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Comparison of guideline- and model-based WWTP design for uncertain influent conditions

Erik U. Lindblom [a,b,*] and Oscar Samuelsson [a]

[a] IVL Swedish Environmental Research Institute, P.O. Box 210 60, Stockholm SE-100 31, Sweden
[b] Division of Industrial Electrical Engineering and Automation (IEA), Department of Biomedical Engineering, Lund University, P.O. Box 118, Lund SE-221 00, Sweden
*Corresponding author. E-mail: erik.u.lindblom@ivl.se

ABSTRACT

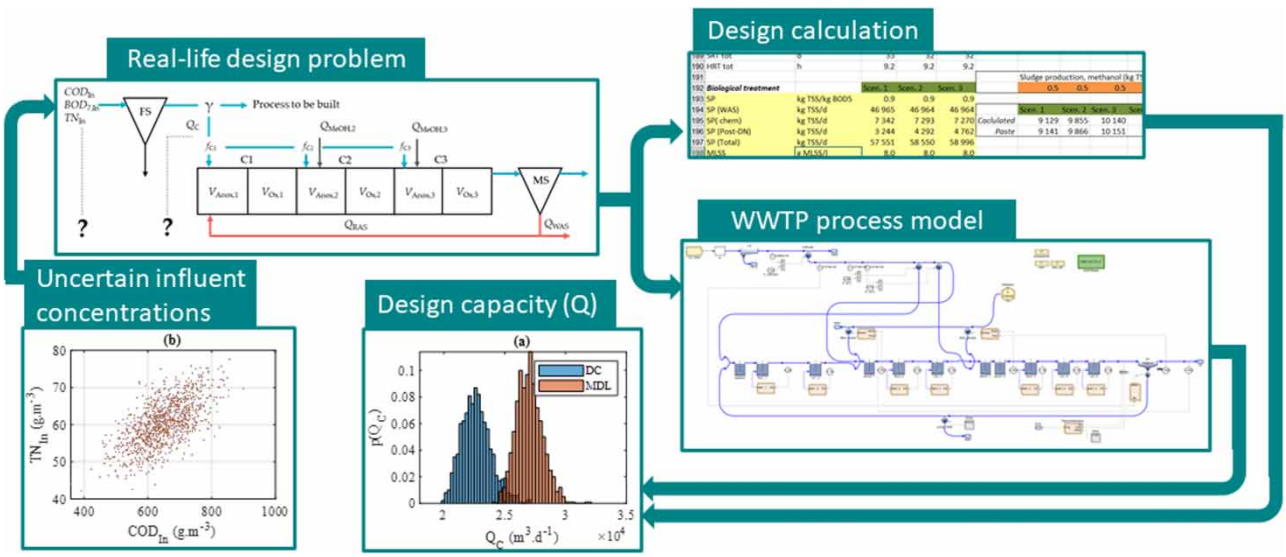
In this study, two methods for wastewater treatment plant (WWTP) dimensioning were compared: (1) a traditional guideline-based approach, and (2) a mechanistic model-based approach. The design outputs depended on uncertainties in correlated influent concentrations, which emphasises the importance of uncertainty analysis. The results showed that model-based design could simplify and reduce the time required for uncertainty and sensitivity analysis compared to a conventional design approach, in which the equations are solved manually and iteratively. A benefit of the conventional design approach was the simple interpretation of which factors limited the design capacity. In the end, this study shows the potential, as well as the need for, model-based design of WWTPs.

Key words: sensitivity, design, guideline, influent concentrations, simulation

HIGHLIGHTS

- Process model-based design can simplify uncertainty and sensitivity analysis compared to a conventional design approach.
- Process models are more detailed than traditional sizing calculations and may require design pre-requirements to be specified in more detail.
- Typical assumed design parameter values differ from the output of mechanistic models.

GRAPHICAL ABSTRACT



INTRODUCTION

Dynamic models are suggested as the modern tool for refined wastewater treatment plant (WWTP) design (Jimenez *et al.* 2018). Additionally, uncertainties must be considered during design (Belia *et al.* 2021) and multiple uncertainty (UA) and sensitivity analysis (SA) methods for model assessment are available (Razavi *et al.* 2021). Yet, these technologies have not reached adoption in practice. Instead, current state-of-the-art design is based on guidelines and textbooks (e.g. ATV 2000; Tchobanoglous *et al.* 2003; Grady *et al.* 2011; Jimenez *et al.* 2018), which typically are based on a combination of physical knowledge, experience and rules of thumb. This approach leaves room for subjective interpretation, commonly conducted by the process design consultant, and might lead to non-transparent and sub-optimal designs.

