

A Parametric Optimization Study of a Hydraulic Valve Actuation System

Michele Battistoni, Francesco Mariani and Luigi Foschini

University of Perugia

Marcello Cristiani

Magneti Marelli Powertrain S.p.A.

Copyright © 2008 SAE International

ABSTRACT

A new camless system (referred to as Hydraulic Valve Control - HVC - system) is in an advanced state of prototyping and development. The present paper aims to support the new incoming activities concerning the possible modifications to the geometrical and mechanical characteristics of the system.

The optimization of the new HVC system prototype is done using a multi-objective tool that integrates the hydraulic/mechanical simulator reproducing the physical model, with an optimization software. The latter tool can be used choosing a specific approach among different probabilistic mathematical models; the Genetic Algorithm approach was chosen to achieve the goal of the present study.

The paper describes design optimization of the pilot stage of the actuator for given characteristics of the power stage and of the poppet valve .

INTRODUCTION

As widely reported in literature [1-5] and commented on a previous paper of the same work group [6], camless engines would offer strong potential, allowing to reduce fuel consumption potentially by up to 20% for gasoline engines equipped with non-VVA mechanical valvetrains. This target can be achieved thanks to the increased flexibility on the engine management, as the valve events could be electronically-controlled, resulting in a higher thermodynamic efficiency in a wide range of operating conditions. However in order to preserve these benefits, the power absorbed by the camless valve actuation system should be comparable to the one of a conventional valvetrain.

The main goal of the present work is to optimize the pilot stage of the HVC system, in order to minimize the energy required by the power stage. Thus, the main focus is the reduction of the camless valvetrain power consumption.

This work, being the first case study, serves also as a template for the setting up of a design procedure (which integrates different software), that could be very useful for further foreseeable developments of the HVC system in the near future.

The paper describes the design workflow of the pilot stage of HVC system. In this issue we assume a fixed valve-assembly, with given diameter, mass and maximum lift of the poppet valve required by a target engine. Then the optimization process starts from a baseline pilot stage prototype and aims at identifying a configuration which improves its performance.

The base question the authors would like to answer is to quantify how far the actual system is from the optimal design and to offer a significant improvement for the prototype manufacturing.

The present study, carried out jointly with Magneti Marelli Powertrain, concerns the following detailed activities:

- tuning and further validation of the HVC physical model used in a previous work [7], developed in AVL - HydsimTM environment [8];
- defining of the objective functions (hydraulic energy consumption concerning the actuation system, repeatability of the system, control of the valve landing phase, etc...);
- defining of the geometrical and mechanical parameters of the HVC system that are involved in the optimization process (diameter of a calibrated hole, mass of the moving spool valve, pilot stage pressure, spring stiffness and precompression of the spool valve);
- defining of the constraints of the optimization problem: the engine valve lift and the spool stroke must be strictly synchronized, the input variables must vary only within feasible ranges, the objective functions should observe specific minimum requirements;
- execution of the multi-objective optimization task in Esteco - ModeFRONTIERTM environment [9].

selection of the “best” individual and experimental check of the new built prototype.

A Genetic Algorithm (GA) approach, implemented by means of the commercial tool, has been selected for the optimization activity of the present paper. The following brief summarization by Agarwal [10] appears to be very meaningful about the potentiality of the GA and in particular of the NSGA-II algorithm.

“Many optimization problems in design and engineering have more than one objective associated with them. For example an engineer designing a reactor would like to maximize safety while minimizing cost. The traditional approach converts these two objectives into a single objective and then uses standard single objective optimization procedures on the resulting problem. NSGA-II, on the other hand, finds an entire set of solutions representing various tradeoffs between safety and cost, which are optimal in the sense that no member of the solution set is better than any other member on both the objectives. What makes NSGA-II significant is that it is able to do this search robustly and efficiently while delivering consistently good results. It was one of the first of a new generation of algorithms which were good enough to be used on real world problems.”

DESCRIPTION AND MODELING OF THE HVC CAMLESS SYSTEM

In order to offer to the reader a basic knowledge about how the camless HVC system works, the functional diagram of the hydraulic circuit is shown in Figure 1 and a brief description of its main features follows.

