OPTEC Optimization in Engineering Center



OPTEC Workshop on

Large Scale Convex Quadratic Programming

Algorithms, Software and Applications

K.U.Leuven, 25-26 November, 2010

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I WELCOME

Dear Participants,

welcome to Leuven, welcome to the OPTEC Workshop on Large Scale Convex Quadratic Programming! Our motivation for organizing this workshop was to bring together researchers working on large scale QP solution algorithms in a small and focused workshop. We are extremely happy and grateful that we could convince three renowned experts as keynote speakers that will each present one of the most important large QP solution strategies in a 45 minute talk: Yurii Nesterov for first order methods, Stephen Wright for structure exploiting interior point methods, and Michael Saunders for sparse active set methods. We are equally happy that we could attract many other high profile scientists to present their latest ideas and experiences on large scale QP solving in form of oral presentations of 25 minutes duration and posters.

The two day program is single track and divided into four major parts. First, fast gradient methods are treated in two talks. Second, after a lunch at the workshop site, recent advances of IP methods are discussed throughout five presentations. In between, on Thursday afternoon at 15:30-16:30, the poster session will take place. The workshop dinner is on Thursday evening at 19:00 in the WOK-Dynasty restaurant. In the third part on Friday morning, four talks treat the world of active set methods. After a lunch in the restaurant Voltaire, the last and fourth session takes place, with two application oriented talks. The workshop ends on Friday at 15:00 with a good-bye coffee.

This workshop was financially supported by K.U. Leuven's Optimization in Engineering Center (OPTEC), and by two European FP7 projects *EMBOCON - Embedded Optimization for Resource Constrained Platforms* and *HD-MPC - Hierarchical and Distributed Model Predictive Control of Large-scale Complex Systems*. Special thanks go to Jacqueline De bruyn (ESAT) for helping in the administrational tasks, to Ioanna Stamati for helping in printing and to Reinhart Paelinck for designing the workshop logo.

We wish all of you pleasant two days in Leuven and are looking forward to a hopefully exciting, interesting and inspiring workshop!

Moritz Diehl and Attila Kozma
K.U.Leuven, November 2010

II Program overview

25 November (Thursday)	
10:30-11:00	Registration
11:00-11:15	Welcome coffee
11:15-12:05	**Yurii Nesterov: Fast gradient methods for large-scale optimization problems**
12:05-12:35	Olivier Devolder: First-order Methods for Convex Optimization with Inexact Oracle
12:35-14:00	Lunch
14:00-14:30	Philippe Toint: Inexact range-space Krylov solvers for linear systems arising from inverse problems
14:30-15:00	Amir Shahzad: A Well-conditioned Interior Point Method for Quadratic Programming with an Application to Optimal Control
15:00-15:30	Nick Gould: CQP: a fortran 90 module for large-scale convex quadratic programming
15:30-16:30	Poster session
16:30-17:20	**Stephen Wright: Efficient methods for structured quadratic programs**
17:20-17:50	Joachim Dahl: Solving large-scale convex QPs with MOSEK
19:00-	Dinner @ WOK

26 November (Friday)	
09:00-09:50	**Michael Saunders: A Regularized Active-set Method for Sparse Convex Quadratic Programming**
09:50-10:20	Christian Kirches: A Block Structured Active Set Method for Mixed–Integer Optimal Control Problems
10:20-10:50	Coffee break
10:50-11:20	Daniel Axehill: A Dual Active Set-Like Quadratic Programming Algorithm Tailored for Model Predictive Control
11:20-11:50	John Bagterp Jørgensen: Convex QP Algorithms for Linear MPC with Soft Output Constraints
11:50-13:50	Lunch @ Voltaire
13:50-14:20	Zdeněk Dostál: Optimal QP algorithms and scalable algorithms for nonlinear problems of mechanics
14:20-14:50	Oleg Burdakov: Monotonicity recovering QP-based methods for postprocessing finite element solutions
14:50-15:00	Closing session
15:00-	Goodbye coffee

III ABSTRACTS OF THURSDAY

11:15 - 12:05	Yurii Nesterov (KEYNOTE TALK)

Fast gradient methods for large-scale optimization problems

For large-scale optimization problems, the gradient methods remain the most powerful optimization tool. In this talk we discuss the primal and dual gradient methods and their accelerated version derived by the estimate function technique. We compare the performance of these methods as applied to the problems with exact and inexact oracle. In the second part of this talk, we show that on huge-scale optimization problems the standard gradient methods should be replaced by their variants based on random coordinate relaxation.

