Global Sensitivity Analysis of the ATV Design Guideline: Which are the most important inputs for a WWTP design?

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ABSTRACT

Dimensioning a wastewater treatment plant (WWTP) using design guidelines requires a set of input factors. However, the information regarding these input factors might be very scarce during the initial stage of design. Therefore these input factors are usually associated with significant uncertainty. In this study, global sensitivity analysis (GSA) is used to rank different uncertain input factors according to their influence on the uncertainty of the design variables. The pre-anoxic zone denitrification configuration (Ludzack and Ettinger, 1962) is selected as the case study and the ATV design guideline (2000) is used for sizing the main design variables. The results of the GSA can help design engineers and decision makers in identifying the most important input factors and enable efficient spending of their resources to reduce the uncertainties associated with them.

INTRODUCTION

Design guidelines are used worldwide for the sizing of WWTPs. These guidelines often use steady state models where the design variables (total volume, secondary clarifier dimensions, oxygen requirements, etc.) are obtained using a set of empirical rules and simple mathematical equations. The design variables are dependent on various factors which need to be determined by the engineer. The knowledge regarding the proper selection of design inputs and explicit safety factors to make a steady state design can be very uncertain during the initial stage of the design. To have an idea regarding the choice of design inputs, reported values in design guidelines such as the Metcalf and Eddy (Tchobanoglous et al., 2003), ATV-DVWK-A (ATV, 2000), and WRC (Ekama et al., 1984) can be used. However, these reported values usually cover a wide range and bench-scale or in-plant testing should be performed to have a more precise estimate of critical design inputs that are dependent on the site-specific conditions (Tchobanoglous et al., 2003). Having limited financial resources and time constraints global sensitivity analysis (GSA) can be applied as a tool to evaluate how the initial assumptions regarding the design inputs can influence the final sizing of a WWTP (Flores-Alsina et al., 2012). The SRC-based GSA was applied to the Metcalf and Eddy guideline (Tchobanoglous et al., 2003) for identifying the important design inputs and the way that the uncertainty in design inputs affects the design variables (Flores-Alsina et al., 2012). Neumann and Vanrolleghem (2011) also applied a GSA method (i.e. Extended-FAST (Saltelli et al., 2008)) to the ATV design guideline (ATV, 2000) to assess the importance of a number of design inputs on the final sizing of the bioreactor volume. However, in that study the sensitivity of only one design variable (i.e. bioreactor volume) was assessed with respect to a set of uncertain inputs and a simplified version of ATV was used in the analysis. Building on this previous study, the current paper presents the GSA of the full ATV (2000) for the dimensioning of single stage activated sludge plants.

METHODS

This section describes the different methodologies used in this study. A general description is provided regarding the different design steps according to the ATV design guideline. The ranges of uncertainty associated with the design input factors and also the analysis techniques for propagating the uncertainty in input factors (i.e. external inputs, safety factors, required parameters, and operating conditions) to the outputs of the ATV design guideline (total reactor volume, fraction of anoxic tank volume, oxygen requirements, area of the secondary clarifier, and depth of the secondary clarifier) are presented here. Moreover, the SRC which is used as the sensitivity index in this study and its calculation from the Monte Carlo simulation results is explained.

ATV Design Guideline and Plant Setup

One of the more commonly used design guidelines is the German "Standard ATV-DVWK-A 131E, Dimensioning of Single-Stage Activated Sludge Plants" (ATV, 2000). This guideline can be used for designing an activated sludge plant for the biological removal of COD, N, and P.

The dimensioning of a WWTP according to the ATV design guideline is achieved using a set of equations based on the mass balance equations of the system under steady state conditions (e.g. the equations used for estimating the daily sludge production), empirical equations (e.g. the equations used for estimating the concentration of sludge in the RAS flow as a function of sludge volume index (SVI) and *sludge thickening time*), and a set of experience-based rules (e.g. permitted *surface overflow rate* and *sludge volume loading rate* for the design of the secondary clarifier).

After determining the design flow, characteristic load constituents, effluent requirements, and safety factors, a process configuration is selected considering the site-specific conditions and design constraints (e.g. area, subsoil, hydraulics, etc). The design process proceeds by selecting a proper value for the SVI and estimating the sludge age or sludge residence time (SRT). The area of the secondary clarifier is determined on the basis of *surface overflow rate* and *sludge volume loading rate*.