- This electro-hydraulic VVA system enables to control the valve opening duration by varying the timing of the signal sent to the pilot stage; the valve lift is adjusted varying the oil pressure of the power stage. A fast-acting three-way solenoid valve is used to control the pilot stage. From the control point of view, the HVC system is an open loop device. The poppet valve is opened by hydraulic forces, while the closure is due to a mechanical spring.
- The key element of the HVC system is the spool valve, which works as a three way / three position valve, even though the center position is not stable because the spool can only go through it. This element is designed to ensure the synchronization of its own motion with that of the poppet valve mass-spring system (see Figure 2). This property enables the HVC system to operate with a low power consumption, because a great part of the work done for the valve opening can be recovered during the closing phase, as shown by the delivered and recovered oil flow rates.

Due to confidentiality agreements some data pertaining to the pilot stage have to be shown in non-dimensional form (see the Definitions, Acronyms, Abbreviations section for a complete list of symbols and explanations).

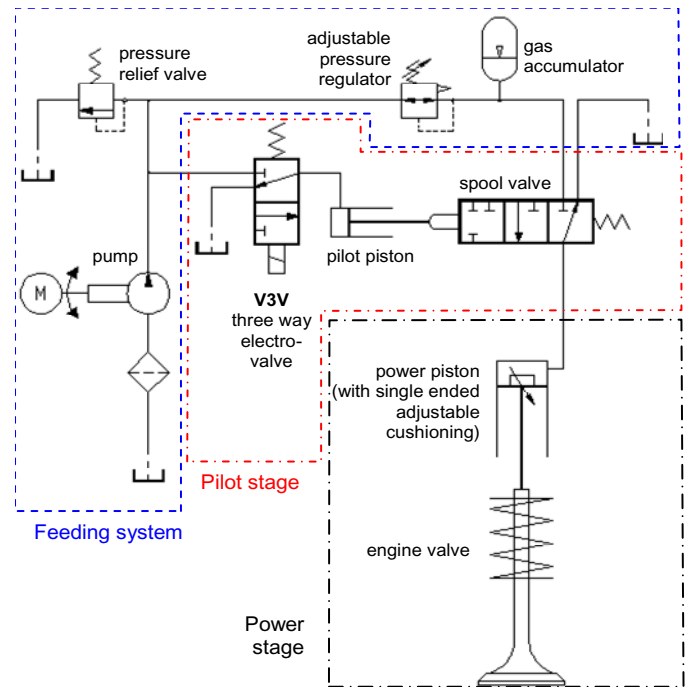


Figure 1. Schematic of the electro-hydraulic valve actuation system.

