was behaving strangely and which was not.
Lessons: Time-series can be statistically compared based on several distinctive features providing an automated check on qualitative behavior of the system.

Determining the Cause of a Known Fault
Section 5.6, p. 102
Summary: We search for the cause of a bent blade of a turbine and do not find it.
Lessons: Sometimes the causal mechanism is beyond current data acquisition and then cannot be analyzed out of it. It is important to recognize that analysis can only elucidate what is already there.

Customer Segmentation
Section 5.10, p. 117
Summary: Consumers are divided into categories based on their purchasing habits.
Lessons: Based on purchasing histories, it is possible to group customers into behavioral groups. It is also possible to extract cause-effect information about which purchases trigger other purchases.

Scrap Detection in Injection Molding Manufacturing
Section 6.6, p. 135

Summary: It is determined whether an injection molded part is scrap or not.
Lessons: Several time-series need to be converted into a few distinctive features to then be categorized by a neural network as scrap or not.

Prediction of Turbine Failure
Section 6.7, p. 140
Summary: A turbine blade tear is correctly predicted two days before it happened.
Lessons: Time-series can be extrapolated into the future and thus failures predicted. The failure mechanism must be visible already in the data.

Failures of Wind Power Plants
Section 6.8, p. 143
Summary: Failures of wind power plants are predicted several days before they happen.
Lessons: Even if the physical system is not stable because of changing wind conditions, the failure mechanism is sufficiently predictable.

Catalytic Reactors in Chemistry and Petrochemistry
Section 6.9, p. 148
Summary: The catalyst deactivation in fluid and solid catalytic reactors is projected into the future.
Lessons: Non-mechanical degradation can be predicted as well and allows for projection over one year in advance.

Predicting Vibration Crises in Nuclear Power Plants
Section 6.10, p. 152
Summary: A temporary increase in turbine vibrations is predicted several days before it happens.
Lessons: Subtle events that are not discrete failures but rather quantitative changes in behavior can be predicted too.

Identifying and Predicting the Failure of Valves
Section 6.11, p. 155
Summary: In a system of valves, we determine which valve is responsible for a non-constant final mixture and predict when this state will be reached.
Lessons: Using data analysis in combination with plant know-how, we can identify the root-cause even if the system is not fully instrumented.

Predicting the Dynamometer Card of a Rod Pump
Section 6.12, p. 157
Summary: The condition of a rod pump can be determined from a diagram known as the dynamometer card. This 2D shape is projected into the future in order to diagnose and predict future failures.

Lessons: It is possible not only to predict time-series but also changing geometrical shapes based on a combination of modeling and prediction.

Human Brains use Simulated Annealing to Think
Section 7.6, p. 183
Summary: Based on human trial, we determine that human problem solving uses the simulated annealing paradigm.
Lessons: Simulated annealing is a very general and successful method to solve optimization problems that, when combined with the natural advantages of the computer, becomes very powerful and can find the optimal solution in nearly all cases.

Optimization of the Müller-Rochow Synthesis of Silanes
Section 7.8, p. 189
Summary: A complex chemical reaction whose kinetics is not fully understood by science is modeled with the aim of increasing both selectivity and yield.
Lessons: It is possible to construct empirical models without theoretical understanding and still compute the desired answers.

Increase of Oil Production Yield in Shallow-Water Offshore Oil Wells
Section 7.9, p. 194
Summary: Offshore oil pumps are modeled with the aim of both predicting their future failures and increasing the oil production yield.
Lessons: The pumps must be considered as a system in which the pumps influence each other. We solve a balancing problem between them using their individual models.

Increase of coal burning efficiency in CHP power plant
Section 7.10, p. 197
Summary: The efficiency of a CHP coal power plant is increased by 1%.
Lessons: While each component in a power plant is already optimized, mathematical modeling offers added value in optimizing the combination of these components into a single system. The combination still allows a substantial efficiency increase based on dynamic reaction to changing external conditions.

Reducing the Internal Power Demand of a Power Plant
Section 7.11, p. 199
Summary: A power plant uses up some its own power by operating pumps and fans. The internal power is reduced by computing when these should be turned off.
Lessons: We extrapolate discrete actions (turning off and on of pumps and fans) from the continuous data from the plant in order to optimize a financial goal.

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