Universidade de Aveiro Departamento de Engenharia Mecânica
2020

Pedro Daniel da Cunha Moreira Nunes

Analysis of the use of variable speed drives in water supply systems

Análise do uso de variadores de velocidade em sistemas de abastecimento de Água

Universidade de Aveiro Departamento de Engenharia Mecânica
2020

Pedro Daniel da Cunha Moreira Nunes

Analysis of the use of variable speed drives in water supply systems

Análise do uso de variadores de velocidade em sistemas de abastecimento de Água

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação científica. do Doutor António Gil D'Orey de Andrade Campos, professor auxiliar com agregação do Departamento de Engenharia Mecânica da Universidade de Aveiro e da Doutora Bernardete da Costa Coelho.

Este trabalho teve o apoio financeiro dos projetos UIDB/00481/2020 e UIDP/00481/2020 - FCT - Fundação para Ciência e Tecnologia; e CENTRO-01-0145-FEDER-022083 - Programa Operacional Regional do Centro (Centro2020), no âmbito do Acordo de Parceria Portugal 2020, através do Fundo Europeu de Desenvolvimento Regional.

o júri / the jury

presidente / president

Professor Doutor Nelson Amadeu Dias Martins
Professor Associado da Universidade de Aveiro

vogais / examiners committee

Doutor Bruno Alexandre Abreu da Silva
Diretor Executivo da Scubic

Professor Doutor António Gil D'Orey de Andrade Campos
Professor Auxiliar C/ Agregação da Universidade de Aveiro (orientador)

acknowledgements

Fortunately, I have had the privilege of being guided by Professor António Campos and Bernardete Coelho, to whom I owe all the patience, knowledge and spectacular mentoring skills and without whom this thesis would not be pass the form of a mere dream. All the encouragement words were crucial for me to keep pushing forward in some personal difficult times. In a work environment they were both able to prove that in addition to being great professionals they are also both incredible people, so I have a huge debt to them.

To my friends, who were always there with me in the long nights of studying, with companionship and help. And for the other moments as well, always with laughter and camaraderie. To my parents, to whom I will never be able to return what they gave me, unconditional love, support and for always rooting for me, I can't thank them enough.

Last but not least, to my brother. The older brother, the one who teaches you everything from a young age, who grows up with you, shapes your personality, always side by side, always together, my best friend from the day I was born. His absence has made this path more tumultuous and difficult, but I know that he would never let me give up, that was also what motivated me to try to move forward, thank you for everything brother.

Thank you all.

Palavras chave Variable speed drives, centrifugal pump, increasing efficiency, affinity laws, hydraulic modelling.

Abstract Currently, operational control at the pumping stations is based on the water levels present in the tanks, ie, each time the water level reaches a certain minimum value, the pumps switch on until the tank is full again. Although this type of control is quite effective, it is also quite inefficient. This type of operation can be largely optimized by adjusting pumping operations to energy prices that vary throughout the day. Additionally, the use of variable speed drives can also increase the efficiency of the pumps due to its adaptations to daily water consumption. However, this type of operation imposes several challenges such as (i) the high difficulty of the operator to accurately predict water consumption patterns every day and for all types of consumers by intuition ; (ii) associate water needs with fluctuations in energy tariffs and with low storage capacity of reservoirs; (iii) know the ideal frequency to pump the water with the lowest energy consumption and (iv) know the equipment used, which, over time, its efficiency decreases substantially. With complex and large systems (such as water supply systems), the attempt to improve operational efficiency can be a "shot in the dark", which can lead to serious implications on the minimum requirements required by final consumers (such as pressures or security of supply). In this thematic area, the goal of this work is to contribute to an increase in the efficiency of these systems. Different studies results are described in the literature, studies concerning the application of VSDs. However, even though they show good results when it comes to energy savings, there is still doubt among the community on the advantages of applying the VSDs, and above all there is still a lack of information on how to use the VSDs. The main goal of this study is to present the benefits of using VSDs, as well as explaining its application. Python simulations were developed with different scenarios for a water distribution network, using VSDs and pumps, even at parallel use. The results achieved were satisfactory and present values of energy savings within expectations.

Palavras chave

Variadores de velocidade, bomba centrífuga, aumentar eficiência, leis da afinidade, modelação hidráulica.

Resumo

Atualmente, o controlo operacional nas estações elevatórias de àgua é feito com base nos níveis de àgua presentes nos reservatório, ou seja, cada vez que o nível da àgua atinge um determinado valor mínimo, as bombas são ligadas até o reservatório ficar cheio novamente. Embora este tipo de controlo seja bastante eficaz, também é bastante ineficiente. Este tipo de operação pode ser amplamente otimizado ajustando as operações de bombeamento aos preços de energia que variam ao longo do dia. Além disso, a utilização de variadores de velocidade também pode aumentar a eficiência das bombas devido às suas adaptações ao consumo diário de àgua. No entanto, este tipo de operação impõe vários desafios, como (i) a grande dificuldade do operador em prever com precisão os padrões de consumo de àgua todos os dias e para todos os tipos de consumidores por intuição; (ii) associar as necessidades de água às flutuações das tarifas de energia e à baixa capacidade de armazenamento dos reservatórios; (iii) saber a frequência ideal para bombear a água com menor consumo de energia e (iv) conhecer os equipamentos utilizados, que, com o tempo, a sua eficiência diminui substancialmente. Com sistemas complexos e grandes (como sistemas de abastecimento de àgua), a tentativa de melhorar a eficiência operacional pode ser um "tiro no escuro", o que pode levar a sérias implicações nos requisitos mínimos exigidos pelos consumidores finais (como pressão ou segurança no fornecimento). Nesta área temática, o objetivo deste trabalho é contribuir para o aumento da eficiência destes sistemas. Resultados de diversos estudos são descritos na literatura, estudos relativos à aplicação de VSDs. Porém, embora apresentem bons resultados no que se refere à economia de energia, ainda há dúvidas na comunidade sobre as vantagens da aplicação dos VSDs e, sobretudo, ainda falta informação sobre como utilizar os VSDs. O objetivo principal deste estudo é então apresentar os benefícios da utilização de VSDs, bem como explicar a sua aplicação. Simulações em Python foram desenvolvidas com diferentes cenários para uma rede de distribuição de água, usando VSDs e bombas hidráulicas, até com utilização em paralelo. Os resultados alcançados foram satisfatórios e apresentam valores de poupança de energia dentro das expectativas.

Contents

Terminology

N_s	synchronous rotation (rpm)
f	frequency
p	number of poles
N_r	engine speed (rpm)
s	slip (%) of synchronous rotation
N_1	original rotation speed of the pump
N_2	adjusted rotation speed of the pump
M	ratio of rotation speed of the pump
Q_1	flow relative to pump 1
Q_2	flow relative to pump 2
H_1	head relative to pump 1
H_2	head relative to pump 2
P_1	power consumption of the pump relative to the pump 1
P_2	power consumption of the pump relative to the pump 2
η_1	original efficiency
η_2	speed adjusted efficiency
H_{par}	head for parallel operation
Q_{par}	flow for parallel operation
h_F	height of reservoir F
A_F	area of reservoir F
$Q_{\mathrm{P},i}$	average flow of the pump
$Tarif_{i,}$	energy cost for each increment
$\boldsymbol{x}_i$	the state / time of the pump in time period i
k	constants describing the total system characteristics
Q_R	consumption R
Q_{VC}	consumption VC

Q_{paux1}	flow for pump 1 with original rotation speed
Q_{paux2}	flow for pump 2 with original rotation speed
h_{aux1}	head for pump 1 with original rotation speed
h_{aux2}	flow for pump 2 with original rotation speed
η_{Paux1}	efficiency for pump 1 with original rotation speed
η_{Paux2}	efficiency for pump 2 with original rotation speed
W_{Paux1}	power for pump 1 with original rotation speed
W_{Paux2}	power for pump 2 with original rotation speed
$Q_{pauxal1}$	flow for pump 1 with adjusted rotation speed
$Q_{pauxal2}$	flow for pump 2 with adjusted rotation speed
h_{auxal1}	head for pump 1 with adjusted rotation speed
h_{auxal2}	head for pump 2 with adjusted rotation speed
$\eta_{Pauxal1}$	efficiency for pump 1 with adjusted rotation speed by affinity laws
$\eta_{Pauxal2}$	efficiency for pump 2 with adjusted rotation speed by affinity laws
η_{PSB1}	efficiency for pump 1 with adjusted rotation speed by SB method
η_{PSB2}	efficiency for pump 2 with adjusted rotation speed by SB method
η_{PCAC1}	efficiency for pump 1 with adjusted rotation speed by CAC method
η_{PCAC2}	efficiency for pump 2 with adjusted rotation speed by CAC method
$W_{Pauxal1}$	power for pump 1 with adjusted rotation speed
$W_{Pauxal2}$	power for pump 2 with adjusted rotation speed

List of Tables

Intentionally blank page.

List of Figures

Chapter 1

Introduction

1.1 Context

Since people started using agriculture and raising animals as a way to produce food, they started to settle in villages. The need to transport and distribute water goes back to those times. Therefore, the operation of water supply systems has always deserved special attention because it is an essential service.
The disorderly growth of large urban centers is identified as one of the main responsible for the operational complexity, forcing the water supply companies to increase their systems in order to meet all the conditions and demands imposed by distances and adverse topographies. Thus, pumping systems are implemented to the operational network aiming at the full service of the most distant points of consumption with adequate pressure and flow.
One of the major obstacles to increase efficiency in water distribution networks is directly related to the complexity of the systems, both in terms of the configuration of the networks and in the number of variables to be controlled, and also due to the low levels of flexibility of operation of this type of systems.
Pumping systems account for nearly 20% of the world's electrical energy demand and range from 25-50% of the energy usage in certain industrial plant operations [1,2]. Pumping systems are widespread; they provide domestic services, commercial and agricultural services, municipal water/wastewater services, and industrial services for food processing, chemical, petrochemical, pharmaceutical, and mechanical industries [1].
With this in mind, it is mandatory to use electrical energy in a sustainable way, which is added in the continuous fight against waste and the physical loss of water from water supply companies. Under such unfavorable conditions, VSDs have never been more important than now, with the mission of rationalizing the use of electric power without affecting the operation of the supply system. The need for energy sustainability in order to help the environment is also a key driver for improving efficiency when applying VSDs [3]. Therefore, the motivation that led to the development of this study is the effective use of variable speed drives in water supply systems. A literature review revealed a lack of pertinent information to guide the proper use of such a device as a mean of reducing the consumption of electricity in water supply companies and, mainly, of an optimized operational control, thus evidencing the interest in the subject.