12:05 - 12:35	Olivier Devolder

First-order Methods for Convex Optimization with Inexact Oracle

In this talk, we analyze the effect on first-order methods of smooth convex optimization (classical and fast gradient methods) if only inexact first-order informations are available. We introduce a notion of approximative first-order oracle. For each method, we develop complexity results and study the link between the desired accuracy on the objective function and the needed accuracy for the oracle.

We obtain that in this inexact case, the superiority of the fast gradient method over the classical one is no more so clear. The optimal scheme suffers from an accumulation of errors contrarily to the classical gradient method and the choice between these two kinds of methods depends on the complexity of the computation of the inexact first-order informations.

We prove that this accumulation of errors does not come from ou analysis but from the fast gradient method itself, more precisely it is an intrinsic property of any first-order method with optimal convergence rate.

We present applications of our results to smooth convex-concave saddle point problems and to the obtention of a universal optimal method for smooth, weakly-smooth and non-smooth convex problems.

14:00 - 14:30	S. Gratton, Ph. L. Toint, J. Tshimanga Ilunga

Inexact range-space Krylov solvers for linear systems arising from inverse problems

The object of the talk is twofold. Firstly, range-space variants of standard Krylov iterative solvers are introduced for unsymmetric and symmetric linear systems. These are characterized by possibly much lower storage and computational costs than their full-space counterparts, which is crucial in data assimilation applications and other inverse problems. Secondly, it is shown that the computational cost may be further reduced by using inexact matrix-vector products: formal error bounds are derived on the size of the residuals obtained under two different accuracy models, and it is shown why a model controlling forward error on the product result is often preferable to one controlling backward error on the operator. Numerical examples finally illustrate the developed concepts and methods.

14:30 - 15:00	Amir Shahzad, Eric C. Kerrigan, George A. Constantinides

A Well-conditioned Interior Point Method for Quadratic Programming with an Application to Optimal Control

Interior point methods (IPMs) have proven to be an efficient way of solving convex quadratic programming problems. A linear system of equations needs to be solved in each iteration of an IPM. The ill-conditioning of this linear system in the later iterations of the IPM prevents the use of an iterative method in solving the linear system due to a very slow rate of convergence; in some cases the solution never reaches the desired accuracy. In this paper we propose the use of a well-conditioned, approximate linear system, which increases the rate of convergence of an iterative method. A computational advantage is obtained by the use of an inexact Newton method along with the use of novel preconditioners. Numerical results indicate that the computational complexity of our proposed method scales well when applied to solving finite horizon optimal control problems with linear dynamics, quadratic cost and linear inequality constraints.

15:00 - 15:30	Nick Gould, Dominique Orban, Daniel Robinson

CQP: a Fortran 90 module for large-scale convex quadratic programming

We describe the design of a new software package CQP for large-scale convex quadratic programming. The method is based on high-order Taylor and Puiseux approximation to a variety of infeasible arcs connecting the current iterate to a better target point. Possible arcs include those by Zhang and by Zhou and Sun based on work by Stoer, Mizuno, Potra and others. The resulting algorithm is provably both globally and polynomially convergent at an ultimately high-order (depending on the series used) in both non-degenerate and degenerate cases. We will illustrate a number of algorithmic options on the CUTEr QP test set. CQP is available as part of the fortran 90 library GALAHAD.

⊙ Beginning of Poster Session ⊙

15:30 - 16:30	Bruno Defraene, Toon van Waterschoot, Moritz Diehl, Marc Moonen

Real-time perception-based clipping of audio signals using a fast projected gradient optimization method

Clipping is an essential signal processing operation in many real-time audio applications (e.g. hearing aids, mobile phones). Still, the application of existing clipping techniques introduces a considerable amount of distortion, which results in a significant reduction of the sound quality of the audio signal. We will present a novel perception-based approach to clipping, in which clipping is formulated as a sequence of convex quadratic programming optimization problems aimed at minimizing perceptible clipping-induced distortion. A fast projected gradient optimization method allows the medium-scale QPs to be solved in real-time. A comparative

perceptual evaluation shows that the application of the presented perception-based clipping technique results in consistently higher sound quality scores than existing clipping techniques.