Several publications have proposed methods for assessing, complementing, and verifying guideline-based designs with dynamic simulation (Corominas *et al.* 2010; Belia *et al.* 2021). Although creating added value, these methods do require additional effort since two calculation tools (guidelines and dynamic models) must be implemented and evaluated. Dynamic WWTP models can be, and are, applied in most stages of the WWTP life cycle (Rieger *et al.* 2012) and due to the reasons mentioned above it would be practical (decreasing the necessary number of digital tools), and possibly result in more efficient WWTPs, if the models were used in the design phase as well. Then, in a long-term perspective, current design, guidelines might even be redundant.

To enable acceptance among users of a new WWTP design methodology, the merits and pitfalls of either design technique must be further assessed by understanding and clarifying their differences. In this study, a design guideline-type calculation (DC, engineering spreadsheet) and a model-based design approach (MDL), subject to similar input data values and design pre-requirements, were therefore compared.

A real-life design task was identified from the preliminary phase of a WWTP upgrade project in Uppsala, Sweden, and a realistic DC was defined based on a combination of the available information in the preliminary design report and experience from other design projects in Sweden. The MDL approach included steady-state results generated with a commercial WWTP simulator.

Both design methods are sensitive to the selection of input data (Sin *et al.* 2011; Flores-Alsina *et al.* 2012) and the results of the two methods were therefore compared using uncertainty and sensitivity analysis. Thereby, it was assessed how input uncertainties were propagated to output uncertainties. The model parameters of both methods were fixed with 'typical' values in the DC approach and the default parameter set in the MDL approach. This was motivated as follows: (1) the early project phase of the design task at hand meant that historical data motivating any parameter value adjustment were scarce, (2) for future applications of the MDL approach in practice it is foreseen that a majority of the model parameters will need to be kept at their default values and (3) the model parameters of the two methods are very different involving that it is difficult to vary them in a fair and comparable way.

Instead of considering model parameter uncertainty, the two methods were assessed by comparing their design results for uncertain influent concentrations of chemical oxygen demand (COD), biological oxygen demand (BOD_7) and total nitrogen (TN). The choice of defining these input data as uncertain benefits from the facts that (1) there are commonly historical data available for determining and motivating the input distributions and (2) they represent basic input data that always needs to be specified in design projects.

MATERIAL AND METHODS

Case study WWTP design task and pre-requirements for dimensioning

The case study WWTP design project involved a plant extension from 200,000 to 330,000 people for the design year 2050. Part of the primary clarified total influent design load (γ), was to be treated in existing fixed anoxic/aerobic and secondary clarifier dimensions, configured as a step-feed process for nitrogen removal in three cascades (C1, C2 and C3), see Figure 1. Given daily average influent concentrations (COD_{In}, $BOD_{7,In}$ and TN_{In}), the design task was to establish the capacity of the process, i.e., the daily average flow rate (Q_C). Further, the following criteria on daily effluent concentrations were met for a process temperature of 9 °C: effluent total nitrogen concentration < 8 g N m^{-3} and effluent ammonia concentration (NH_4-N) < 1 g N m^{-3}. The choice of establishing the capacity for the relatively low temperature of 9 °C (representing the coldest weekly temperature) was in accordance with the real-life design task and motivated by the fact that the plant should produce low effluent concentrations all year round to meet the effluent requirements.

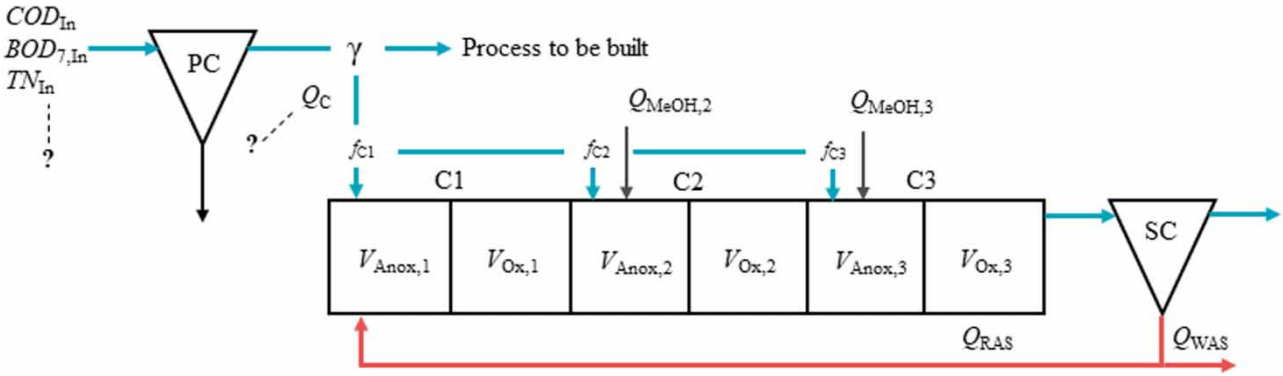


Figure 1 | Layout of the WWTP in the case study design task in which a fraction γ of the design load was to be treated in existing volumes. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2022.426.