1.2 Objectives

It is well known that the use of variable speed drives can reduce the energy consumption of hydraulic pumps by more than 10% in water supply systems. However, there is some skepticism and lack of knowledge from the industry in using such equipments. This work aims to analyze the use of variable speed drives in real and virtual situations in order to demonstrate its usefulness and added value to the industry.

Moreover, the following goals of this work were also defined:

(i) To know the advantages of VSDs in pumping stations of water supply networks;

(ii) Analyze the use of variable speed drives in real and virtual situations in order to demonstrate their usefulness and added value to the industry.

(iii) Develop methodologies for the efficient use of VSDs in hydraulic systems.

Chapter 2

Literature Review

Water pumping stations are essential parts of public water supply systems and are used throughout the process of abstraction, treatment, storage and distribution of water. Its main components are pipes and electro-mechanical equipment (pump and motor).
The pumps are classified as kinetic or positive displacement. The kinetic pumps supply energy to the water in the form of velocity, transforming that velocity of the fluid inside the pumps into pressure energy.
In positive displacement pumps there is no internal energy exchange in the liquid mass. The liquid undergoes internal pressure and because it is confined it moves from a static position to a higher one. The flow is proportional to the speed of the machine driver.
Here, before looking at the pump curves and their specifications, it is necessary to understand how they work. The most important component of hydraulic pumps is their rotor, attached to a shaft moved at the speed of rotation provided by the electric motor.

2.1 Characteristic Pump Curves

The centrifugal pumps are turbo machines designed and built to work in the same rotation under different flow conditions and manometric height. These conditions are represented in characteristic curves according to Figure 2.1.
There is, however, a well-defined interdependence between these flow values and manometric height, which is obtained through tests made in the manufacturers' laboratories.

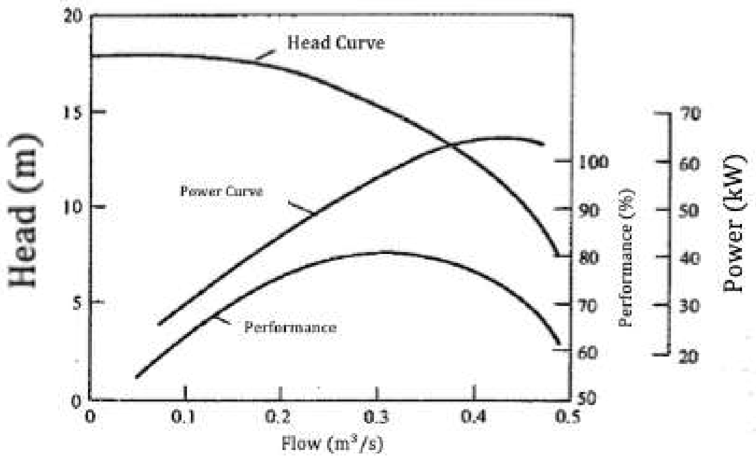


Figure 2.1: Characteristic curves of centrifugal pumps. [4,Tsutiya (2004)]

It is common for the manufacturer to provide the characteristic curves of his products for various rotor diameters, relating manometric height, required power and performance, as a function of flow.
The knowledge of the characteristic curves is of fundamental importance, since each pump is designed basically to elevate a certain flow to a total manometric height in conditions of maximum performance. The operating point of a centrifugal pump is the intersection of the pump curve with the system curve (Figure 2.2).

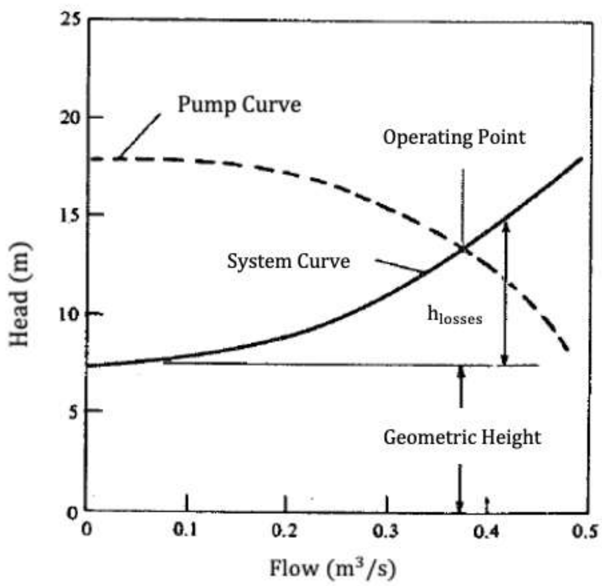


Figure 2.2: Characteristic curve of the system. [4,Tsutiya (2004)]

2.2 Electric Motor

Electric motors are machines designed to transform electrical energy into mechanical energy. The energy saving potential of the electric motor is huge, since motor systems use more than 60% of the electrical energy consumed by industry [5].
DC motors are used in applications that require fine tuning and precise speed control. For their operation they use a source of direct current, or a device that converts the common alternating current into direct current. Due to its high cost its application is restricted to special cases and rarely used in water lifting stations.
AC motors are more common because the power distribution is carried out in alternating current. Synchronous motors operate at fixed speed and are only used for large powers (due to their high cost in smaller sizes) or when invariable speed is required. Induction or asynchronous motors, however, operate at constant speed, which varies slightly with the mechanical load applied to the shaft.
Asynchronous or induction motors are the most commonly used, because they combine the advantages of low cost electrical use, ease of transportation, cleanliness and simplicity of control due to their simple construction, low cost and high versatility, adaptation to the loads of the most diverse types and better performances.
Three-phase induction motors, like any other electrical motor, have two main parts : the rotor and the stator.
Stator as the name indicates is a stationary part of induction motor. A three phase supply is given to the stator of the induction motor.
The synchronous motors name is due to their speed is in synchronism with the frequency of the power network, depending solely on that frequency and the number of poles and independent of the load to be overcome.
The synchronous rotation is obtained by equation:

$$N_{\mathrm{s}} = \frac{120f}{p}, \tag{2.1}$$

where N_s = synchronous rotation (rpm), f = frequency (Hz), p = number of poles.
The difference between the motor speed and the synchronous speed is called slip, which can be expressed in rpm, or as a fraction of the synchronous speed, or as a percentage of it. The following equation shows the slip as a percentage of the synchronous rotation.

$$s = \frac{N_{\mathrm{s}} - N_{\mathrm{r}}}{N_{\mathrm{s}}} \tag{2.2}$$

Where N_s = synchronous rotation (rpm), N_r = engine speed (rpm), s = slip (%) of synchronous rotation.
The following equation shows the relation between rotation, frequency, number of poles and slip:

$$N_{\mathrm{r}} = \frac{120f(1-s)}{p} = N_{\mathrm{s}}(1-s). \tag{2.3}$$

Electric motors have dominated fixed speed applications for many years but with the use of VSDs they are also establishing themselves in controlled speed applications [6]. With about two-thirds of the motors in industry being applied in fans and pumps, which do not need constant motor speeds [7], there's is a good opportunity to explore the VSDs in a larger scale in the industry in order to save energy.

2.3 Variable Speed Drives in Hydraulic Pumps

An hydraulic pump is composed by the pump itself and a power generation. Generally, the power generator is a AC motor. Centrifugal pumps accelerate the liquid mass through the centrifugal force provided by the rotor rotation, yielding kinetic energy to the moving mass and internally transforming the kinetic energy into pressure energy at the rotor outlet through the pump casing. In general, the centrifugal pumps have: pump housing, rotor, seal and bearings, which are attached to a metal base.

AC motor speed is controlled in two ways - either by controlling the voltage or frequency. Frequency controlling gives better control than voltage control due to constant flux density. This is where the working of Variable Speed Drives (VSD) comes to play. It is a power conversion device which converts the fixed voltage and fixed frequency of the input power to the variable voltage and variable frequency output to control AC induction motors. The resulting output voltage and frequency are determined by input power of the motor. Most motors can benefit from VSD to provide different frequency outputs[2]. In a water supply system if the load decreases, significant energy savings can be achieved when the rotational speed of the motor is decreased to match with the new load requirement [8]. VSDs consists of mainly four sections (figure 2.3):

- Converter or rectifier: It is the first stage of variable speed drives, it converts commercial AC power fed from the mains to DC power[9]. A maximum of six diodes are required for the three-phase conversion, so the rectifier unit is considered as six pulse converter.

- Smoothing circuit or DC bus: This section consists of capacitors and inductors to smooth against ripples and store the DC power. The main function of this section is to receive, store and deliver DC power.

- Inverter: This section comprises of electronic switches like transistors. It receives DC power from DC link and converts into AC. It generates AC by sequentially switching a DC in alternate directions through the load [10], which is delivered to the motor. It uses modulation techniques such as pulse width modulation to vary output frequency for controlling the speed of the induction motor;

- Control circuit: It consists of a microprocessor unit and performs various functions like controlling, configuring drive settings, fault conditions and interfacing communication protocols. It receives feedback signal from the motor as current speed reference and accordingly regulates the ratio of voltage to frequency to control motor speed.

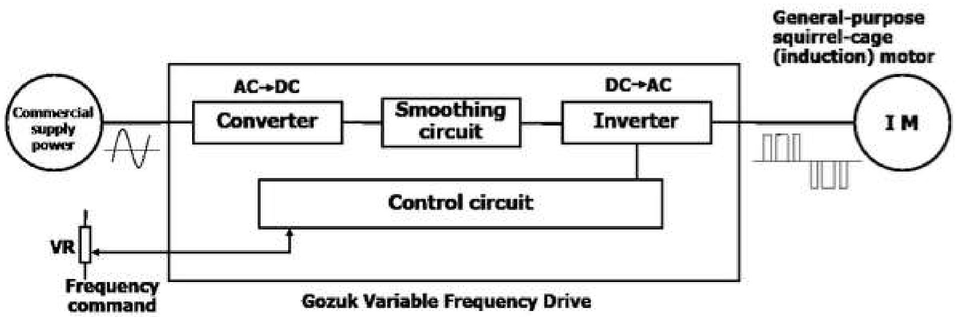


Figure 2.3: VSD main components (adapted from [10].)