The total depth of the secondary clarifier comprises of four depths including: 1) *clear water zone*, 2) *separation/clear water zone*, 3), *density flow and storage zone*, 4) *thickening and sludge removal zone*. The depths of these zones are calculated according to certain rules and mass balance equations under steady state conditions. A summary of these rules is listed in Table 1.

Table 1 List or rules for determining the depth of the secondary clarifier

Different depths	Rules
clear water zone	Set to 0.5m
separation/clear water zone	Must be large enough so that the inflow to the secondary clarifier including the RAS flow has a detention time of 0.5h
density flow and storage zone	Must be large enough to accommodate the additional volume of sludge being expelled from the aeration tank during 1.5 hours under wet weather condition
thickening and sludge removal zone	Must be large enough so that the influent sludge load to the secondary clarifier can be thickened to the bottom sludge concentration within the selected thickening time

The total size of the bioreactor is estimated by dividing the total daily solids production by the concentration of the sludge in the bioreactor. The total solids mass is calculated as the sum of solids produced daily from the carbon removal estimated according to an empirical equation using the Hartwig (1993) coefficients and solids production due to phosphorous removal including biological phosphorous removal and removal through simultaneous precipitation.

The ratio of the anoxic to the total volume of the bioreactor is empirically calculated as a function of the ratio of the concentration of nitrate to be denitrified to the concentration of BOD and of the type of configuration. Another design variable considered in this study is the oxygen requirement. To estimate the hourly rate of oxygen requirement, the daily oxygen utilization rate due to carbon removal and nitrification is calculated. Moreover, the amount of oxygen saving due to denitrification is estimated (i.e. that fraction of COD consumed during the denitrification process without using oxygen). The total hourly oxygen uptake rate is estimated by applying peaking factors to daily oxygen uptake rates of carbon removal and nitrification according to Equation 1.

$$OU_h = \frac{f_C \times \left(OU_{d,c} - OU_{d,D}\right) + f_N \times OU_{d,N}}{24}$$ **Equation 1**

Where OU_h is the hourly rate of oxygen uptake, f_C is the peaking factor for carbon removal, $OU_{d,c}$ is the daily oxygen uptake due to carbon removal, $OU_{d,D}$ is the oxygen saving due to denitrification, f_N is the peaking factor for nitrification, and $OU_{d,N}$ is the daily oxygen uptake due to nitrification. As a rule, the peak oxygen uptake rate for nitrification occurs before the peak oxygen rate for carbon removal (ATV, 2000). Therefore, to avoid overestimation of the hourly oxygen uptake, one of the peak factors (for example f_C) is set to unity and the other one (in the example f_N) is selected from the recommended values to estimate OU_h in Equation 1. Next, the process is repeated on the other way around (f_N is set to unity and f_C is selected from the recommended values and OU_h is calculated again). The highest value for OU_h is selected and further transformed into the hourly oxygen transfer requirement. In this study the pre-anoxic zone denitrification configuration (Ludzack and Ettinger, 1962) is selected as the case study (Figure 1).

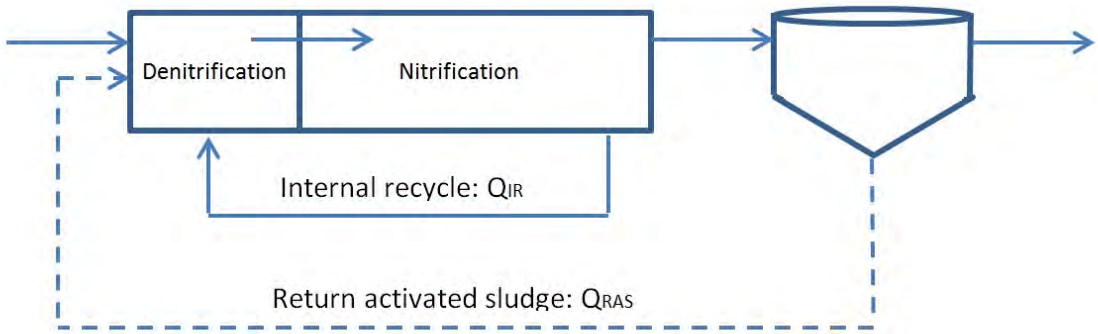

Figure 1 Pre-anoxic zone denitrification configuration

The list of uncertain factors including the design values for external inputs (e.g. flow and the concentration of different wastewater constituents), different safety factors, required parameters, and operational inputs are illustrated in Table 2.