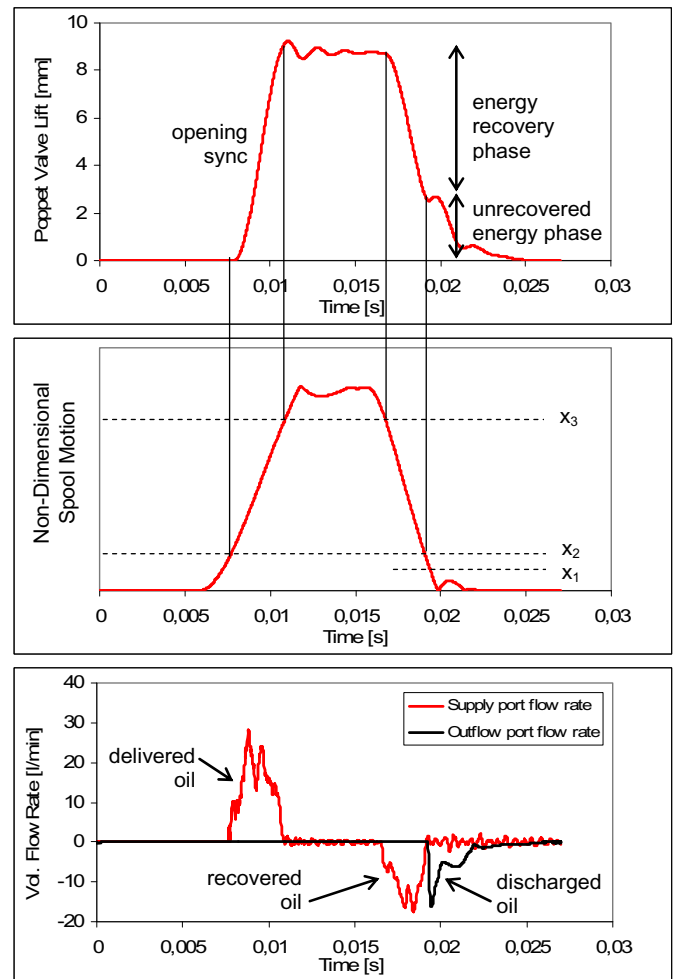


Figure 2. Example of valve lift, spool motion, supply oil flow rate and discharged oil flow rate – Supply pressure (SP) = 80 bar, Energizing Time (ET) = 10 ms.

The HVC system described in this paper has been modeled in AVL-HydsimTM environment [8]. A lumped parameter discretization approach was used: mechanical elements are analyzed according to the vibration theory of multi-body systems; fluid elements are modeled as volumes (0D element) or pipes (1D element). An isothermal flow approach was used in order to obtain a reasonable compromise between accuracy level and computational time.

The HVC model (whose schematic is reported in Figure 3) has been already presented in previous works of the same research group [6, 7] where also the HVC working principle was fully described.

It is worth pointing out that the model refers to the HVC experimental prototype configuration operated at the laboratory of the University of Perugia, characterized by its specific actuator test bench [7]. This approach allows to effectively exploit the synergies between the numerical and the experimental methodologies in order to improve the results achievable in the development process.

As an example, the comparison between numerical results, already presented in [7], and experimental data is shown in Figure 4 (baseline-1). As can be seen, the model was able to capture the dynamics of the HVC system and showed a good prediction capability.