The speed variation in pumping systems with the use of VSDs can be used in all situations

that it is desired to modify the operation of the equipment driven by electric motors to control any system [11].
In a supply system, when the pumping of water is aimed directly to the consumer, it becomes necessary to control the flow depending on the demand. The purpose of flow control is to maintain the pressure constant or at a preset value.
The pressure control of the pumping systems, when variable speed drives allows the increase or the gradual decrease of the pumping flow rate as a function of the demand variation. When VSDs are used, the decrease of the speed of rotation causes the flow rate to decrease to a value by the simple displacement of the curve of the pump on the curve of the system, as can be seen in the figure 2.4.

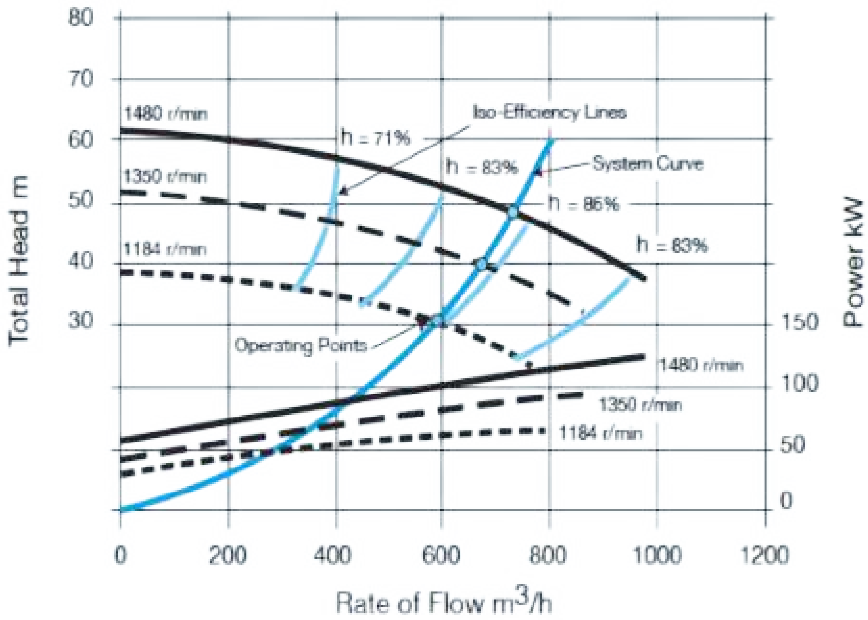


Figure 2.4: Characteristic pump curves with different speeds Source: [Europump and Hydraulic Institute]

It's recommend operating ranges for centrifugal pumps varying from 70 to 120% of the optimum efficiency of pumps and frequency inverters with frequencies of 30 to 60 Hz (Figure 2.5) [4].

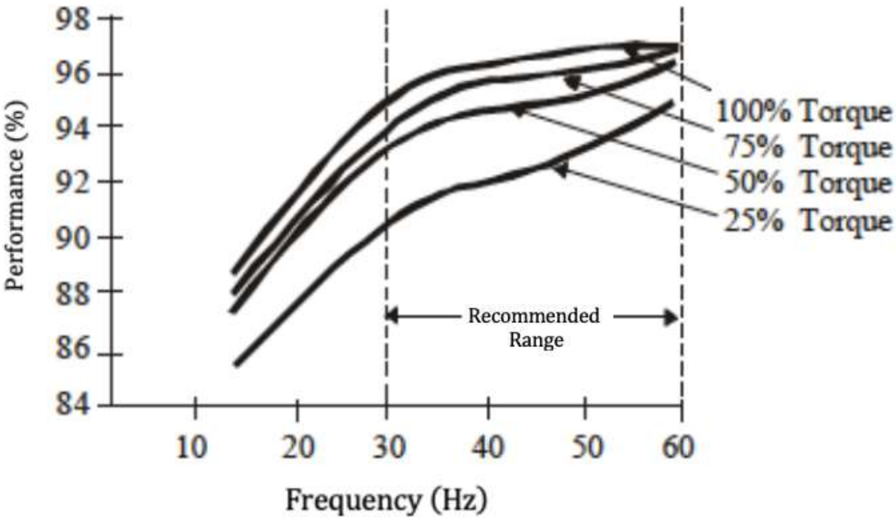


Figure 2.5: Recommended operating ranges for VSD

2.4 Cost reduction with VSD

According to researched literature, the main advantage of the use of VSDs in water supply systems is the saving of electricity. Even though Variable speed pumping has become more popular over the last years due to improvements in speed control technology for pumps and the reduction in the initial cost of the devices [5], it is still not used to its maximum potential since operators don't use it properly and most of the times only use to perform a smother start-stop. Even though it can perform a smoother start-stop and shutdown, using VSD systems can also provide the opportunity to save about 15 to 40% of the energy and extend equipment lifetime [12].
Lucarelli, Brucoli and Souza [13] studied in a theoretical way the direct pumping in the supply networks with variable speed pumps without distribution tank and obtained a reduction of the costs of implantation of the direct pumping of approximately 66% in relation to the cost of a system with high reservoir.
Altmann [14] reported the results of the application of VSDs installed in submersible pumps and booster stations in the city of New Hamburg, where was obtained from July 2004 a monthly energy savings of 62.3%.
Europump and Hydraulic Institute [1] claimed case studies where reductions in energy consumption ranging from 30 to 50% and an average return of investment of 12 months were obtained.
Sarbu presented a case study [15] to compare the efficiencies of different control methods (valve, start-stop and variable speed). The case study consists of a pumping station operating with 6 pumps of 12 NDS-1450 types in the water distribution system of a large urban center in Romania, which must guarantee the daily water supply of 172,800 m^3.
The obtained numerical results are based on the characteristic curves for different parallel-connected pump designs.They compared the specific energy consumption and the energy savings obtained during a 360-day operation period by applying throttling or rotational speed control and the classical control (start-stop).
They concluded that rotational speed control can save up to 20% when compared to the classical (start-stop) adjustment method and up to 8,4% when compared to throttle valve control.

Saidur, Mekhilef, Ali, Safari and Mohammed [2] state that currently VSDs are the most effective controller and energy saver for mechanical machines in industries, being affordable, reliable, flexible, and its use results in significant electrical energy savings.

Intentionally blank page.

Chapter 3

Method

3.1 Characteristic relations of centrifugal pumps

There are certain relationships that allow the characteristic curves of the pumps to be obtained for a different rotation from that whose characteristic curves are known. Other relationships allow the curves to be predicted for new curves of a pump if the diameter of the motor is reduced, within the limits depending on the type of pump.

3.1.1 Affinity Laws

Affinity laws (AL) are commonly used to predict these curves [16,17,18]. The AL state that pump flow, head and power can be described, respectively, by the following linear, quadratic and cubic equations:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} = \frac{1}{M} \Leftrightarrow Q_2 = MQ_1 \tag{3.1}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 = \frac{1}{M^2} \tag{3.2}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 = \frac{1}{M^3} \tag{3.3}$$

where N_1 and N_2 are the rotation speed of the pump, Q_1 and Q_2 are flow relative to pump rotation 1 and 2, H_1 and H_2 are the head relative to pump rotation, P_1 and P_2 are the power consumption of the pump relative to the pump speed, 1 and 2, respectively.
These relationships, known as affinity laws, are used to determine the theoretical effect of rotational variation on the flow, height, and power of a pump.
Figure 3 presents the affinity laws in a system whose pump varies its characteristics by the variation of its speed of rotation.

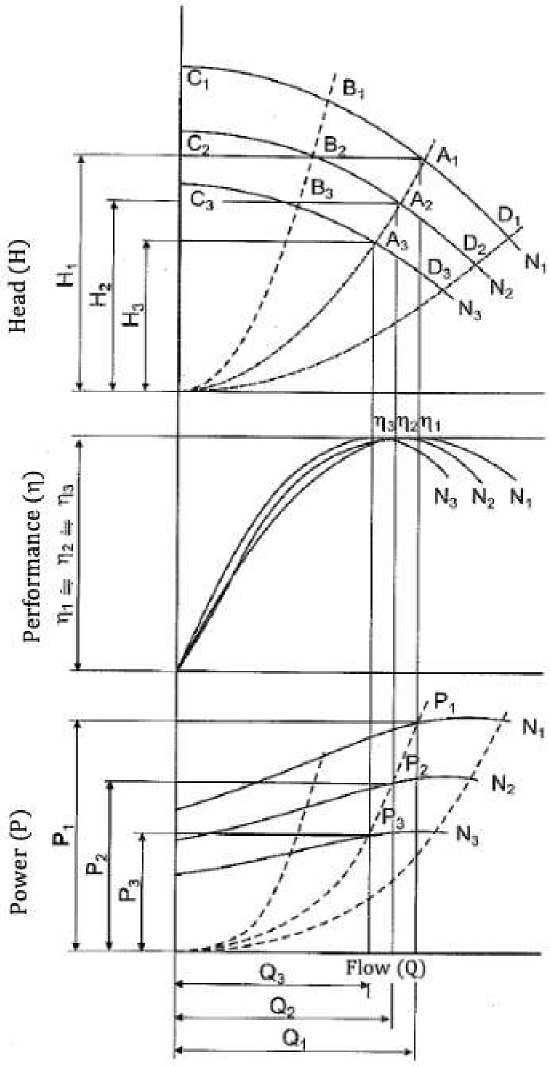


Figure 3.1: Variation of the speed characteristics by varying the rotation speed Source: Tsutiya (2004)

Considering the following standard hydraulic curve (in standard frequency **M**=1.0):

$$H_1 = a + bQ_1{}^n \tag{3.4}$$

the previous hydraulic entities can be calculated using the AL as:

$$H_2 = M^2\left(a + b\frac{Q_2{}^n}{M^n}\right) \tag{3.5}$$

$$\eta_2 = \eta_1(Q_1) = \eta_1\left(\frac{Q_2}{M}\right) \tag{3.6}$$

and

$$P_2 = M^3 P_1 = M^3\left(\rho g \frac{Q_1 H_1}{\eta_1}\right) = \rho g \frac{M^3 \frac{Q_2}{M} M^2 \left(a + b\frac{Q_2{}^n}{M^n}\right)}{\eta_1\left(\frac{Q_2}{M}\right)} = \rho g \frac{M^4\left(a + b\frac{Q_2{}^n}{M^n}\right)}{\eta_1\left(\frac{Q_2}{M}\right)} \tag{3.7}$$

3.1.2 Sárbu and Borza

Sárbu and Borza [19] proposed an equation describing the effect of the variation of speed on the efficiency of the pumps. Taking into consideration that below 50% of the full-speed [20] threshold, the reduction of efficiency often becomes more evident for smaller pumps.

$$\eta_2 = 1 - (1-\eta_1)\left(\frac{N_1}{N_2}\right)^{0.1} \tag{3.8}$$

where η_1 is the original efficiency, η_2 is the speed adjusted efficiency and N_1 and N_2 are the original and adjusted rotation speed of the pump, respectively. This equation is an approximation to the equation proposed by Gulich [21], Simpson and Marchi [22], and was originally introduced by Osterwalder and Hippe [23].