Table 2 Different uncertain factors required for design

Type of Uncertain Factors	Uncertain Factors
External inputs	• Max. hourly dry weather flow rate as 2 hour mean • Max. hourly wet weather flow rate as 2 hour mean • Daily wastewater flow during dry weather • Concentration of BOD entering the bioreactor • Concentration of nitrogen entering the bioreactor • Concentration of TSS entering the bioreactor • Concentration of COD entering the bioreactor • Temperature
Safety factors	• Safety factor for max. NO_3 concentration in the effluent • Safety factor for SRT
Required parameters	• Percentage of nitrogen in the biomass • Percentage of particulate COD in COD • Percentage of inert part. COD in part. COD • Percentage of inorganic TSS in TSS • Percentage of soluble inert COD in total COD • Sludge Volume Index (SVI)
Operating conditions	• Permitted sludge volume loading rate

Global Sensitivity Analysis by Linear Regression of the Monte Carlo Simulations
Standardized regression coefficients (SRCs) are used as the sensitivity indices to rank the level of importance corresponding to different uncertain factors. SRC can be used as a proper sensitivity index if the outputs of the model calculated as functions of the input factors can be approximated by a linear model of the uncertain factors with a *coefficient of determination* $R^2 \geq 0.7$ (Saltelli et al., 2008). For a model with r uncertain factors and a single desired output Y, N vectors of the r factors

are sampled (using Monte Carlo simulation) from their probability distribution functions (PDFs) that describe their uncertainty:

$$\boldsymbol{X} = \begin{bmatrix} x_1^{(1)} & x_2^{(1)} & \dots & x_r^{(1)} \\ x_1^{(2)} & x_2^{(2)} & \dots & x_r^{(2)} \\ \dots & \dots & \dots & \dots \\ x_1^{(N-1)} & x_2^{(N-1)} & \dots & x_r^{(N-1)} \\ x_1^{(N)} & x_2^{(N)} & \dots & x_r^{(N)} \end{bmatrix}$$ **Equation 2**

Where $\boldsymbol{X}$ is an $N \times r$ matrix in which each row represents a vector of the r input factors randomly sampled from their PDFs. Each row of the $\boldsymbol{X}$ matrix is an input of the model to generate a N vector of the output Y (Equation 3).

$$\boldsymbol{Y} = \begin{bmatrix} y^{(1)} \\ y^{(2)} \\ \dots \\ y^{(N-1)} \\ y^{(N)} \end{bmatrix}$$ **Equation 3**

To estimate the SRCs, a multivariate linear regression model according to Equation 4 is fitted to the generated inputs and Monte Carlo simulation outputs.

$$Y = \sum_{i=1}^{r} b_i . x_i + a$$ **Equation 4**

Where Y is the desired output, x_i is the ith uncertain factor and b_i and a are the parameters of the regression model determined using the-least square method (i.e. minimization of the squared differences between the regression model outputs and the actual model output produced by Monte Carlo simulation). The SRCs, β_i, are obtained by scaling the regression coefficients b_i using the standard deviations of design inputs (σ_{x_i}) and output (σ_y) of the Monte Carlo simulations (Equation 5).

$$\beta_i = b_i \times \frac{\sigma_{x_i}}{\sigma_y}$$ **Equation 5**

In the above equation σ_{x_i} can easily be estimated using the sampled values from each uncertain input factor and σ_y is estimated using the values of each output resulted from the Monte Carlo simulation. The β_i^2 approximate the first-order variance contribution to the overall variation of the design model outputs. In general, the higher the absolute value of $\beta_i$the more important the input factor.

CASE STUDY

The sensitivity analysis is performed on a hypothetical case study: an urban WWTP needs to be upgraded by the ATV design guideline. The new facility needs to accomplish carbon and nitrogen removal. The uncertain factors are summarized in Table 3. They include: safety factors (F1 to F2), required parameters (F3 to F9) and input values for concentration, flow and temperature (F10 to

F17). All the uncertain input factors are characterized by uniform distributions by setting the lower and upper limits of uncertainty corresponding to each input factor to the possible minimum and maximum values of that input factor and assigning equal probabilities to the values between the maximum and the minimum.