15:30 - 16:30	Minh Dang Doan, Tamás Keviczky, Bart De Schutter

A dual method for solving large-scale QPs in distributed MPC

Large-scale Quadratic Programs (QP) are often encountered in distributed model predictive control (MPC) problems. Several types of large-scale interconnecting systems require using distributed methods to solve MPC optimization problems that are convex QPs with large numbers of variables and constraints. In the literature a number of distributed algorithms have been proposed that can be applied to large-scale QPs, many of them are based on dual decomposition approach. One issue of dual decomposition-based methods is to find a feasible primal value, so that MPC feasibility is assured. We present a dual subgradient-based algorithm that provides a feasible solution for the distributed MPC problem. Moreover, a bound on suboptimality is given, so that the resulting MPC controller is a stabilizing controller.

15:30 - 16:30	Joachim Ferreau, Moritz Diehl

Real-World Applications of the Online Active Set Strategy

Model predictive control (MPC) relies on the fast and reliable solution of convex quadratic programs (QPs) in real-time. We developed an online active set strategy for dealing with MPC sampling times in the order of milliseconds. Its efficient opensource C++ implementation qpOASES has been successfully applied to several real-world academic as well as industrial applications.

15:30 - 16:30	François Glineur

Complexity of Low-Rank Matrix Approximation with Weights and Missing Data

Weighted low-rank approximation (WLRA) is a dimensionality reduction technique for data analysis which has been successfully used in several applications, e.g., in collaborative filtering to design recommender systems or in computer vision to recover structure from motion.

In this paper, we study the computational complexity of WLRA and prove that it is NP-hard to find an approximate solution even in the rank-one case. The proof is based on a reduction of the maximum-edge biclique problem, and applies for both positive and binary weights (the latter corresponding to low-rank matrix approximation with missing data).

15:30 - 16:30	Attila Kozma, Moritz Diehl

Distributed solution of convex QPs as a first step towards disributed Model Predictive Control

We solve convex Quadratic Programs with decoupled objective and coupled equality constraints by introducing a two-level optimization. On the low-level independent subproblems are solved on a set of slave nodes of a computer cluster, on the high-level a gradient-type method is applied running on the master node to make the equality constraints hold.

15:30 - 16:30	Tomas Kozubek

Numerically and Parallel Scalable FETI Based Algorithms for Contact Problems of Mechanics and Their Powerful Ingredients

We first briefly review the TFETI based domain decomposition methodology adapted to the solution of 2D and 3D multibody contact problems with Tresca and Coulomb friction Recall that TFETI imposes the prescribed displacements by the Lagrange multipliers, so that all the subdomains are floating and their kernels are a priori known. Then we show that the natural coarse grid of the rigid body motions introduced by Farhat, Mandel, and Roux defines a projector to the subspace of Lagrange multipliers with the solution. Moreover, the preconditioning by the projector reduces the condition number of the dual Schur complement so that it is independent on the discretization parameter h and accelerates also the non-linear steps.

Then we present our in a sense optimal algorithms for the solution of resulting quadratic programming problems together with their powerful ingredients such as parallel implementation, stable generalized inverse computation, contact direction correction, fixing rigid body modes and domain decomposition correction. The unique feature of these algorithms is their capability to solve the class of quadratic programming problems with spectrum in a given positive interval in $O(1)$ iterations. The theory yields the error bounds that are independent on conditioning of constraints and the results are valid even for linearly dependent equality constraints.

Finally, we put together the above results to develop scalable algorithms for the solution of both coercive and semi-coercive variational inequalities. Rather surprisingly, the results are qualitatively the same as the classical results on scalability of FETI for linear elliptic problems. We give results of numerical experiments with parallel solution of 2D and 3D contact problems discretized by up to more than 10 million of nodal variables to demonstrate that the scalability can be observed in computational practice. The power of the results is demonstrated also by the solution of difficult real world problems as analysis of the yielding clamp connection of the arc steel support used in mining industry, the roller bearing of wind generator etc.