3.1.3 Coelho and Andrade-Campos

Coelho and Andrade-Campos [24] introduced later on an equation describing a graphical representation of the speed-adjusted efficiency similar to the curves proposed by Morton [20] and Sárbu and Borza [19]. The equation for the new efficiency is written as:

$$\left(\frac{\eta_2}{\eta_1}\right) = \left(\frac{N_2}{N_1} - 1\right)^3 + 1 = (M-1)^3 + 1 \tag{3.9}$$

where η_1 is the original efficiency, η_2 is the speed adjusted efficiency and N_1 and N_2 are the original and speed adjusted rotation speed of the pump, respectively.
The efficiency method proposed by CAC, represented in the equation above, approximates the results and observations presented by Morton[20] and Sárbu and Borza[19]. The improvement on this new method is that it never leads to negative efficiency values. Still, regardlees of the original efficiency considered, the dependency of the efficiency on the speed is unchanged, meaning that the speed adjusted curve is always the same independently of the original efficiency[24].
Knowing the original efficiency curve given by:

$$\eta_1 = \eta_1(Q_1), \tag{3.10}$$

where it can be defined by a polynomial function, the new CAC function is calculated as:

$$\eta_2 = \eta_1\left(\frac{Q_2}{M}\right)\left((M-1)^3 + 1\right) \tag{3.11}$$

3.2 Parallel Operation

In order to operate two pumps in parallel it is necessary to adjust the pump's head curves accordingly. The new head curve for the parallel operation can be calculated by the following equations:

$$H_{\text{par}} = H_1 = H_2, \tag{3.12}$$

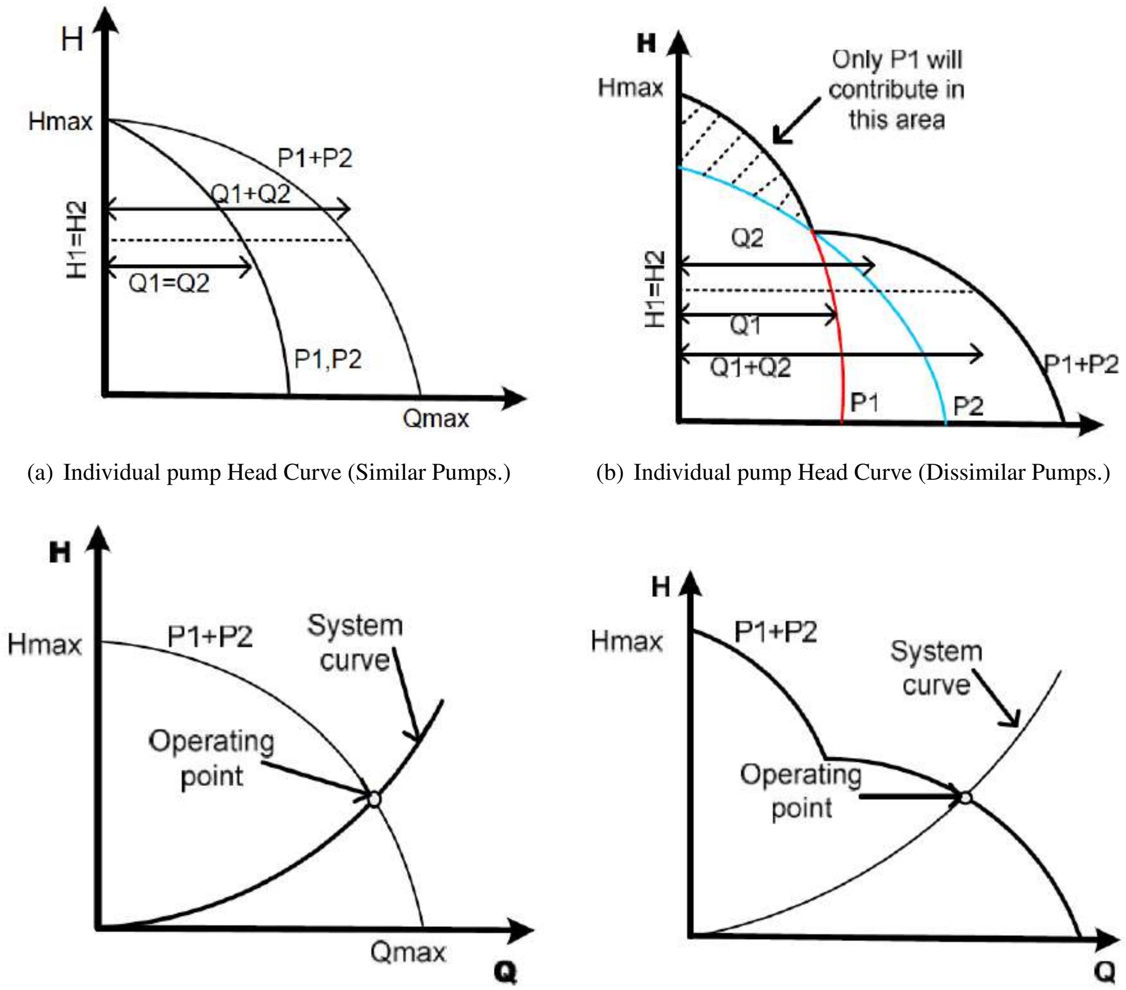
$$Q_{\text{par}} = Q_1 + Q_2. \tag{3.13}$$

When the pumps are dissimilar, the larger pump can operate alone. This happens in the area where $H_{larger\,pump}$ is bigger than $H_{smaller\,pump}$, as it can be seen highlighted in the figure 3.2. Then, making the curve for this specific area be:

$$H_{\text{par}} = H_1, \tag{3.14}$$

$$Q_{\text{par}} = Q_1, \tag{3.15}$$

where H_{par} is the Head for parallel operation, H_1 is Head curve for pump 1, H_2 is Head curve for pump 2, Q_{par} is Flow for parallel operation, Q_1 is Flow for pump 1 and Q_2 is Flow for pump 2. In figure 3.2 P_1 stands for Pump 1 and P_2 for Pump 2.



(a) Individual pump Head Curve (Similar Pumps.)

(b) Individual pump Head Curve (Dissimilar Pumps.)

(c) Resultant pump Head Curve with system curve (Similar Pumps.)

(d) Resultant pump Head Curve with system curve (Dissimilar Pumps.)

Figure 3.2: Head Curves with Parallel Operation. Adapted from [25]

3.3 VSD's Efficiency

To establish the energy savings that are possible when a VSD is applied to a system it's mandatory to consider the efficiency of the VSD, as well as the efficiency of the pump itself. Therefore, the efficiency of the whole system can be calculated as:

$$\eta_{\text{system}} = \eta_{\text{vsd}} \eta_{\text{pump}}. \tag{3.16}$$

That is, the efficiency of the system consists of the combination of the efficiency of the pump (already mentioned above) and the efficiency of the VSD. The VSD efficiency is calculated considering efficiency values representative of typical VSD performance, even though there is no widely accepted test protocol that allows for efficiency comparisons between different drive models or brands, and there are many ways to set up a VSD that can affect the operating efficiency. [26]

Table 3.1: VSD's Efficiency [26]

Variable Drive hp Rating	**Efficiency (%)**						
	Load, Percent of Drive Rated Power Output						
	1.6	**12.5**	**25**	**42**	**50**	**75**	**100**
5	35	80	88	91	92	94	95
10	41	83	90	93	94	95	96
20	47	86	93	94	95	96	97
30	50	88	93	95	95	96	97
50	46	86	92	95	95	96	97
60	51	87	92	95	95	96	97
75	47	86	93	95	96	97	97
100	55	89	94	95	96	97	97
200	61	81	95	96	96	97	97

To find the VSD efficiency value, it is necessary to first understand how to read table 3.1. In the case of a VSD with 200 variable drive horse power rating (suitable for this case) what the table tells us is that if we have a reduction of 50 % of the rotation speed, this means that only 1/8 ($(1/2)^3$) of the initial power is required, resulting in a VSD efficiency of 81 %.

Intentionally blank page.

Chapter 4

Case study, model and implementation

Here, the problem of minimizing the costs of pumping is addressed. A water supply subsystem is presented, where Variable Speed Drives are used. This system already has the most efficient pumping operation taking into account the required water consumptions and the deposit limit levels, being necessary to introduce variable speed drives in order to study their viability and efficiency for the case study.

4.1 Case Study: subsystem F

It is intended to minimize the cost of pumping for a supply subsystem which is composed of a tank F, a pump P and the consumption points VC and R as shown in the figure.

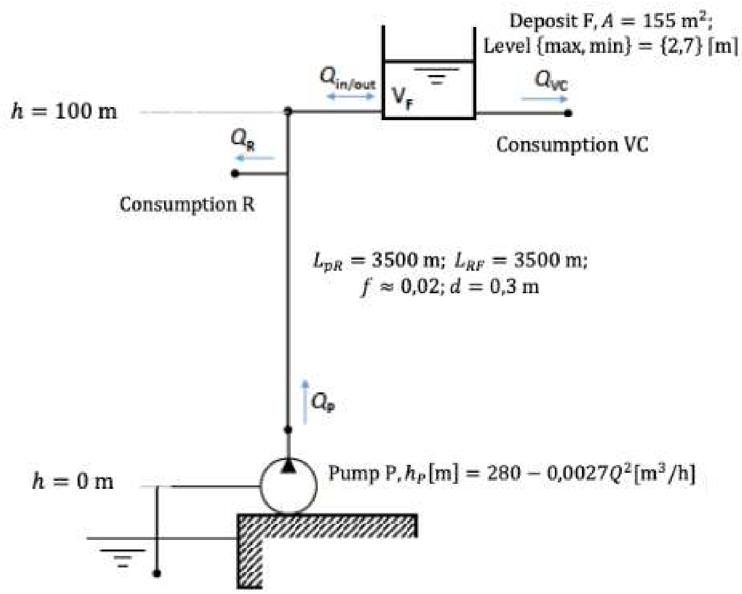


Figure 4.1: subsystem F scheme.