The following realistic operational settings were selected based on operational experience and to keep the case study manageable:

- a Q_{RAS}/Q_C ratio of 1.7,
- a sludge loading rate to the secondary clarifier (including Q_{RAS}) of 3.8 kg TSS m^{-2} h^{-1},
- a distribution of pre-settled wastewater to the three cascades ($f_{C1\text{-}3}$) of 36.5/32/31.5%,
- a methanol (MeOH) flow rate to C2 ($Q_{MeOH,2}$) of 0.5 m^3 d^{-1}. $Q_{MeOH,3}$ was allowed to be adjusted without constraints to fulfil the effluent TN requirement.

Design calculation approach (DC)

In this study, two general difficulties were recognised for defining a typical conventional design methodology:

1. Details about the applied equations were not readily available in the preliminary design documents. Documentation on how the process was historically designed was lacking as well.
2. The design guideline equations were not presented in a closed-form expression and required manual iterations to converge to the final design.

Facing difficulty 1, the DC was defined taking inspiration from Swedish practice and available information in the WWTP's preliminary design report as presented by the process design consultants. It must be emphasised, however, that, although being realistic, the DC developed in this study was unlikely to match the one used by the consultants exactly. To enable automatic iterations, the DC equations were implemented in MATLAB. Below, the DC equations are conceptually introduced. In the results section the model parameters and the applied values, of the DC are shown (Table 1), which provides further explanation of the included calculations.

The DC take the design flow, $BOD_{7,In}$ and TN_{In} as influent input variables. The first process unit, the primary clarifier load reduction was modelled by fixed removal percentages for BOD_7 and TN. Then, the main output of the DC is the dimensioned capacity, e.g., the maximum value of Q_C, for which the pre-requirements defined in the section above are met. To find Q_C, the flow was iteratively increased until either nitrification or denitrification limited the capacity of the existing volumes and configuration. For each flow rate a steady-state nitrogen mass balance was therefore calculated to check if the effluent requirements could be met without violating any of three design criteria, valid for the process temperature 9 °C:

Crit. 1: The necessary amount of N to nitrify (N_{Nit}, kg N d^{-1}) is obtained without exceeding the maximum allowed nitrification rate (1.1 g NH_4-N (kg VSS)$^{-1}$ h^{-1}).

Crit. 2: The necessary amount of N to denitrify (N_{Dn}, kg N d^{-1}) is obtained without exceeding the maximum allowed denitrification rate with methanol (2.6 g NO_3-N (kg VSS)$^{-1}$ h^{-1}) in C3.

Crit. 3: The aerobic sludge age (SRT_{Aer}) exceeds the minimum allowed (9 d).

Table 1 | Comparison of assumed parameter values in the DC and corresponding outputs of the MDL

Parameter/variable	Unit	DC		MDL
		Par.	Observed Mean (min/max)	Observed Mean (min/max)
Primary clarifier removal efficiency	% COD	–		**63.5** (63.5/63.5)
	% BOD_7	53.0		**53.3** (53.3/53.3)
	% TN	18.0		**17.9** (13.3/23.6)
Nitrification rate	g NH_4-N (kg VSS)$^{-1}$ h^{-1}	1.10[a]	**1.08** (1.06/1.10)	**1.55** (1.05/2.07)
Aerobic SRT	d	9[b]	**16** (12/23)	**14** (13/17)
DN rate	g NO_3-N (kg VSS)$^{-1}$ h^{-1}	1.20[a]	**1.20** (1.20/1.20)	**1.86** (1.46/2.09)
DN rate, MeOH	g NO_3-N (kg VSS)$^{-1}$ h^{-1}	2.60[a]	**1.99** (1.78/2.15)	**2.94** (1.35/4.31)
BOD_7 req., DN	g BOD_7 (g NO_3-N) $^{-1}$	4.3		
MeOH req., DN	g COD (g NO_3-N) $^{-1}$	5.0		
SP fac., BOD_7	g TSS (g BOD_7)$^{-1}$	0.75		**0.72** (0.64/0.88)
SP fac., MeOH	g TSS (g COD)$^{-1}$	0.33		**0.14** (0.05/0.16)
MLVSS/MLSS	g VSS (g TSS)$^{-1}$	0.75		**0.77** (0.70/0.81)
N content in sludge	g N (g VSS)$^{-1}$	0.08		**6.2** (5.3/6.9)

Abbreviations: DN, denitrification; MeOH, methanol. The column 'Par.' indicates fixed parameter values used in the DC, whereas columns 'DC' and 'MDL' show the corresponding values obtained during the Monte Carlo-iterations.
[a]Maximum allowed (DC).
[b]Minimum allowed (DC).