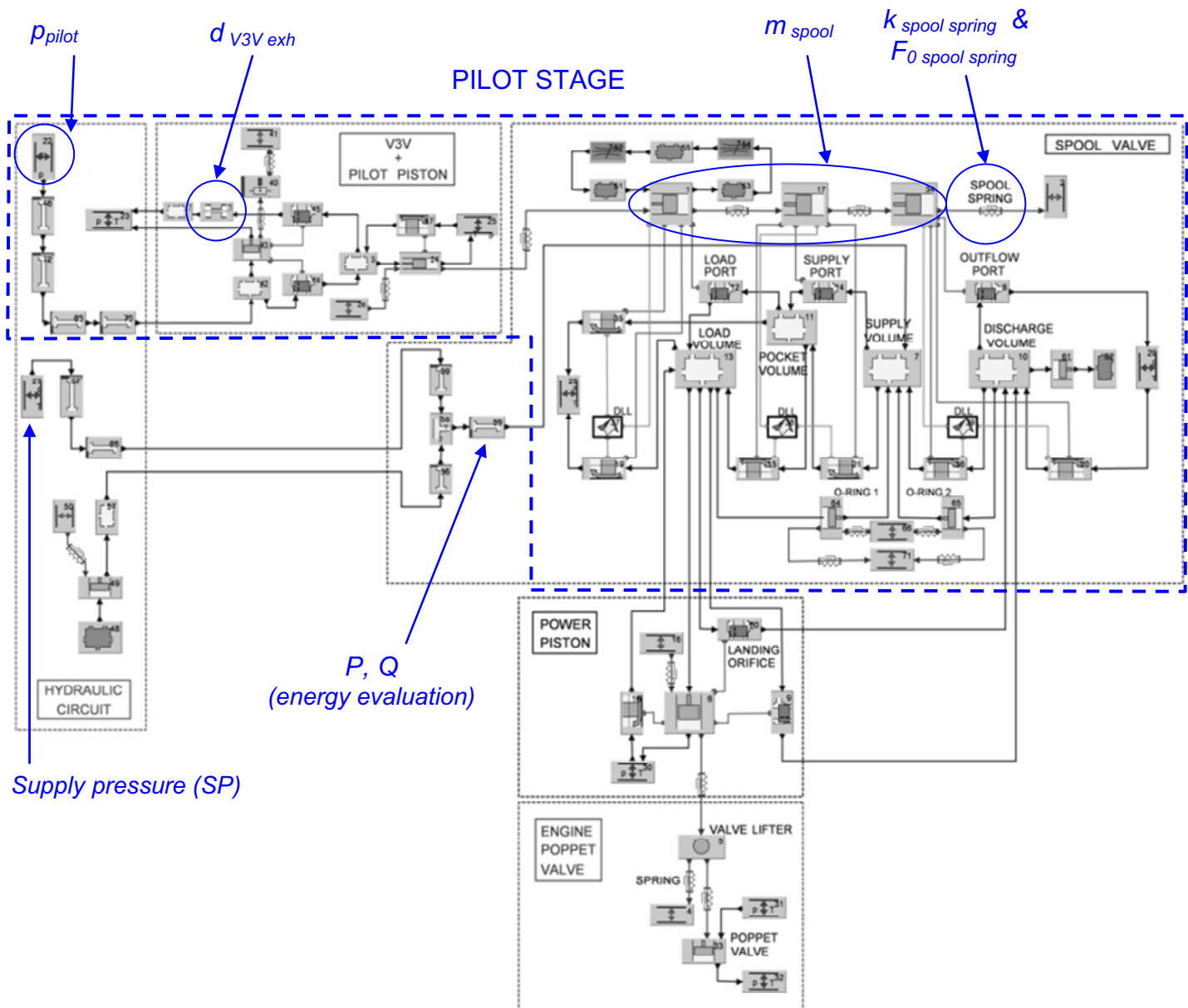


Figure 3. HydsimTM model of the HVC system [6, 7].

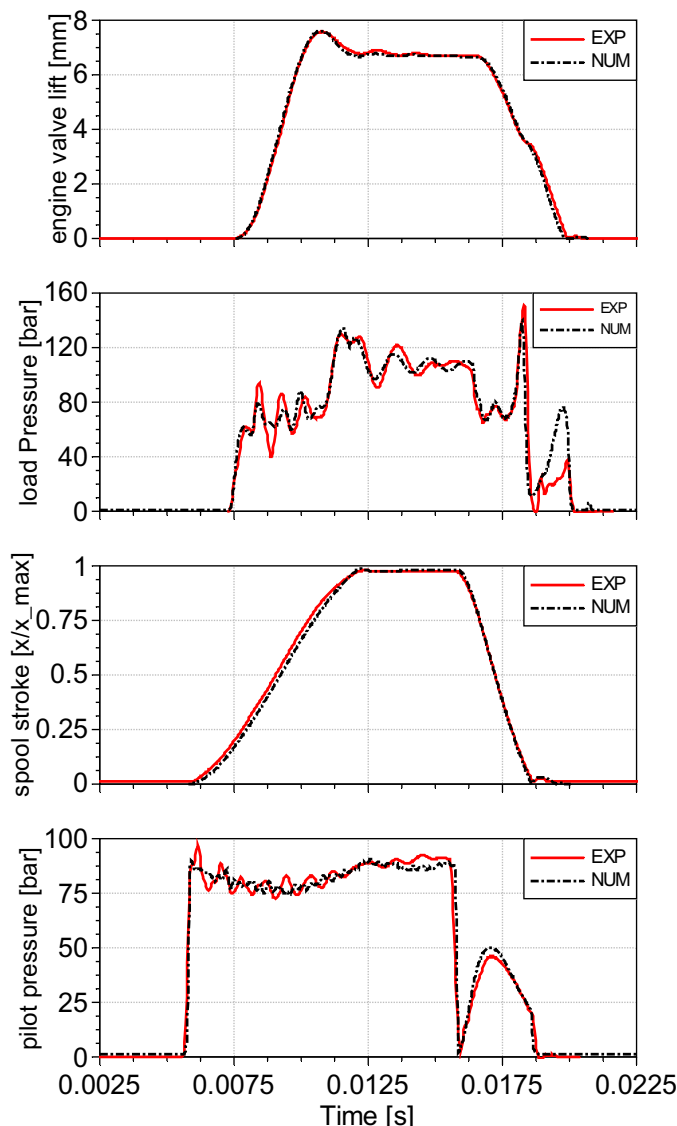


Figure 4. HVC model validation (baseline-1 actuator configuration) - valve lift, load pressure, spool stroke, pilot pressure – SP = 70 bar, ET = 10 ms.