For the safety factors and parameters the uncertainty ranges correspond to the ranges recommended by the guideline. For the input characteristics the ranges reflect uncertainty about the design concentrations, flows and temperature.

The ATV design guideline was implemented in Matlab (2007). The Latin Hypercube Sampling (Iman and Conover, 1980) method is used to draw 1000 samples of the input factors. Monte Carlo simulations are performed and the uncertainty propagation of the inputs leads to 1000 design outputs.

Table 3 Uncertain factors characterized by uniform probability distributions

Factor	Description	Min	Max	Units
F1	Safety factor for max. NO_3 concentration in the effluent	0.6	0.8	-
F2	Safety factor for SRT	1.45	1.8	-
F3	Percentage of nitrogen in the biomass	0.04	0.05	-
F4	Percentage of particulate COD in COD	0.2	0.6	-
F5	Percentage of inert part. COD in part. COD	0.2	0.35	-
F6	Percentage of inorganic TSS in TSS	0.2	0.3	-
F7	Percentage of soluble inert COD in total COD	0.05	0.1	-
F8	Permitted sludge volume loading rate	250	500	$l/m^3.h$
F9	Sludge Volume Index (SVI)	100	150	*l/kg*
F10	Max. hourly dry weather flow rate as 2 hour mean	1200	1600	m^3/h
F11	Max. hourly wet weather flow rate as 2 hour mean	2000	3000	m^3/h
F12	Daily wastewater flow during dry weather	20000	22000	m^3/day
F13	Concentration of BOD entering the bioreactor	150	250	mg/l
F14	Concentration of Nitrogen entering the bioreactor	38	62	mg/l
F15	Concentration of TSS entering the bioreactor	150	250	mg/l

F16	Concentration of COD entering the bioreactor	300	500	mg/l
F17	Temperature	8	12	$°C$

The design outputs calculated in this study using the equations and rules available in the ATV design guideline were: the total reactor volume, the fraction of the anoxic to the total volume, oxygen requirements, the area of the secondary clarifier, and the depth of the secondary clarifier.

RESULTS AND DISSCUSION

The results of the GSA are shown in Figure 2. The coefficients of determination are above 0.7 for all the design variables except for the fraction of anoxic volume (R^2=0.23). In this case the results are not reliable (the GSA results are only able to explain 23% of the total output variation) and a more sophisticated method for sensitivity analysis, such as Extended-FAST (Saltelli et al., 2008), should be employed. The most important input factors with respect to the *total reactor volume* (Figure 2) are: the SVI (explains 33% of the total variance), the influent concentrations (28%), and the temperature (25%). The SRC of the temperature is negative, indicating that a decrease in temperature (logically) makes the required total volume increase. Note that the the safety factor for SRT explains only 3.3% of the remaining variance.

The *oxygen requirements* mainly depend on the influent concentration values, which together explain 75% of the total variability: the COD for 56%, total nitrogen for 13% and BOD for 6%. The uncertainty about the fractionation of the influent wastewater (F3 to F7) is responsible for 5% of the total variance, while the daily wastewater flow during dry weather explains 2.3%. Figure 2 also shows that perhaps increasing the BOD concentration (F13) implies a saving in oxygen (negative regression coefficient). However, this can be explained by the fact that more BOD increases the denitrification capacity. High percentages of particulate COD (F4) are also associated to oxygen savings because of its low degradability.