15:30 - 16:30	Ion Necoara

Parallel and distributed optimization methods for estimation and control in networks

System performance for networks of interconnected subsystems can be increased if the traditionally separated subsystems are jointly optimized. Recently, parallel and distributed optimization methods have emerged as a powerful tool for solving estimation and control problems in large-scale network systems. In this presentation we review and analyze the optimization-theoretic concepts of parallel and distributed methods for solving coupled optimization problems and demonstrate how several estimation and control problems related to complex network systems can be formulated in these settings. We present a systematic framework to exploit the potential of the decomposition structures as a way to obtain different parallel algorithms, each with a different tradeoff among convergence speed, message passing amount, and distributed computation architecture.

15:30 - 16:30	Jan Poland

Quadratic and Nonlinear Programming in past ABB Corporate Research Projects

In ABB Corporate Research, a couple of projects have been executed in the past and present where the core task is nonlinear optimization, often quadratic programming. Most of these projects involve a combination of optimal control and estimation. They fall into two groups, which are addressed with different methods: fast applications, mostly in power electronics control, with sampling times below in the millisecond range and below, and slow applications in process control with sampling times of the order of seconds or minutes. In this poster, we briefly highlight the following projects: HVDC converter control, moving horizon estimation for DC converters, model predictive direct torque control, cement kiln control, and froth flotation control.

15:30 - 16:30	Andreas Potschka, Christian Kirches, Hans Georg Bock

Improving reliability of parametric QP algorithms

Parametric Quadratic Programming algorithms are a special class of iterative active set methods for the solution of Quadratic Programming (QP) problems. These algorithms are based on a homotopy between two problems – from a QP with a known solution to the QP which is to be solved. Two consecutive iterates of the algorithm differ by a small change in the active set but possibly large changes in the primal and dual variables. The property that each iterate of the algorithm is a solution to an intermediate QP on the homotopy path is very appealing for backward error analysis. Parametric QP algorithms are especially efficient when solving a sequence of related QPs, e.g., in Sequential Quadratic Programming for the solution of nonlinear optimization problems.

In this talk we present several algorithmic techniques and heuristics which we have found to be important for reliability of a Parametric QP algorithm. These techniques include improvements for numerical checks of linear dependency, choice of termination criteria, iterative

refinement for ill-conditioned problems, a "Ramping" technique to reduce cycling of the active sets, and Flipping Bounds in connection with "Far Bounds" to allow for the treatment of semi-definite Hessians.

We present numerical results of the resulting algorithm on a subset of the Maros-Mészáros Convex QP test set and compare the method with other QP solvers (CPLEX, OOQP, qpOASES, quadprog).

In an outlook we discuss the application to non-convex QPs.

⊙ End of Poster Session ⊙

16:30 - 17:20	Stephen Wright (KEYNOTE TALK)

Efficient methods for structured quadratic programs

The usefulness of quadratic programming in control is well established, and the paradigm continues to find applications in such important modern areas as compressed sensing and machine learning. In all these areas, the chosen algorithm must provide a solution that is accurate enough for purposes of the application in a reasonable amount of computation time. The ability of the algorithm to exploit problem structure is often a key issue. In this talk, we start by surveying both new applications and the wide range of algorithic techniques that are being applied to them, both well established and modern. We then focus on a few topics of interest, including gradient descent methods, continuation and partial enumeration for parametrized problems, the use of GPUs in compressed sensing solvers, and the code generation techniques that are being pioneered by Boyd's group.

17:20 - 17:50	Joachim Dahl

Solving large-scale convex QPs with MOSEK

In this talk we discuss how to solve large-scale convex QPs using MOSEK. We consider advantages of alternative formulations to typical QPs, and we discuss practically occurring issues such convexity, duality, infeasibility detection, as well as quadratic versus conic formulations. We also give an overview of the different algorithms implemented in MOSEK and present numerical results emphasizing some of the points made in this talk.