Deposit F is a reservoir which is at a height h of 100 m, has 155 m^2 of area A. For safety reasons, it can only operate between levels 2 and 7 m and, at the beginning of day, it presents a level of 4 m. The deposit F supplies consumers in the VC region. It also supplies consumers in the R region when the pump is not running, using the pipeline RF as return. The pump has the hydraulic curve:

$$h_{\mathrm{p}}[m] = 280 - 0,0027Q^2 \tag{4.1}$$

and the efficiency curve:

$$\eta = -1 \times 10^{-5} + 0.0093Q - 3 \times 10^{-5}Q^2. \tag{4.2}$$

The pump is at 0 m and is responsible for pumping water to the reservoir F and for consumers R. The ducts are made of cast iron, with a Fanning friction factor of f=0,02 , with lenghth L_{PR} =3,5 km and L_{RF}=6 km between the pump and consumption R, and between the consumption R and the reservoir F, respectively. Daily consumption of the VC and R regions was foreseen and are represented in Figure. The energy cost (tariff) varies throughout the day, as is listed in table 4.1.

Table 4.1: Tarif throughout the day [27].

Interval [h]	**Cost [€/kWh]**
[0, 2[	0,0737
[2, 6[	0,06618
[6, 7[	0,0737
[7, 9[	0,10094
[9, 12[	0,18581
[12, 24[	0,10094

The comsuptions throughout the day are defined by $Q_{VC} = -5.7280 \times 10^{-5}\, t^6 + 3.9382 \times 10^{-3}\, t^5 - 9.8402 \times 10^{-2}\, t^4 + 1.0477\, t^3 - 3.8621\, t^2 -1.1695\, t + 7.5393 \times 10^1$, $Q_R = - 0.004\, t^3 + 0.09\, t^2 + 0.1335\, t + 20$, as seen in figure 4.2.

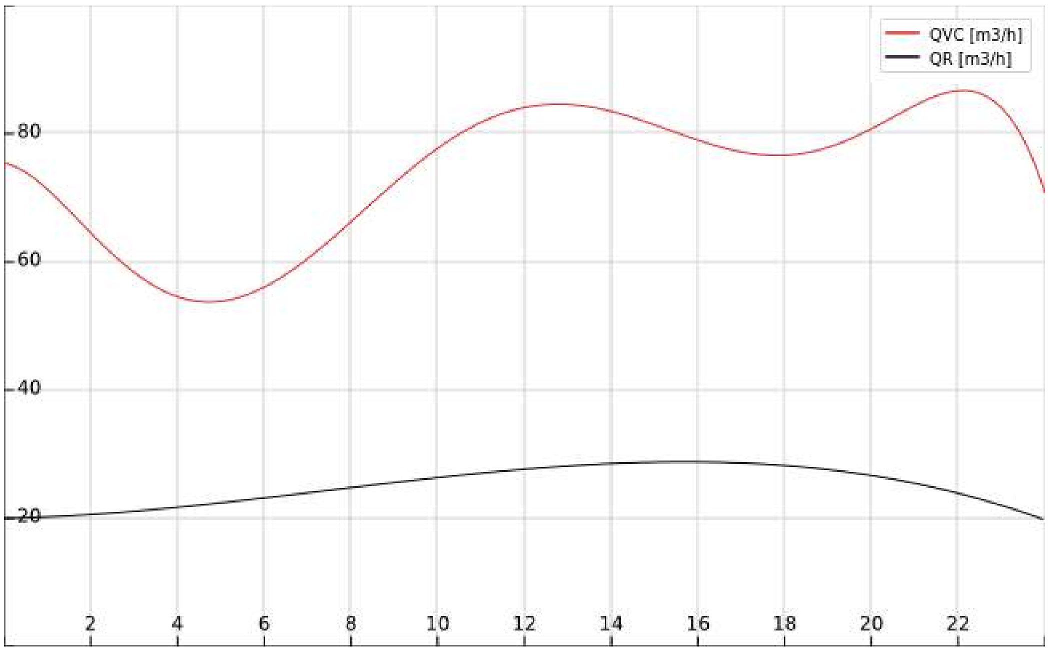


Figure 4.2: Comsuptions throughout the day.

4.1.1 Hydraulic system formulation

According to Figure 4.1, the mass balance equations in reservoir F and water pipeline PR can be written respectively as

$$\frac{dV_{\mathrm{F}}}{dt} = \frac{Q_{\mathrm{in}}}{Q_{\mathrm{out}}} - Q_{\mathrm{VC}}, and \tag{4.3}$$

$$Q_{\mathrm{P}} = Q_{\mathrm{R}} + \frac{Q_{\mathrm{in}}}{Q_{\mathrm{out}}}. \tag{4.4}$$

These can be aggregated into the following equation:

$$A_{\mathrm{F}} \frac{dh_{\mathrm{F}}}{dt} = Q_{\mathrm{P}} - Q_{\mathrm{R}} - Q_{\mathrm{VC}}, \tag{4.5}$$

where h_F and A_F are the height and area of reservoir F, respectively. The condition of energy balance in the pump operation is given by

$$h_{\mathrm{P}} - h_{\mathrm{PR\ losses}} - h_{\mathrm{RF\ losses}} = h_{\mathrm{F}} + h_{\mathrm{heightF}} \tag{4.6}$$

where $h_{heightF}$=100 m is the height of the deposit F. Knowing that the pump and load losses are given by the following hydraulic equations:

$$h_{\mathrm{P}} = a_1 + a_2 {Q_{\mathrm{P}}}^2 = 280 - 0,0027 {Q_{\mathrm{P}}}^2, \tag{4.7}$$

$$h_{\mathrm{losses}} = \frac{32 f L}{d^5 g \pi^2} Q^2, \tag{4.8}$$

then the equation takes the form:

$$a {Q_{\mathrm{P}}}^2 + b Q_{\mathrm{P}} + (c - h_{\mathrm{F}}) = 0, \tag{4.9}$$

with:

$$a = a_2 - \gamma L_{\mathrm{PR}} - \gamma L_{\mathrm{RF}} \tag{4.10}$$

$$b = 2 \gamma L_{\mathrm{RF}} Q_{\mathrm{R}} \tag{4.11}$$

$$c = a_1 - h_{\mathrm{heightF}} - \gamma L_{\mathrm{RF}} {Q_{\mathrm{R}}}^2 \tag{4.12}$$

$$\gamma = \frac{32 f}{d^5 g \pi^2}. \tag{4.13}$$

4.1.2 Case Study Optimization

The pump operation was previously optimized in order to minimize the cost of pumping. In the case of a simple hydraulic pump (yet without VSD), the pumping operation comes down to finding the periods of pump activity. Thus, **x** can take the following settings:

- Continuous variable **x** $\in$ [0,1] which represents the time fraction of operating time of the pump over a period of time Δt $\in$ [0,24] h;

- Binary variable **x** ∈ [0,1] which represents the pump state (on/off) over a period of time Δt ∈ [0,24] h.

Pump operating cost is a function of tariff energy, power W_P and pump efficiency η, and the pump state or operating time of the pump. This cost was formulated for one day of operation as:

$$C(x) = \int_0^{24h} \frac{W_P(Q,h)}{\eta} x(t) Tarif(t) dt. \tag{4.14}$$

Knowing that:

$$W_P = rgQ_P h_P, \tag{4.15}$$

and that the pump obeys the hydraulic equation:

$$h_P = a_1 + a_2 Q_P{}^2, \tag{4.16}$$

the operating cost can be written to a discrete sum of $n_{inc.t}$ periods of time that fill up the 24h in the following form:

$$C(x) = \sum_{i=1}^{n_{\text{int.t}}} \frac{\rho g}{\eta} (a_1 Q_{\text{P,i}} + a_2 Q_{\text{P,i}}{}^3) x_{\text{i}} Tarif_{\text{i}} \tag{4.17}$$

where $Q_{\text{P},i}$, $Tarif_{i,}$, and $\boldsymbol{x}_i$ are the average flow of the pump, the energy cost and the state / time of the pump in time period i, respectively.
In addition to the constraints of the variables, the problem must take into account the limit of the deposit levels:

$$2 \leq h_{\text{F}} \leq 7. \tag{4.18}$$

However, these constraints must be met for all the time periods throughout the day. For one time interval i, with i = 1,..., $n_{\text{inc.t}}$,

$$g_{\text{i}} = \begin{bmatrix} g_{1,i} \\ g_{2,i} \end{bmatrix} = \begin{bmatrix} 2 - h_{\text{F},i} \\ h_{\text{F},i} - 7 \end{bmatrix} \leq \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{4.19}$$

Integrating equation for a general time period i of duration Δt_i , the height of deposit F at the end of the increment is given by

$$h_{\text{F},i}(x_i) = h_{\text{F},i}(x_{i\text{-}1}) + \frac{1}{A_{\text{F}}} x_i Q_{\text{P},i} \Delta t_i - \beta, \tag{4.20}$$

Where β= $\int_{t_{i\text{-}1}}^{t_i} Q_{\text{VC}} \int_{t_{i\text{-}1}}^{t_i} Q_{\text{R}} dt$. Therefore, the problem can be formulated as:

Find the state/time x of pump operation P in order to:

Minimize $C(x)$ (4.21)

with $g_{\text{i}} \leq 0, i = 1, \ldots, n_{\text{inc.t}}$. (4.22)