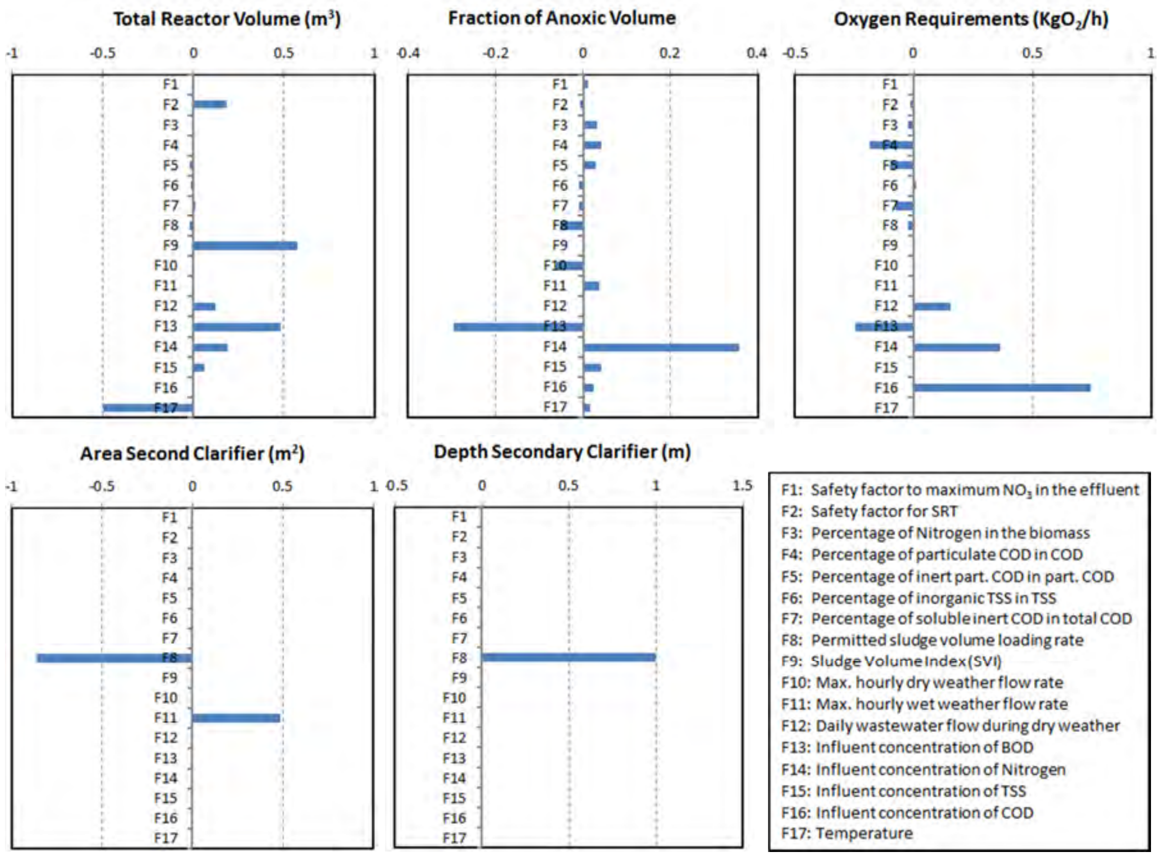

Figure 2 Standardized Regression Coefficients from the Global Sensitivity Analysis

The most important factors with respect to the *area of the secondary clarifier* are: the permitted sludge volume loading rate (explains 74% of the total variance) and the maximum value of the hourly dry weather flow rate (explains 24% of the total variance). The *depth of the secondary clarifier* only depends on the permitted sludge volume loading rate (explaining 100% of its variance). The surface overflow rate (directly proportional to the permitted sludge volume loading rate) is the driving force: an increase of this variable leads to a decrease of the area of the secondary clarifier and an increase of the depth.

The design variables obtained from the 1000 design results tend to be independent (Figure 3). There are only two exceptions: the relationship between the area and depth of the secondary clarifier with R^2=0.72 (already detected by the sensitivity analysis), and the relationship between the fraction of anoxic volume and oxygen requirements with R^2=0.40. For increasing values of total nitrogen concentration in the influent, the nitrate to be denitrified increases, and therefore the fraction of anoxic volume increases (results not shown).

The results obtained in the GSA are coherent with the general knowledge about activated sludge plants. However, it is useful to quantify the importance of the parameters with respect to each design variable and to clarify the particularities of the design guideline (for instance one might think that SVI would have an important effect on the depth of the secondary clarifier but it does not).

The results show the usefulness of the methodology. Further research is being carried out to investigate the effect of other load and temperature scenarios. The GSA will also be used as a standard framework to compare different design guidelines.

CONCLUSIONS

GSA with SRC as the sensitivity index was applied to the ATV design guideline to assess the relative importance of different uncertain input factors. The uncertainties of 17 input factors were characterized in terms of uniform PDFs whose parameters were determined using the recommended values in the ATV design guideline and engineering judgement. Monte Carlo simulation was performed to propagate the uncertainties of input factors to five important design variables. Then a multivariate linear regression model was fitted to the Monte Carlo results and the derived SRCs were used to rank the relative importance of the uncertain input factors to the design variables. In general, the GSA results were in agreement with the general knowledge regarding the activated sludge plants. It was concluded that the SRC is a suitable sensitivity index for determining the relative importance of the uncertain input factors ($R^2 \geq 0.7$) for the calculated design variables except for the ratio of the anoxic to the total bioreactor volume. Moreover, the design variables obtained from the 1000 design results tend to be independent except for the significant relationship between the anoxic volume and oxygen requirements and also the relationship between the area and depth of the secondary clarifier.