IV ABSTRACTS OF FRIDAY

9:00 - 9:50	Michael Saunders, Christopher Maes (KEYNOTE TALK)

QPBLUR: A Regularized Active-set Method for Sparse Convex Quadratic Programming

We develop an active-set algorithm for convex quadratic programs (QPs) that have many degrees of freedom:

$$\begin{array}{ll} \underset{x}{\text{minimize}} & c^T x + \frac{1}{2} x^T H x \\ \text{subject to} & \ell \leq \begin{pmatrix} x \\ Ax \end{pmatrix} \leq u, \end{array}$$

where A and H are sparse, H is positive definite or semidefinite, and the number of variables may be far more than the number of active constraints. The algorithm employs primal and dual regularization within what we call a BCL method (bound-constrained augmented Lagrangian method). This leads to a sequence of QP *subproblems* that are strictly convex and feasible, and whose KKT systems are guaranteed to be nonsingular for any active set.

A simplified, single-phase algorithm is possible for each QP subproblem. There is no need to control the inertia of the KKT system defining each search direction, and a simple step-length procedure may be used without risk of cycling in the presence of degeneracy. Since all KKT systems are nonsingular, they can be factored with a variety of sparse direct linear solvers such as UMFPACK or MA57 (and no basis repair or KKT repair is needed). Block-LU updates allow for active-set changes without altering the initial KKT factors.

The principal benefit of primal and dual regularization is that warm starts are possible from any given active set. This is vital inside a sequential quadratic programming (SQP) method for nonlinear optimization such as SNOPT. The algorithm has been implemented as the QPBLUR solver (MATLAB and Fortran 95 versions), and the Fortran version has been integrated into SNOPT. We evaluate the performance of QPBLUR on a test set of large convex QPs, and on the sequences of QPs arising from SNOPT's SQP method.

QPBLUR provides a reliable approach for solving sparse examples of Paige's generalized least-squares problem. Ordinary least-squares problems with Tikhonov regularization and bounds can be solved as a single QP subproblem.

9:50 - 10:20	Christian Kirches, Andreas Potschka, Sebastian Sager, Hans Georg Bock

A Block Structured Active Set Method for Mixed–Integer Optimal Control Problems

Solving mixed–integer optimal control problems under real–time constraints is a challenging problem of high practical relevance. Outer convexification and relaxation has emerged as a highly successful numerical approach to this end. Approximate solutions with bounded loss of optimality can be obtained by solving a single continuous optimal control problem, although with a significantly increased number of control parameters.

We present a block structured active set method for the solution of quadratic subproblems arising from a direct multiple shooting discretization of outer convexified mixed–integer optimal control problems. Its computational complexity is advantageous for problems with fine control

discretizations in time and for problems with many control parameters as in the case of outer convexification.

Path constraints depending directly on an integer control introduce structural nonconvexity into the arising QPs that are identified as Quadratic Programs with Vanishing Constraints. A new nonconvex extension to a parametric primal–dual active set method is introduced that allows to find stationary points of these subproblems.

We discuss the applicability and efficiency of the presented numerical method for several nonlinear real–world problems.

10:50 - 11:20	Daniel Axehill, Anders Hansson

A Dual Active Set-Like Quadratic Programming Algorithm Tailored for Model Predictive Control

The objective of this work has been to develop a QP algorithm tailored for MPC. More specifically, the primary target application is MPC for discrete-time hybrid systems. A desired property of the algorithm is that warm starts should be possible to perform efficiently. This property is important for on-line linear MPC, and it is crucial in branch and bound for hybrid MPC. In this work, a dual active set-like QP method was chosen because of its warm start properties. A drawback with classical active set methods is that they often require many iterations in order to find the active set in optimum. This is due to the fact that every change to the active set costs an iteration. Gradient projection methods are methods that are known to be able to allow large changes to the active set in each iteration. Such a method was therefore chosen as the backbone in this work. In order to improve performance, the search directions based on first order information are combined with search directions based on second order information. The method was applied to the dual QP problem and the linear algebra was tailored for the MPC application. Results from numerical experiments indicate that the performance of the algorithm is very good, both for linear MPC as well as for hybrid MPC. It is also noticed that the number of QP iterations is significantly reduced compared to classical active set methods.

11:20 - 11:50	John Bagterp Jørgensen

Convex QP Algorithms for Linear MPC with Soft Output Constraints

In this contribution, we describe algorithms and computational performance of quadratic programming algorithms tailored for linear MPC with soft output constraints. We consider a primal active-set algorithm, a dual-active set algorithm, and a primal-dual interior-point algorithm for solution of convex QPs and tailor these algorithms for the special structure of linear MPC with soft output constraints.