In order to simplify the application of affinity laws, a variable **M** was introduced. This variable is defined as:

$$M = \frac{N_2}{N_1} \tag{4.23}$$

where N_2 is the new nominal speed and N_1 is the original nominal speed.Thus, the new curves (flow, head, efficiency and power) are defined as:

$$Q_2 = Q_1 M, \tag{4.24}$$

$$H_1 = a_1 + a_2 {Q_1}^2 \tag{4.25}$$

$$H_2 = M^2 a_1 + a_2 {Q_2}^2 \tag{4.26}$$

$$\eta_1 = b_1 + b_2 Q_1 + b_3 {Q_1}^2 \tag{4.27}$$

$$\eta_2 = (b_1 + b_2 \frac{Q_2}{M} + b_3 \frac{Q_2}{M}{}^2)((M-1)^3 + 1) \tag{4.28}$$

$$P_1 = \frac{\rho g}{\eta_1} H_1 Q_1 \tag{4.29}$$

$$P_2 = \left(\frac{\rho g}{\eta_2} H_1 \frac{Q_2}{M} \right) M^3 \tag{4.30}$$

4.1.3 Hydraulic system formulation with VSD

Knowing that the pump and load losses are given by the following hydraulic equations:

$$h_{\mathrm{P}} = M^2 a_1 + a_2 {Q_{\mathrm{P}}}^2 = M^2 280 - 0,0027 {Q_{\mathrm{P}}}^2, \tag{4.31}$$

$$h_{\mathrm{losses}} = \frac{32 f L}{d^5 g \pi^2} Q^2, \tag{4.32}$$

then the equations can be aggregated and take the form:

$$M^2 a_1 + a_2 {Q_{\mathrm{P}}}^2 - \gamma L_{\mathrm{PR}} Q^2 - \gamma L_{\mathrm{RF}} Q^2 - h_{\mathrm{F}} - h_{\mathrm{heightF}} = 0, \tag{4.33}$$

$$a {Q_{\mathrm{P}}}^2 + b Q_{\mathrm{P}} + (c - h_{\mathrm{F}}) = 0, \tag{4.34}$$

with:

$$a = a_2 - \gamma L_{\mathrm{PR}} - \gamma L_{\mathrm{RF}}, \tag{4.35}$$

$$b = 2 \gamma L_{\mathrm{RF}} Q_{\mathrm{R}}, \tag{4.36}$$

$$c = M^2 a_1 - h_{\mathrm{heightF}} - \gamma L_{\mathrm{RF}} {Q_{\mathrm{R}}}^2, \tag{4.37}$$

$$\gamma = \frac{32 f}{d^5 g \pi^2}. \tag{4.38}$$

4.1.4 Case Study Optimization with VSD

In order to optimize this system **M** can take the following settings:

- Continuous variable $\mathbf{M} \in [0.7\ ,1.2]$ which represents the ratio between the nominal speeds, operating over a period of time $\Delta t \in [0,24]$ h.

Pump operating cost is a function of tariff energy, power W_{P} and pump efficiency η, and the pump state or operating time of the pump. This cost was formulated for one day of operation as:

$$C(x) = \int_{0}^{24h} \frac{W_{\mathrm{P}}(Q,h)}{\eta_{\mathrm{system}}} x(t) Tarif(t) dt \tag{4.39}$$

Knowing that

$$W_{\mathrm{P}} = rgQ_{\mathrm{P}}M^2 h_{\mathrm{P}}, \tag{4.40}$$

and that the pump obeys the hydraulic equation

$$h_{\mathrm{P}} = M^2 a_1 + M^2 a_2 Q_{\mathrm{P}}{}^2. \tag{4.41}$$

The operating cost can be written to a discrete sum of $n_{\mathrm{inc,t}}$ periods of time that fill up the 24h in the following form:

$$C(x) = \sum_{i=1}^{n_{\mathrm{int.t}}} \frac{\rho g}{\eta} (M^2 a_1 Q_{\mathrm{P,i}} + M^2 a_2 Q_{\mathrm{P,i}}{}^3) x_{\mathrm{i}} Tarif_{\mathrm{i}} \tag{4.42}$$

where $Q_{\mathrm{P},i}$, Tarif$_{i,}$ and x$_i$ are the average flow of the pump P, the energy cost and the state / time of the pump in time period i, respectively.
The remaining constraints are given by equation 4.18 for any period of time during the day (equation 4.19). The height of deposit F at the end of the increment can be calculated as stated in equation 4.20.
Therefore, the problem can be formulated as:
Find the state/time **x** and **M** of pump P operation in order to:

$$\text{Minimize } C(\mathbf{x}) \tag{4.43}$$

$$\text{with } g_{\mathrm{i}} \leq 0, i = 1, ..., n_{\mathrm{inc.t}} \tag{4.44}$$

$$0.7 \leq M \leq 1.2 \tag{4.45}$$

$$0.0 \leq x \leq 1.0 \tag{4.46}$$

4.1.5 Parallel Operation with VSD

To operate two pumps in parallel with VSD it is necessary to adjust the pump's head curves, having in consideration the new points of operation. The new head curve for parallel operation can be calculated by the following equations:

$$\begin{cases} H_{\mathrm{par}} = M^2 a_1 + a_2 Q_1{}^2 \\ Q_{\mathrm{par}} = Q_1 + Q_2 = Q_1 + Q_1 M \end{cases} \tag{4.47}$$

With these equations it is possible to find points that belong to the parallel operating curve solving the system of non-linear equations. The system is solved using the substitution method.

The first equation can be solved for Q_1 for one specific desired H_{par}.

$$\begin{cases} Q_1 = \sqrt[2]{\frac{H_{\text{par}} - M^2 a1}{a2}} \\ Q_{\text{par}} = Q_1 + Q_1 M \end{cases} \tag{4.48}$$

Here two possible values are obtained for Q_1, being necessary to choose the most pertinent one. Then, solving the second equation of this system of equations the value for Q_{par} is found. It is then possible to discover the resulting curve through polynomial regression with multiple points found.
Subsequently, the operating points can be calculated, being the point of intersection of the parallel head curve with the system curve that dictates where the points of operation are located on the curve. The flow rate of the parallel operating points will then correspond to the sum of the flow rate of the intersection point of the parallel curve with the system curve plus the average distances that the original operating points have in relation to the intersection point of their own head curve with the system curve.
Finally, having found the operating points for parallel operation the equation 4.47 can be used, this time to know the corresponding operating points for each pump when using it in parallel.

Intentionally blank page.

Chapter 5

The approach

The goal is to evaluate the direct use of the VSD's in the subsystem explained above. The subsystem was modeled in python and the VSD's were introduced by applying the affinity laws, SB and CAC method directly in the code, also taking into account the increased energy consumption with the introduction of the VSD's. The use of VSD's to keep the rotational speed constant over time was evaluated, and subsequently the use of different rotational speeds over the different periods of time throughout the 24h period was optimized in order to evaluate different approaches to the same problem resulting in different solutions.
Realizing the goals to achieve and how to do it, several cases were studied. 3 different cases were created, each with different scenarios.

1. Case 1 is created to evaluate the use of VSD operation in different scenarios with different rotation speed, with **M** optimized and **M** and **x** optimized, over the 24 hour period.

2. Case 2 is created to evaluate the use of VSD operation with 2 similar pumps in parallel in different scenarios with different rotation speed, with **M** optimized and **M** and **x** optimized, over the 24 hour period..

3. Case 3 is is quite similar to case 2 but using 2 dissimilar pumps in different scenarios with different rotation speed, with **M** optimized and **M** and **x** optimized, over the 24 hour period..

The method proposed is similar for the 3 cases, with the difference being the need to find the operating points in parallel for cases 2 and 3. The study consists of evaluating its use in the 3 different cases, presented in table 5.1.

Table 5.1: Scenarios created.

Case	Scenario	Pump 1		Pump 2	
		M	**X**	**M**	**X**
1	A	1.0	1/0	-	-
	B	0.9	1/0	-	-
	C	optimized	1/0	-	-
	D	optimized	optimized	-	-
2	A	1.0	1/0	1.0	1/0
	B	1.0	1/0	0.9	1/0
	C	0.9	1/0	0.9	1/0
	D	optimized	1/0	optimized	1/0
	E	optimized	optimized	optimized	optimized
3	A	1.0	1/0	1.0	1/0
	B	1.0	1/0	0.9	1/0
	C	0.9	1/0	1.0	1/0
	D	0.9	1/0	0.9	1/0
	E	optimized	1/0	optimized	1/0
	F	optimized	optimized	optimized	optimized

5.1 Pump Curves

The following hydraulic curves are used in the 3 different case studies: **Case 1** : One Pump

$$H(m) = 280 - 0.0027Q^2 \tag{5.1}$$

$$\eta = -1 \times 10^{-15} + 0.0093Q - 3 \times 10^{-5}Q^2 \tag{5.2}$$

Case 2: Two Pumps in Parallel (equal pumps)

$$H_1(m) = H_2(m) = 280 - 0.0027{Q_1}^2 \tag{5.3}$$

$$\eta_1 = \eta_2 = -1 \times 10^{-15} + 0.0093Q_1 - 3 \times 10^{-5}{Q_1}^2 \tag{5.4}$$

Case 3 : Two Pumps in Parallel (one smaller pump acting as a backup)

$$H_1(m) = 280 - 0.0027{Q_1}^2 \tag{5.5}$$

$$\eta_1 = \eta_2 = -1 \times 10^{-15} + 0.0093Q_1 - 3 \times 10^{-5}{Q_1}^2 \tag{5.6}$$

$$H_2(m) = 220 - 0.0027{Q_2}^2 \tag{5.7}$$

5.2 Application

All the scenarios presented above were modeled in python. In order for this document not to become too exhaustive, two chosen models are presented with the criterion of covering all the variables present in the different cases. Thus, scenario D in case 1 and scenario F in case 3 are presented in detail. Both cases use the CAC method.