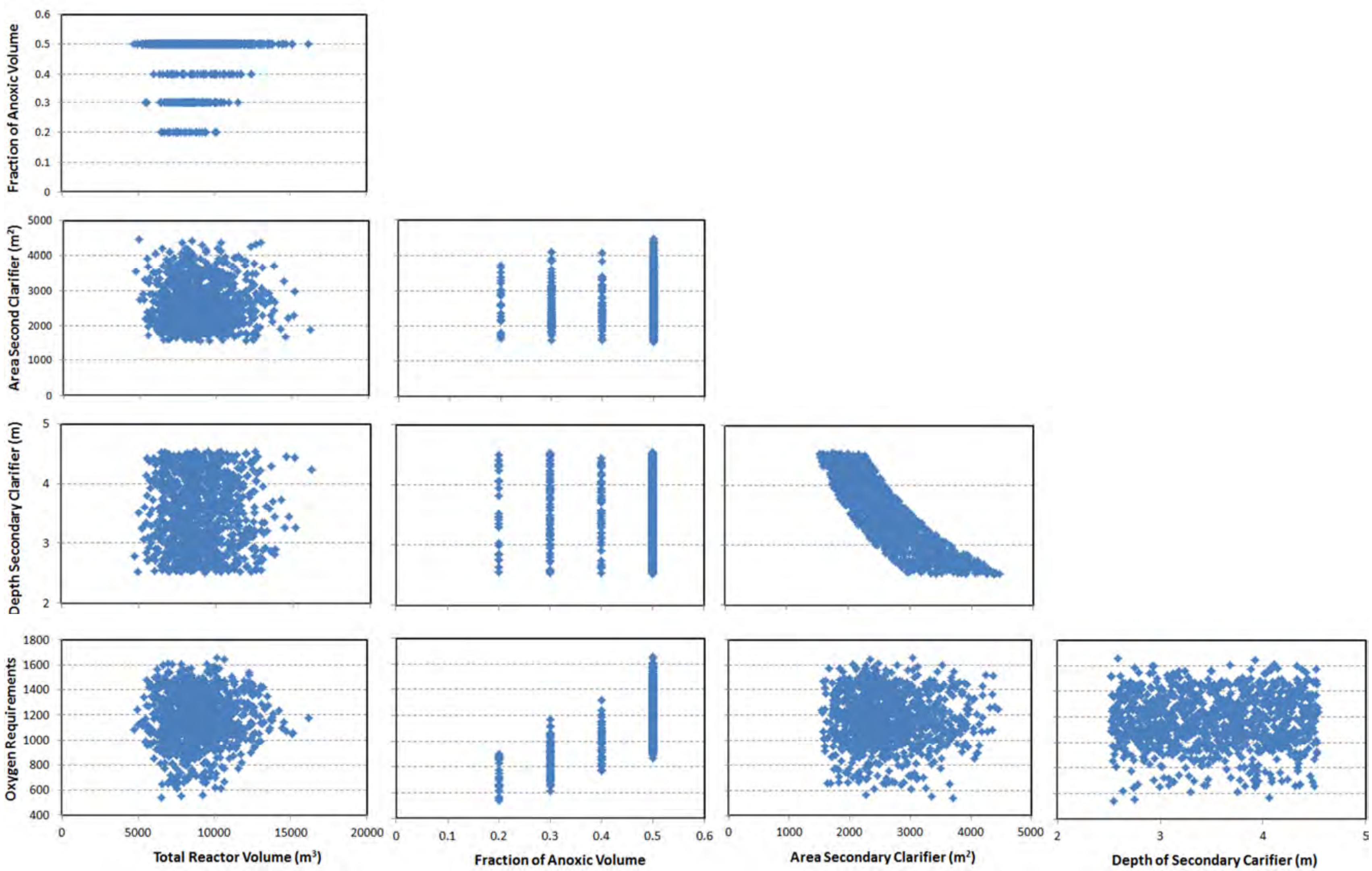

Figure 3 Scatter-plots of the MC results (1000 values of the design variable)

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