The maximum allowed concentration of mixed liquor suspended solids (MLSS) in Cascade 3 was determined from the influent flow rate and assumed maximum sludge loading rate to the secondary clarifier. The MLSS in Cascade 1 and Cascade 2, and the concentration of total suspended solids (TSS) in the RAS flow, were then calculated from a static solids mass balance assuming that TSS in presettled and secondary settled wastewater is negligible. The volatile (organic) part of the suspended solids (VSS) was assumed to be a fixed fraction of the TSS (0.75 g VSS (g TSS)$^{-1}$).

Nitrification: N_{Nit} was calculated as the mass balance difference between the total nitrogen load to the three cascades, and the nitrogen in the effluent and waste-activated sludge (WAS). More specifically, the effluent nitrogen was assumed to consist of inert soluble N (assumed to be 1 g N m^{-3}), nitrogen in the effluent suspended solids (assumed to be 0.5 g N m^{-3}), and the effluent NH_4-N and NO_3-N. The sludge was assumed to contain a constant nitrogen fraction (0.08 g N (g VSS)$^{-1}$).

The DC assumed (according to the design pre-requirements) complete nitrification and a residual concentration of 1 g NH_4-N m^{-3} in the cascades as well as in the effluent. The necessary nitrification rate was then calculated by dividing N_{Nit} with the mass of volatile suspended solids (VSS) in the aerobic volumes and compared to *Crit. 1*.

Denitrification: N_{Dn} was given by subtracting the load of effluent NO_3-N (allowed concentration 8.0 – 1.0 – 0.5 – 1.0 = 5.5 g N m^{-3}) from N_{Nit}. It is thus assumed that there was no NO_3-N in the influent. The denitrification process in each of the three cascades was limited by either:

- the amount of organic matter in the inlet to the cascades, or
- the amount of NO_3-N in the inlet to the cascades, or
- the assumed maximum allowed denitrification rates.

The DC calculation assumed yield parameters determining the requirement of influent BOD_7 and added methanol for denitrification, see Table 1. The denitrification process was assumed to primarily oxidize the more easily degradable carbon source (in this case methanol). Only when methanol was fully oxidized, the influent BOD_7 was consumed. The maximum allowed denitrification rate in a certain volume was assumed to depend on the fraction of nitrogen that is denitrified with the easily degradable substrate. For example, in Cascade 1, denitrification was assumed to be with influent BOD_7 only and the resulting maximum rate at 9 °C was thus set to 1.20 g NO_3-N (kg VSS)$^{-1}$ h^{-1}, see Table 1. In Cascade 3, conversely, denitrification could potentially be with methanol only and the maximum rate was set to 2.60 g NO_3-N (kg VSS)$^{-1}$ h^{-1}. For a certain flow rate and influent TN and BOD_7 concentration, the DC calculates the actual amounts of N that is denitrified in

Cascade 1 and Cascade 2. The necessary denitrification rate in Cascade 3 was then calculated by dividing the remaining amount of N_{Dn} with the mass of volatile suspended solids (VSS) in the anoxic volume in Cascade 3 and compared to *Crit. 2*. In this way it was verified whether the effluent requirements were met with methanol addition and the associated required dosage flow rate ($Q_{MeOH,3}$).

Sludge production: Despite the nitrification rate (*Crit. 1*) a necessary condition for complete nitrification according to the DC was a sufficient aerobic sludge age (SRT_{Aer}), which was calculated by dividing the mass of sludge into the aerobic volumes by the sludge production (SP, kg TSS d^{-1}) and then compared to *Crit. 3*. The sludge production was calculated as the sum of sludge produced due to the mass loading rate of BOD_7 in the effluent of the primary clarifier and the total amount of dosed external carbon (here methanol), assuming two fixed sludge production factors, depending on the type of carbon source only.