5.2.1 Case 1 - Scenario D

The following list presents the flowchart of the model:

1. To start it is necessary to create 24 increments that represent one hour each and define **x** and **M**.

2. The consumptions are defined (see figure 4.2).

3. The tarif for each increment si defined (see table 4.1).

4. Set constants: $g = 9.81$; density = 1000.0; $h_{\text{min}} = 2.0$; $h_{\text{max}} = 7.0$; $h_{\text{fixo}} = 100.0$; $A_{\text{F}} = 155.0$; $V_0 = 620.0$; $h_{F0} = 4.0$; $\text{delta}_{hF} = 0.0$; $L_{PR} = 3500$; $L_{RF} = 6000$; f = 0.02; d= 0.3;

5. Set pump curve's information (equations: 5.1,5.2).

6. Set constant variables:

$$f32gpi2d5 = 32.0 \times \frac{f}{g\pi^2 d^5} \tag{5.8}$$

   $a_{\text{Res1}} = a_2 \times 3600^2$; $a_{\text{Res2}} = -$ f32gpi2d5 $\times L_{PR}$ - f32gpi2d5 $\times L_{RF}$; $a_{\text{Res}} = a_{\text{Res1}} + a_{\text{Res2}}$; $h_{\text{Fini}} = h_F$; $h_{\text{Fmed}} = h_F$; $\text{delta}_{\text{hFold}} = 0$;

$$b_{\text{Res}} = \frac{2 \times f32gpi2d5 \times L_{\text{RF}} \times Q_{\text{Rmed}}}{3600} \tag{5.9}$$

$$c_{\text{Res}} = a_1 - h_{\text{Fixo}} - f32gpi2d5 \times L_{\text{RF}} \times \left(\frac{Q_{\text{Rmed}}}{3600}\right)^2 - h_{\text{Fmed}} \tag{5.10}$$

7. Then, finally it is possible to obtain the operations points for **M** = 1.0:

$$Q_{\text{paux1}}[i] = \frac{-b_{\text{Res}} - \sqrt[2]{b_{\text{Res}}{}^2 - 4 \times a_{\text{Res}} \times c_{\text{Res}}}}{2 \times 3600 \times a_{\text{Res}}} \tag{5.11}$$

$$h_{\text{aux1}}[i] = a1 + a2 \times Q_{\text{paux1}}[i]^2 \tag{5.12}$$

$$\eta_{\text{Paux1}}[i] = b1 + b2 \times Q_{\text{paux1}} + b3 \times Q_{\text{paux1}}[i]^2 \tag{5.13}$$

$$W_{\text{Paux1}}[i] = g \times \frac{density}{\eta_{\text{Paux1}}[i]} \times \frac{Q_{\text{paux1}}[i]}{3600} \times (a1 + a2 \times Q_{\text{paux1}}[i]^2) \tag{5.14}$$

8. Using AL, SB method or CAC method it's possible to get the operations points for the desired **M**:

$$Q_{\text{pauxal1}}[i] = \left(\frac{-b_{\text{Res}} - \sqrt[2]{{b_{\text{Res}}}^2 - 4 \times a_{\text{Res}} \times c_{\text{Res}}}}{2 \times 3600 \times a_{\text{Res}}} \right) \times M[i] \tag{5.15}$$

$$h_{\text{auxal1}}[i] = M[i]^2 \times a1 + a2 \times Q_{\text{pauxal1}}[i]^2 \tag{5.16}$$

$$\eta_{\text{Pauxal1}}[i] = \frac{g \times density \times Q_{\text{pauxal1}}[i] \times (M[i]^2 \times a1 + a2 \times Q_{\text{pauxal1}}[i]^2)}{(g \times density \times Q_{\text{paux1}}[i] \times (a1 + a2 \times Q_{\text{paux1}}[i]^2)) \times M[i]^3} \tag{5.17}$$

$$\eta_{\text{PSB1}}[i] = 1 - (1 - (b1 + b2 \times Q_{\text{paux1}} + b3 \times Q_{\text{paux1}}[i]^2)) \times \left(\frac{1}{M[i]} \right)^{0.1} \tag{5.18}$$

$$\eta_{\text{PCAC1}}[i] = (b1 + b2 \times Q_{\text{paux1}} + b3 \times Q_{\text{paux1}}[i]^2) \times ((M[i] - 1)^3 + 1) \tag{5.19}$$

$$W_{\text{Pauxal1}}[i] = (g \times \frac{density}{\eta_{\text{PCAC1}}[i]} \times \frac{Q_{\text{paux1}}[i]}{3600} \times (a1 + a2 \times Q_{\text{paux1}}[i]^2)) \times M[i]^3 \tag{5.20}$$

9. Introduce table 3.1 as a function "efficiency$_{\text{vsd}}$" and use interpolate from python to get VSDs efficiency value, in order to obtain the system performance (equation 3.10).

10. Calculate the cost (equation 4.13)

11. Optimize using python's "minimize", in order to obtain the minimum value of **x** and **M** taking into account the constraints introduced.

5.2.2 Case 3 - Scenario F

The following list presents the flowchart of the model for parallel operation:

1. To start it is necessary to create 24 increments that represent one hour each and define $\mathbf{x}_1$, $\mathbf{x}_2$, $\mathbf{M}_1$ and $\mathbf{M}_2$.

2. The consumptions are defined (see figure 4.2).

3. The tarif for each increment is defined (see table 4.1).

4. Set constants (same as point 4 in the previous scenario for case 1)

5. Set pump curve's information (equations: 5.7,5.8,5.9,5.10).

6. Set system curve as a function of flow:

$$Sys(Q) = k \times Q^2 \tag{5.21}$$

   where, k = constants describing the total system characteristics - including major and minor losses.

7. Set constant variables (same as point 6 in the previous scenario for case 1). Adding only the following equations for pump 2: $a_{Res12} = a_{22} \times 3600^2$; $a_{Res22} = a_{Res12} + a_{Res2}$;

$$c_{\text{Res2}} = a_{11} - h_{\text{Fixo}} - f32gpi2d5 \times L_{\text{RF}} \times \left(\frac{Q_{\text{Rmed}}}{3600}\right)^2 - h_{\text{Fmed}} \tag{5.22}$$

8. Then, finally it is possible to obtain the operations points for **M** = 1.0:

$$Q_{\text{paux1}}[i] = \frac{-b_{\text{Res}} - \sqrt[2]{b_{\text{Res}}{}^2 - 4 \times a_{\text{Res}} \times c_{\text{Res}}}}{2 \times 3600 \times a_{\text{Res}}} \tag{5.23}$$

$$Q_{\text{paux2}}[i] = \frac{-b_{\text{Res}} - \sqrt[2]{b_{\text{Res}}{}^2 - 4 \times a_{\text{Res22}} \times c_{\text{Res2}}}}{2 \times 3600 \times a_{\text{Res22}}} \tag{5.24}$$

$$h_{\text{aux1}}[i] = a1 + a2 \times Q_{\text{paux1}}[i]^2 \tag{5.25}$$

$$h_{\text{aux2}}[i] = a11 + a22 \times Q_{\text{paux2}}[i]^2 \tag{5.26}$$

$$\eta_{\text{Paux1}}[i] = b1 + b2 \times Q_{\text{paux1}} + b3 \times Q_{\text{paux1}}[i]^2 \tag{5.27}$$

$$\eta_{\text{Paux2}}[i] = b11 + b22 \times Q_{\text{paux2}} + b33 \times Q_{\text{paux2}}[i]^2 \tag{5.28}$$

$$W_{\text{Paux1}}[i] = g \times \frac{density}{\eta_{\text{Paux1}}[i]} \times \frac{Q_{\text{paux1}}[i]}{3600} \times (a1 + a2 \times Q_{\text{paux1}}[i]^2) \tag{5.29}$$

$$W_{\text{Paux2}}[i] = g \times \frac{density}{\eta_{\text{Paux2}}[i]} \times \frac{Q_{\text{paux2}}[i]}{3600} \times (a11 + a22 \times Q_{\text{paux2}}[i]^2) \tag{5.30}$$

9. At this point, using AL, SB method or CAC method it's possible to get the operations points for the desired **M**:

$$Q_{\text{pauxal1}}[i] = \left(\frac{-b_{\text{Res}} - \sqrt[2]{b_{\text{Res}}{}^2 - 4 \times a_{\text{Res}} \times c_{\text{Res}}}}{2 \times 3600 \times a_{\text{Res}}}\right) \times M[i] \tag{5.31}$$

$$Q_{\text{pauxal2}}[i] = \left(\frac{-b_{\text{Res}} - \sqrt[2]{b_{\text{Res}}{}^2 - 4 \times a_{\text{Res22}} \times c_{\text{Res2}}}}{2 \times 3600 \times a_{\text{Res22}}}\right) \times M_2[i] \tag{5.32}$$

$$h_{\text{auxal1}}[i] = M[i]^2 \times a1 + a2 \times Q_{\text{pauxal1}}[i]^2 \tag{5.33}$$

$$h_{\text{auxal2}}[i] = M_2[i]^2 \times a11 + a22 \times Q_{\text{pauxal2}}[i]^2 \tag{5.34}$$

$$\eta_{\text{Pauxal1}}[i] = \frac{g \times density \times Q_{\text{pauxal1}}[i] \times (M[i]^2 \times a1 + a2 \times Q_{\text{pauxal1}}[i]^2)}{(g \times density \times Q_{\text{paux1}}[i] \times (a1 + a2 \times Q_{\text{paux1}}[i]^2)) \times M[i]^3} \tag{5.35}$$

$$\eta_{\text{Pauxal2}}[i] = \frac{g \times density \times Q_{\text{pauxal2}}[i] \times (M_2[i]^2 \times a11 + a22 \times Q_{\text{pauxal2}}[i]^2)}{(g \times density \times Q_{\text{paux2}}[i] \times (a11 + a22 \times Q_{\text{paux2}}[i]^2)) \times M_2[i]^3} \tag{5.36}$$

$$\eta_{\text{PSB1}}[i] = 1 - (1 - (b1 + b2 \times Q_{\text{paux1}} + b3 \times Q_{\text{paux1}}[i]^2)) \times \left(\frac{1}{M[i]}\right)^{0.1} \tag{5.37}$$

$$\eta_{\text{PSB2}}[i] = 1 - (1 - (b11 + b22 \times Q_{\text{paux2}} + b33 \times Q_{\text{paux2}}[i]^2)) \times \left(\frac{1}{M_2[i]}\right)^{0.1} \tag{5.38}$$

$$\eta_{\text{PCAC1}}[i] = (b1 + b2 \times Q_{\text{paux1}} + b3 \times Q_{\text{paux1}}[i]^2) \times ((M[i]-1)^3 + 1) \tag{5.39}$$

$$\eta_{\text{PCAC2}}[i] = (b11 + b22 \times Q_{\text{paux2}} + b33 \times Q_{\text{paux2}}[i]^2) \times ((M_2[i]-1)^3 + 1) \tag{5.40}$$

$$W_{\text{Pauxal1}}[i] = (g \times \frac{density}{\eta_{\text{PCAC1}}[i]} \times \frac{Q_{\text{paux1}}[i]}{3600} \times (a1 + a2 \times Q_{\text{paux1}}[i]^2)) \times M[i]^3 \tag{5.41}$$

$$W_{\text{Pauxal2}}[i] = (g \times \frac{density}{\eta_{\text{PCAC2}}[i]} \times \frac{Q_{\text{paux2}}[i]}{3600} \times (a11 + a22 \times Q_{\text{paux2}}[i]^2)) \times M_2[i]^3 \tag{5.42}$$

10. To achieve the head curve for parallel, some points were chosen at random. These points can be obtained according to the following equations: $H_{par} = H_1 = H_2$, $Q_{par} = Q_1 + Q_2$. After obtaining these points, the "polyfit" python tool is used to obtain the expression for the head curve for parallel operation.