Recent improvements have been made in the design of the sealing system and in the landing phase control (implementing a hydraulic brake device). As a consequence the model has been modified and its prediction capability has been rechecked also for the most recent configuration of the HVC actuator (baseline-2).

Figure 5 shows measured and computed valve lifts related to the baseline-2 HVC actuator prototype (only one operating condition is reported for the sake of brevity). The good agreement between experimental and numerical data confirmed the reliability of the model which proved to be able to capture the dynamics of the HVC system even for different actuator configurations.

As the actuator energy consumption is one of the objectives of the optimization process, a specific experimental campaign was carried out in order to evaluate the prediction capability of the model in terms of energy demand. To this end an approximate analysis

was carried out: only the energy consumption of the power stage was concerned (both the pilot stage energy consumption and the feeding system losses were neglected); the oil was supposed to be provided at a constant pressure level. These assumptions allowed to experimentally evaluate the energy consumption of the actuator by measuring the mean oil mass provided to the power stage during one cycle (i.e. experimental data are averaged over 5000 valve events). Experimental and numerical results about the HVC energy consumption are reported in Figure 6. The energy analysis confirms the potentiality of the model and so it can be considered suitable for the implementation in an optimization process involving both dynamic and energetic aspects.

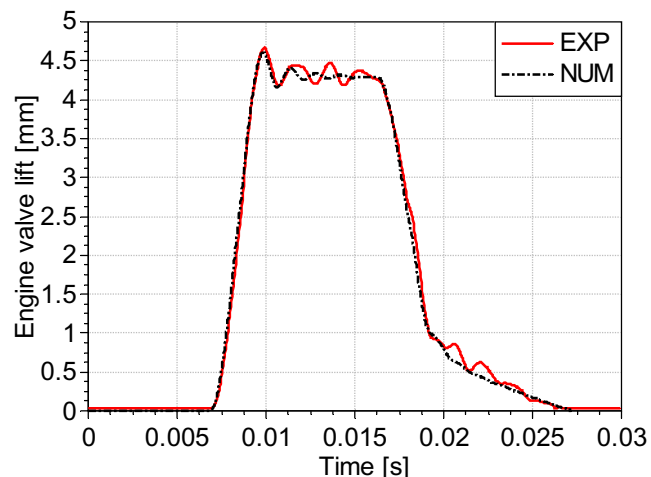


Figure 5. HVC model validation (baseline-2 actuator configuration) - Engine valve lift - SP = 50 bar, ET = 10 ms.

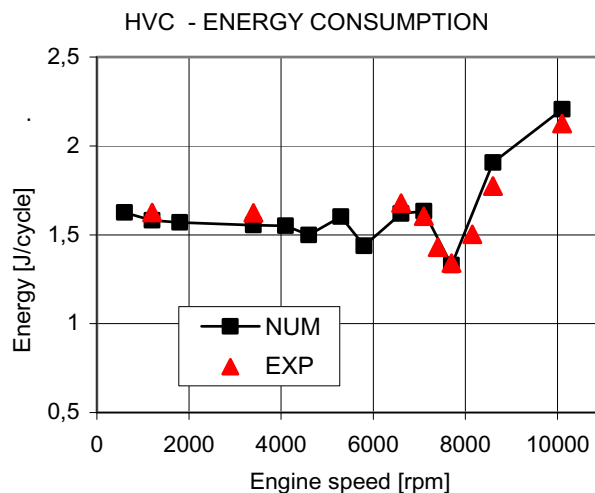


Figure 6. HVC model validation (baseline-2 actuator configuration) - energy consumption – SP = 50 bar.

OVERVIEW OF THE OPTIMIZATION STRATEGY

The "core" of the optimization model (called later on: *engine*), is the model of the HVC hydraulic system just described. The time taken by this *engine* for a complete simulation is certainly acceptable, but it can become excessive if inserted in a optimization process that requires a large number of evaluations. Then, the choice

of the optimization algorithm is particularly disadvantageous if it falls on traditional techniques or algorithms estimating the fitness function in relation to their gradient.