Model-based design approach

In the MDL approach, the iterations of the DC approach were replaced by a steady-state simulation, e.g., by solving the model mass balances for constant design influent concentrations. The variables Q_C and $Q_{MeOH,3}$ were first manipulated by PI control loops to maintain the effluent requirements (effluent concentration of NH_4-N and TN, respectively). In case the denitrification capacity was limited (e.g. compliant values of NH_4-N but too high TN), the Q_C controller was switched from measuring NH_4-N to TN, leading to a decreased flow rate. The requirement of the secondary clarifier sludge loading rate was maintained by controlling the Q_{WAS} flow rate, i.e. while Q_C increases, the MLSS of Cascade 3 is automatically lowered (recall that the Q_{RAS}/Q_C ratio was considered to be fixed). In this way, the maximum capacity Q_C, conditioned by the influent concentrations, was established.

To run the steady-state simulations, the configuration (Figure 1) was implemented in the software Simba# 5.0 (ifak, Germany) using the built-in biokinetic process model ASM_inCtrl (inCTRL Solutions Inc., Canada). This model is, although significantly extended, based on the same principles as the activated sludge models described in Henze *et al.* (2000). For the application in this paper, the significant processes of the model are the growth of ammonia and nitrite-oxidizing bacteria (two-step nitrification), growth of ordinary heterotrophs (resulting in denitrification in the absence of oxygen) and the growth of methylotrophs (resulting in denitrification with methanol in the absence of oxygen). The applied primary clarifier model is based on Otterpohl & Freund (1992) and the secondary clarifier on the three-layer model described in Alex (2011). For the simulated conditions in this paper, the effluent TSS were always close to 6 g m^{-3}. Thus, any change in clarifier performance due to changes in the design flow rate was not seen. With few exceptions, as discussed in the following, the parameter values of the Simba# WWTP model were kept at their default values.

A main difference between the MDL and DC approaches is that in the MDL, COD is used as an input variable for the total concentration of organic matter while BOD_7 (used in the DC) is a calculated model output. In Simba#, BOD_7 is calculated from the COD state variables and several decay, yield and empirical parameters. These parameters, which are specific for the BOD calculation, were kept at their default values and the MDL influent concentration of inert particulate COD was modified to match the design figures for influent TSS and BOD_7.

The TSS removal of the primary clarifier was adjusted to obtain the design value (80%), while the fraction of soluble influent COD was modified to obtain a fit with the design primary clarifier BOD_7 removal (53%). Eventually, the influent fractionation and primary clarifier parameter values involved that the MDL (with COD as main input) produced the same BOD_7 concentrations in influent and pre-settled wastewater compared to the DC. The observed TN removal in MDL was used as the design figure and inserted in the DC in this case study. A validated methodology for dealing with influent fractionation and pre-treatment during an MDL approach for WWTP dimensioning is regarded to be an important and challenging topic for future research.

Influent uncertainty distributions

Historic data (2011–2020) of influent daily volume proportional samples ($n = 303$–517) of BOD_7, TOC (converted to COD), and TN were first processed to represent the current state (year 2020). This was achieved by correcting for trends in the specific loads (i.e., the daily mass loads per person) and thereby achieving stationary time series with concentrations and flow. The influent flow was modelled with two components, a specific (per person) drinking water consumption, and a person-independent infiltration water component. Both components were corrected to stationarity. Extreme flows (above the 95 percentile) were omitted. Next, the future influent load (year 2050) was modelled as the 2020 load plus the added load from the increase in population times the specific load. Thus, the wastewater production per person was assumed to

be constant between 2020 and 2050. Also, the infiltration water in 2050 was increased based on estimates from a separate project. Finally, a multivariate Gaussian distribution was estimated from the processed and stationary data, which was then used to sample the influent uncertainties from the model outputs, see Figure 2.

Method for uncertainty and sensitivity analysis

In total, 1,000 Monte Carlo samples were sampled from the multivariate Gaussian distribution, in which each sample was independently and identically distributed. Each sample was then thought to represent a realization of a future (daily) concentration and load. Since the concentration samples were derived with data from the entire year, while the design was done for a fixed cold temperature scenario (9 °C), it was assumed that the variability in influent concentrations was independent of the temperature. The samples were used as inputs to the uncertainty and sensitivity analysis, where Q_C was the output. A so-called random sampling with binning approach (estimates of the conditional variance and expectations from Monte Carlo data) was used for the sensitivity analysis to estimate the main effects of the variance (commonly abbreviated S_i). Random sampling with binning was used instead of the more common standardized regression coefficients due to the strong correlations in influent data. The sensitivity analysis was executed in MATLAB with code kindly provided by Gürkan Sin (DTU, Denmark).