Linear MPC with soft output constraints is an attractive optimization model for control of uncertain linear systems and systems with asymmetric penalty functions. However, the size of the decision variables grows with the number of soft output constraints and slack variables introduced to shape the penalty function for the MPC problem. The resulting convex QP for the linear MPC with soft constraints easily becomes much larger than the equivalent linear

MPC without soft output constraints. Due to the realtime computational requirement off-the-shelf QP algorithms are often too slow and efficient convex QP algorithms tailored for this problem are needed.

Using Schur-complement techniques, we demonstrate that the key computational step in the primal-active set, the dual-active set, and the primal-dual interior point algorithms for linear MPC with soft output constraints reduce to solution of a KKT-system of the same size and structure of an extended linear-quadratic optimal control problem. In doing this reduction, we demonstrate efficient handling of hard input-constraints (bounds and rate-of-movement constraints). The KKT system of the extended linear-quadratic optimal control problem may be solved by either state elimination, Riccati iterations, or direct sparse matrix solvers. We compare the computational performance of these solution technique on a set of test problems. We also describe how a major part of the KKT-matrix factorization may be done off-line for the active-set algorithms for the Linear MPC with soft output constraints.

13:50 - 14:20	Zdeněk Dostál

Optimal QP algorithms and scalable algorithms for nonlinear problems of mechanics

In the first part of our talk we review our results in development of in a sense optimal algorithms for the solution of bound and/or equality constrained quadratic programming (QP) problems. Their unique feature is the rate of convergence in terms of bounds on the spectrum of the Hessian, independent of representation of the constraints. When applied to the class of convex problems with the spectrum in a given positive interval and a sparse Hessian matrix, the algorithms enjoy optimal complexity. We also briefly mention generalization of these results to the solution of problems with separable inequality constraints (such as separable spherical constraints) and preconditioning by conjugate projector which improves efficiency of not only linear steps, but also of nonlinear steps.

The efficiency of our algorithms is demonstrated on the solution of quadratic and QPQC problems arising from the discretization of contact problems of mechanics with application of duality based domain decomposition methods. In particular, we give results of numerical experiments with the solution of academic problems that demonstrate numerical scalability of our algorithms, i.e., their capability to find an approximate solution in a number of matrixvector multiplications that is independent of the discretization parameter. The dimension of the test problems ranges from fifty to more then thirty millions. We conclude our talks by presentation of the results for complex industrial contact problems, including ball bearings of wind mill with fifty balls, mining support, or impact of three bodies.

14:20 - 14:50	Oleg Burdakov, Ivan Kapyrin, Yuri Vassilevski

Monotonicity recovering QP-based methods for postprocessing finite element solutions

Partially lost monotonicity of the numerical solution is a typical drawback of the conventional methods of approximation, such as finite elements (FE), finite volumes, and mixed finite elements. The problem of monotonicity is particularly important in cases of highly anisotropic

diffusion tensors or distorted unstructured meshes. Another drawback of the conventional methods is a possible violation of the discrete maximum principle, which establishes lower and upper bounds for the solution.

In this talk, we suggest a least-change correction to available finite element (FE) solution. This postprocessing procedure is aimed on recovering the monotonicity and some other important properties that may not be exhibited by the FE solution. It is based on solving a monotonic regression problem with some extra constraints. One of them is a linear equality-type constraint which models the conservativity requirement. The other ones are box-type constraints, and they originate from the discrete maximum principle. The resulting postprocessing problem is a large scale convex quadratic optimization problem. We show that the postprocessed FE solution preserves the accuracy of the discrete FE approximation.

We present an algorithm for solving the postprocessing problem. It can be viewed as a dual ascent method based on the Lagrangian relaxation of the equality constraint. Its efficiency is demonstrated by the results of numerical experiments.