The GAs are based on the emulation of the natural evolutionary process of animals; the *fitness* function defines the degree of adhesion of the single individual of the current population to the objectives of the problem under investigation. The fundamental operations of *selection* and *cross-over* determine the evolution of the species, generating populations characterized from gradually higher values of the aforesaid *fitness* function. In particular, the *cross-over* function is what determines the genetic exchange of information between pairs of selected individuals.

OPTIMIZER SETUP

The optimizer tool is an open system built on the requirements of the industry and, in particular, with the most recent formulations of “concurrent engineering”. The tool allows:

- the integration of different applications located anywhere on the net;
- the multi-objective optimization, based on the concept of non-dominated solutions on the objectives space (or Pareto optimum frontier), for continuous, discrete or mixed variable problems, subject to limits/conditions that can change during the evolution of a process;
- the computer aided decision-making process, in order to select an optimum individual among the database of the evaluated designs (MCDM technique for the location of the utility function, Goal Programming, etc.).

The specific algorithm used in the present paper is based on the Non-dominated Sorting Genetic Algorithm II (NSGA-II) developed by K. Deb et al. [11]. NSGA-II is an elitist multi-objective evolutionary algorithm. Its main features are described in the Appendix.

The NSGA-II version implemented in the adopted tool automatically recognizes continuous (real-coded) and discrete (binary-coded) variables according to the value specified in the Base field. Continuous variables have a Base equal to 0, while discrete variables have a Base equal to a positive integer that stands for the number of divisions of the range concerned. In the present work all the input variables have been discretized with a very high Base, in order to attain a high resolution, hence using the binary-coded approach.

The parameters the user must set-up are listed below along with the values that have been actually used in the current work (see also Figure 7):

- Number of Generations: it is the value that defines the maximum size of the run. *Value used* = 50.
- Crossover Probability: it specifies the occurrence probability of the Classical Cross-Over operator.
 - For binary-coded variables the Cross-Over operator exchanges some genetic material between two individuals, cutting the DNA binary strings at a random location and then pasting together the opposite segments belonging to the different individuals. *Value used* = 0.9.
 - For real-coded variables NSGA-II uses a Simulated Binary Cross-Over operator [13]: this operator emulates the behavior of the classical binary cross-over, handling directly the real-coded variables, with no need to code the continuous variables into any arbitrary binary base.
- Mutation Probability for Binary Strings: this value gives the probability that binary-coded variables are randomly changed. *Value used* = 1.0.
- Crossover Type for Binary-Coded Variables: two selections are possible for this field.
 - *Simple*: this is the usual Classical Cross-Over operator. It cuts the DNA binary strings of two individuals at a single random location and then pastes together the opposite segments belonging to the different individuals.
 - *Uniform*: this operator scans the two parents' DNA binary strings, performing a random selection between the two bits values for each single location.
Value used = *Simple*.
- Random Generator Seed: it is an integer number used for sequence repeatability. The modification of this value allows the execution of different runs starting from the same initial population. If two sequences are evaluated with the same seed, they will generate and return identical sequences of numbers. *Value used* = 1.

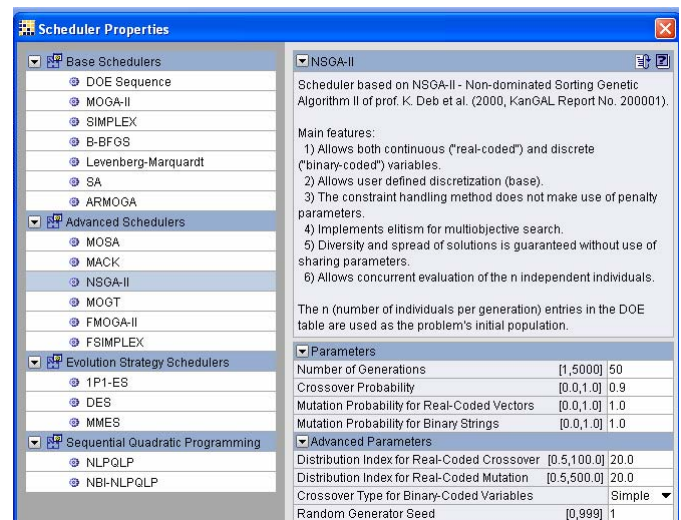


Figure 7. Snapshot of the scheduler preferences: set-up of the NSGA-II parameters.