RESULTS AND DISCUSSION

Practical considerations

The (initially assumed) simple task of automating the DC iterations was time-consuming but necessary since manual tweaking of the DC to fulfil one new design scenario could take up to one hour. Having automated the DC calculations, both design approaches were fast to simulate, and in the order of seconds on a desktop computer. Thus, the bottleneck in time was to manually set up and configure the methods. Our experience from this study is that it was both faster and less error prone to conduct uncertainty analysis and the Monte Carlo simulations with commercial software including validated model libraries, compared to the DC approach using spreadsheets. This challenges the common perception of models being complicated and time-consuming.

Uncertainty analysis of design capacity

The uncertainty analysis of the maximum dimensioned capacity (Q_C) showed that the MDL indicates a higher capacity than the DC, although with similar uncertainty, see Figure 3(a). In Figure 3(b) the same data sets are presented as cumulative frequency distributions, showing the probability P of compliance at different design flow rates. According to the DC, a mean flow rate of 27,000 $m^3\ d^{-1}$ can never be treated sufficiently in the existing volumes while with the MDL, this is possible for 50% of the possible influent concentrations, i.e., with 0.5 probability.

We interpret the difference between the DC and the MDL capacity as the total effect of all accumulated safety factors in the DC, i.e., the built-in resilience towards influent load and concentration variations with respect to Q_C. As expected, the DC was more restrictive than the model, which does not include safety factors.

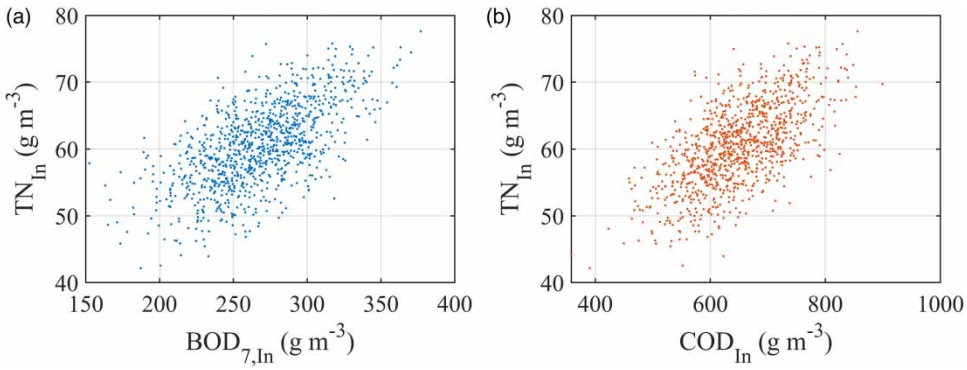


Figure 2 | The 1,000 samples from the uncertain influent distribution used in the study. (a): DC influent data. (b) MDL influent data. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2022.426.

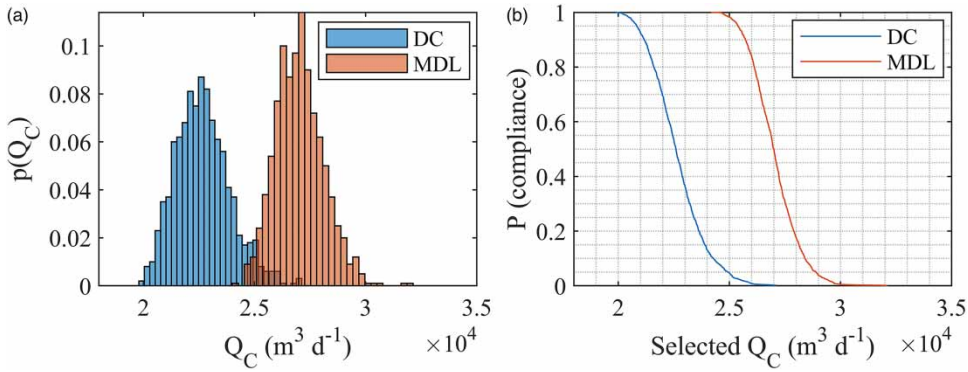


Figure 3 | Distributions of the capacity (average flow rate, Q_C) from the uncertainty analysis, presented in two different ways. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2022.426.