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VI Space for notes

VII LOCATION

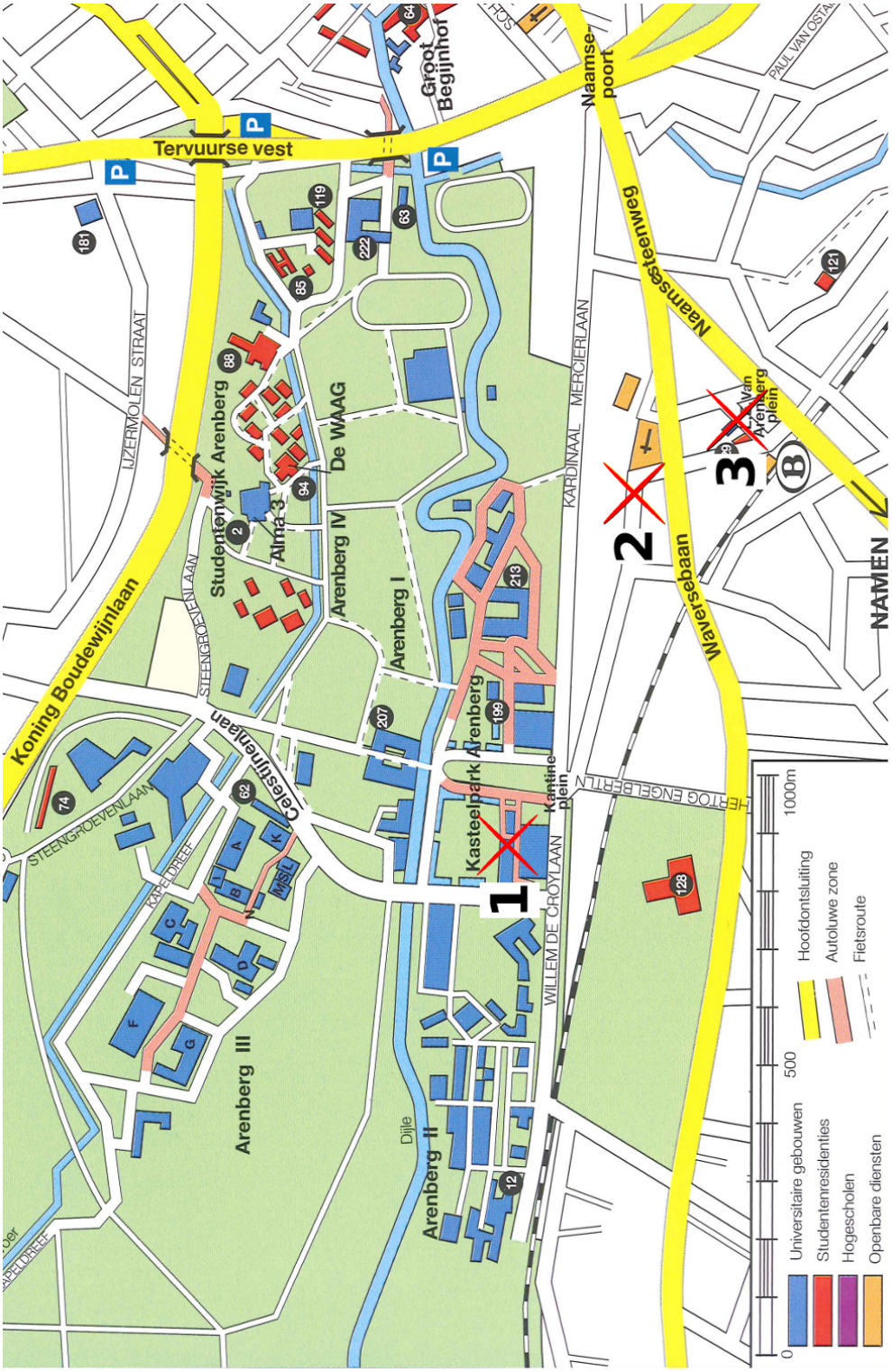
The workshop site is located at:

Auditorium 'De Tweede Hoofdwet'
Thermotechnisch Instituut
Kasteelpark Arenberg 41
B-3001 Heverlee

The dinner on Thursday will take place in WOK Dynasty restaurant. The lunch on Friday will be in Voltaire. Their addresses can be found below and their location is indicated on the map on the next page.

WOK Dynasty
L.E. Van Arenbergplein 11-1
B-3001 Heverlee
(Thursday evening)

Voltaire
Jules Vandenbemptlaan 6a
B-3001 Heverlee
(Friday noon)



1. Auditorium 'De Tweede Hoofdwet'
2. WOK Dynasty Restaurant
3. Voltaire Restaurant

LARGE

QP

WORKSHOP

LEUVEN

2010