Sensitivity analysis of design capacity

Figure 4 shows scatter plots of correlated influent data versus the dimensioned maximum average flow rate as well as the variance sensitivity indices (main effects). The total nitrogen concentration limited Q_C in the DC (Figure 4(a)) because of *Crit. 1* (nitrification rate) violation (a direct output of the DC approach calculations is the actual criterion that limited a further increase of Q_C). For example, for the DC approach and a given TN_{In} of 60 g m^{-3}, the capacity is about 23,000 m^3 d^{-1} with only minor variations (Figure 4(a)) although $BOD_{7,In}$ (recall Figure 2) varies between 200 and 300 g m^{-3} conditional on this TN concentration. Then, although much smaller, a reasonable explanation for the sensitivity of $BOD_{7,In}$ (Figure 4(b)) is that this design input affects how much sludge is being produced and thereby how much of the influent total nitrogen needs to be nitrified. With a higher value of $BOD_{7,In}$, more nitrogen is assimilated in the sludge, and the criteria for nitrification allows a higher Q_C.

In the MDL, the influent concentration of organic matter (expressed as COD) has the highest sensitivity (compare Figure 4(a) and 4(c)). For a given COD_{In} of 600 g m^{-3}, for example, the capacity was about 27,500 m^3 d^{-1} when TN_{In} was varied between 50 and 70 g m^{-3} (recall Figure 2). A reasonable explanation is that the COD of the methanol dosage to Cascade 3, used to compensate for the impact of the influent nitrogen to COD ratio, gives a quite different model response compared to the COD of the influent (e.g. a lower sludge production per denitrified nitrogen), which do not significantly impact the capacity. However, in this case, the equation structure is significantly more complex compared to the DC and the UA/SA of this study do not directly provide an answer to *why* the influent COD concentration is the limiting factor.

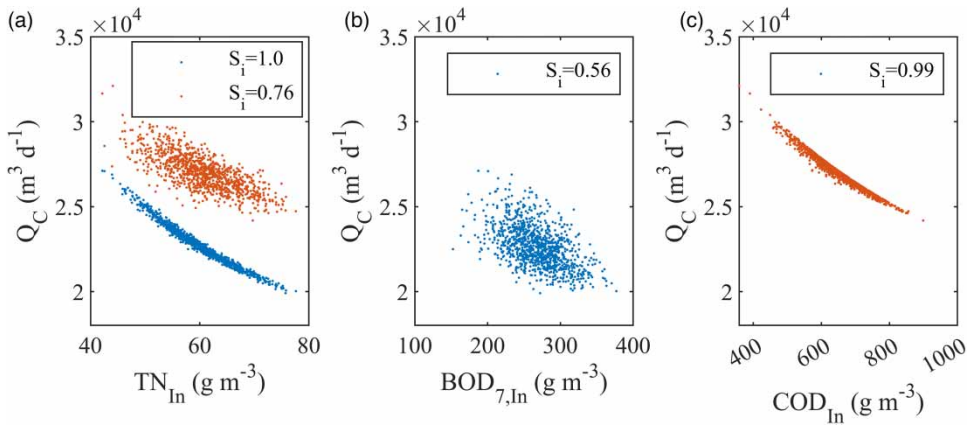


Figure 4 | Scatter plots of the compliant influent flow Q_C (capacity) for the correlated Monte Carlo sampled influent concentrations. The design guideline (DC) is indicated with blue dots, and the model-based approach (MDL) with red dots. Sensitivity indices (main effects) are shown in the legends. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2022.426.

Although all equations are available, it requires time and deep model understanding to understand the root-cause effect, which is a challenge and drawback of using models for design.

Finally, the magnitude of the sensitivity indices did not directly match the corresponding variance in the corresponding slopes in Figure 4, i.e., the standardized regression coefficients (data not shown). The reason is that the input data were correlated, and therefore overestimated the impact of each input factor if the correlations were disregarded. The applied random sampling with the binning method coped with this issue for the estimation of the main effects. However, the total effects (including interactions) are critical when more influent parameters are considered. For this situation, methods such as the one described by Kucherenko *et al.* (2012) are needed and will be a topic for future research.

Comparison of dimensioning methodology behaviour

In Table 1, assumptions and results of the DC and MDL approach for this case study are summarised. As described in the methods section, the removal in the primary clarifier was set by fixed percentages (design pre-requirements) in the DC while in the MDL, the influent fractionation and TSS removal were adjusted to mimic these. A consequence of this was that the MDL removal of nitrogen varied between 13.3 and 23.6% in the Monte Carlo runs depending on the influent COD/TN ratio. With a higher ratio, more COD and nitrogen are in particulate form, which increases the TN removal. This exemplifies the fact that it may sometimes be difficult to exactly match pre-defined design requirements with a model-based approach.

As mentioned, the nitrification rate in the DC limited a further increase of Q_C for all influent concentrations. The assumed maximum nitrification rate (1.1 gNH_4-N (kg VSS)$^{-1}$ h^{-1}) in the DC was restrictive, but not unrealistic, for the combination of low design temperature (9 °C) and a strict effluent ammonia requirement (<1 g NH_4-N m^{-3}). Note that the MDL, on average, had a higher nitrification rate than the DC (Table 1). The observed aerobic sludge retention times for both the DC and the MDL were well above (12–23 d) the set criterion (>9 d). Accordingly, manual simulations (results not shown) showed that the maximum effluent NH_4-N (and not denitrification) limited an increase in Q_C in the MDL.

The DC results from Cascade 1 (no addition of methanol) showed that the assumed maximum denitrification rate (1.2 g NO_3-N (kg VSS)$^{-1}$ h^{-1}) was reached at all times, indicating that the denitrification rate, and not the inlet BOD_7 load, was a limitation in Cascade 1. In the MDL, a similar 'maximum rate' was not seen, and the observed rates were higher (1.46–2.09 g NO_3-N (kg VSS)$^{-1}$ h^{-1}). The denitrification rate in the MDL was instead limited by the actual BOD_7 load, fed to Cascade 1.

With access to two substrates, the DC conceptually assumes that the methanol is utilized prior to the wastewater BOD_7 for denitrification. By adding methanol, the potential denitrification rate can, according to the DC, be increased to the assumed maximum rate with methanol (2.6 g NO_3-N (kg VSS)$^{-1}$ h^{-1}). Figure 5(a) shows a clear correlation between high TN influent concentrations (requiring high denitrification rates to comply with effluent TN limits) and the associated required methanol addition, for the DC (blue dots). In the MDL, the wastewater BOD_7 content to a higher degree impacted the necessary methanol dosage. This is seen from the correlation between the BOD_7/TN ratio of pre-settled wastewater and the required methanol dosage (Figure 5(b)).

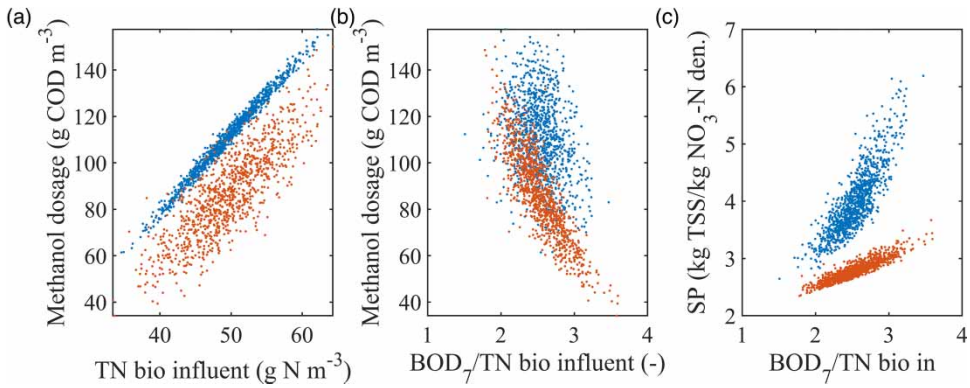


Figure 5 | Scatter plots of characteristics in pre-settled wastewater versus the required addition of external carbon (a, b) and sludge production (c) for the MDL (red markers) and DC (blue markers). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2022.426.

Finally, the conceptual two-substrate-denitrification model used in the DC shows a high impact on the calculated sludge production (Figure 5(c)). In both methods, the specific sludge production per kg denitrified N increased with the influent BOD_7/TN ratio. In the MDL, this is due to the higher yield parameter values for wastewater COD compared to methanol COD. This is also true in the DC approach (3.2 and 1.7 kg TSS/kg NO_3-N denitrified with BOD_7 and methanol, respectively) but the resulting dependence on BOD_7/TN was, in this case, higher. Overall, the DC predicts a significantly higher sludge production compared to the MDL. For many dimensioning projects, the sludge production plays a crucial role, and the differing behaviour of the approaches is therefore important to consider.

CONCLUSIONS AND IMPACT

The capacity of the existing process for future conditions depends on uncertainties in influent concentrations, which emphasises the importance of uncertainty analysis during design. The results show that model-based design can simplify and reduce the time required for uncertainty and sensitivity analysis compared to a conventional design approach, in which the equations are solved manually and iteratively. A benefit with the conventional design approach is the simple interpretation regarding which factors limit the design capacity. However, the validity of these observations should be questioned since they differ from the mechanistic model output. Sensitivity analysis is effective in quantifying how correlated influent variations affect the capacity and more research is needed on how to quantify interactions for correlated input data. In the end, this study shows the potential, as well as the need for, model-based design of WWTPs.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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