11. Find intersection between the system curve and parallel head curve in order to find the parallel points of operation. Since at the point of intersection, the two equations will have the same value for H and Q, this point is possible to find by setting the two equations equal to each other, resulting into an equation that can be solved for Q.

12. It is then calculated the point of intersection between the head curve for parallel operation with the head curve of the smallest pump in operation, in order to obtain the point that determines the operation in parallel. Hence, if the flow in the operating point is greater than the flow intersection point between these 2 curves, then it is known that only the largest pump is operating, while if the flow rate is greater, the two pumps will be operating in parallel. To obtain the operating points in parallel at this point it's simple since the operating points are already known with the pumps at **M** = 1.0, as the system curve and the head curve for parallel operation.

13. Obtaining the Q_{par} and H_{par} points, it is necessary to find the corresponding points for each pump. Using an if cycle in python, it is determined at this point that if Q_{par} is less than $Q_{\text{intersection point}}$ then $Q_{par} = Q_1$, if this does not occur, the points for each pump are determined using a system of equations with 3 equations:

$$\begin{cases} H_{\text{par}} = H_1 = H_2 \\ Q_{\text{par}} = Q_1 + Q_2 \\ H_1 = a1 + a2 \times Q_1{}^2 \end{cases} \tag{5.43}$$

In this way, operating points are obtained for parallel operation for all increments, knowing when the two pumps are running or just one. From this point on, the process is in all resembles that of the other cases. Having new operating points, it is now necessary to calculate their efficiencies and power. The operation points are re-calculated using the equations mentioned above, for each variable (η_{Pauxal1} [i], η_{Pauxal2} [i], η_{PSB1} [i], η_{PSB2} [i], η_{PCAC1} [i], η_{PCAC2} [i], W_{Pauxal1} [i], W_{Pauxal2} [i]), having in consideration the new values of flow and head obtained for parallel operation.

14. Introduce table 3.1 as 2 different functions (one for each pump) "efficiency$_{1vsd}$", "efficiency$_{2vsd}$" and use interpolate from python to get VSDs efficiency value for each pump (equation 3.10).

15. Calculate the cost for each increment (equation 4.33).

16. Optimize using python's "minimize", in order to obtain the minimum value of $\mathbf{x}_1$, $\mathbf{x}_2$, $\mathbf{M}_1$, $\mathbf{M}_2$ taking into account the constraints introduced.

5.3 Results Summary

Table 5.2: Results Summary for Case 1

	Scenario	Cost	Savings (%)	Savings (% €/ m^3)
	A (**M** = 1.0)	153.121	-	-
AL	B (**M**=0.9)	111.770	27.005	19.066
AL	C (**M** optimized)	100.965	34.062	24.946
AL	D (**M** & **x** optimized)	64.194	58.076	51.343
SB	B (**M**=0.9)	112.384	26.604	18.621
SB	C (**M** optimized)	101.608	33.642	24.468
SB	D (**M** & **x** optimized)	65.367	57.310	50.454
CAC	B (**M**=0.9)	111.882	26.932	18.985
CAC	C (**M** optimized)	101.399	33.779	24.624
CAC	D (**M** & **x** optimized)	65.928	56.944	50.029

Table 5.3: Results Summary for Case 2

	Scenario	Cost	Savings (%)	Savings (% €/ m^3)
	A (Both Pumps, **M** = 1.0)	139.519	-	-
AL	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	120.906	13.341	6.403
AL	C (Both Pumps, **M** = 0.9)	101.150	27.501	18.109
AL	D (Both Pumps, **M** optimized)	65.574	53.000	60.972
AL	E (Both Pumps, **M** & **x** optimized)	59.109	57.633	63.934
SB	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	121.215	13.119	6.164
SB	C (Both Pumps, **M** = 0.9)	101.607	27.173	17.738
SB	D (Both Pumps, **M** optimized)	66.764	52.147	60.264
SB	E (Both Pumps, **M** & **x** optimized)	60.327	56.761	63.203
CAC	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	120.953	13.307	6.367
CAC	C (Both Pumps, **M** = 0.9)	101.251	27.428	18.027
CAC	D (Both Pumps, **M** optimized)	66.796	52.124	60.245
CAC	E (Both Pumps, **M** & **x** optimized)	60.249	56.817	63.341

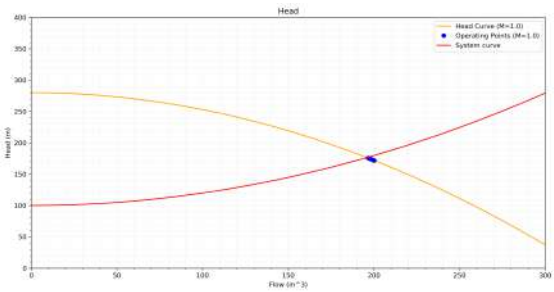
Table 5.4: Results Summary for Case 3

	Scenario	Cost	Savings (%)	Savings (% €/ m^3)
	A (Both Pumps, **M** = 1.0)	128.795	-	-
AL	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	117.437	8.819	-1.978
AL	C (Pump 1 **M** = 0.9, Pump 2 **M** = 1.0)	106.392	17.394	13.617
AL	D (Both Pumps, **M** = 0.9)	93.176	27.655	17.350
AL	E (Both Pumps, **M** optimized)	65.209	49.370	61.967
AL	G (Both Pumps, **M** & **x** optimized)	61.570	52.195	64.133
SB	F (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	119.006	7.600	-3.342
SB	C (Pump 1 **M** = 0.9, Pump 2 **M** = 1.0)	99.099	23.057	19.539
SB	D (Both Pumps, **M** = 0.9)	93.787	27.181	16.808
SB	E (Both Pumps, **M** optimized)	65.959	48.787	61.529
SB	F (Both Pumps, **M** & **x** optimized)	63.044	51.051	63.245
CAC	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	117.468	8.795	-2.006
CAC	C (Pump 1 **M** = 0.9, Pump 2 **M** = 1.0)	98.925	23.192	19.681
CAC	D (Both Pumps, **M** = 0.9)	93.269	27.583	17.267
CAC	E (Both Pumps, **M** optimized)	66.286	48.534	61.338
CAC	F (Both Pumps, **M** & **x** optimized)	63.164	50.957	63.191

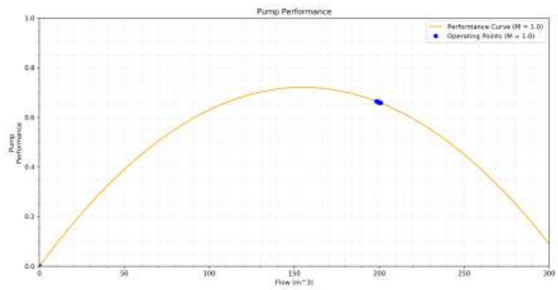
5.4 Graphic Results

Case 1 - Scenario A

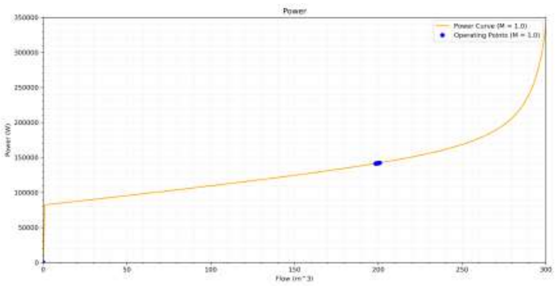
The scenario A is created with the objective of being a reference case. The system in this scenario only works with a pump operating at its original speed, using start-stop during the day, being switched off at the hours of the day where there is less consumption. Having an average efficiency for the pump of 0.661 and a total cost of 153,121 euros, it is the ideal case to work as a basis of comparison for the other scenarios created. It is interesting the changes occurred when applying VSDs, not only in final cost but taking into account all points of interest in the study. Figure 5.1 presents the results for case 1, scenario A.



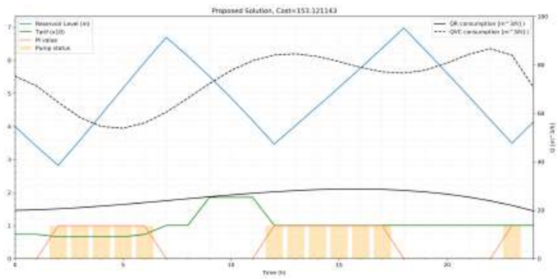
(a) Head Curve, Case 1 - Scenario A



(b) Performance Curve, Case 1 - Scenario A



(c) Power Curve, Case 1 - Scenario A



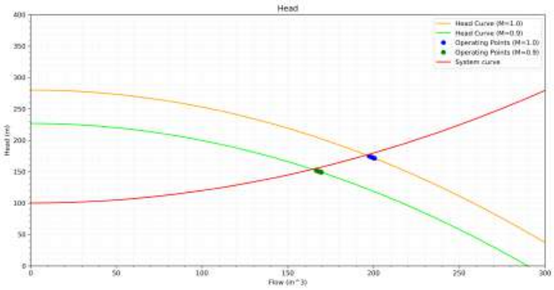
(d) Resume, Case 1 - Scenario A

Figure 5.1: Case 1 - Scenario A

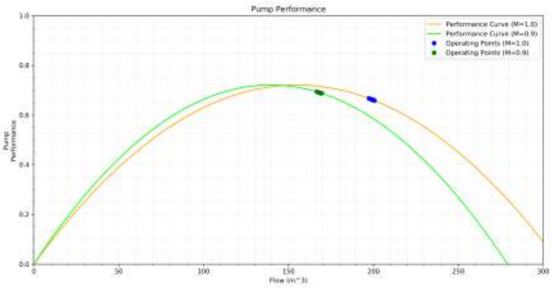
Case 1 - Scenario B - AL

Scenario B for case 1 is created in order to simulate the manual introduction of the VSD by establishing a rotation speed equal to 0.9 of the original. The operating time of the pump is kept unchanged and in the same time spaces in order to become comparable to scenario A, with only the rotation speed being changed.

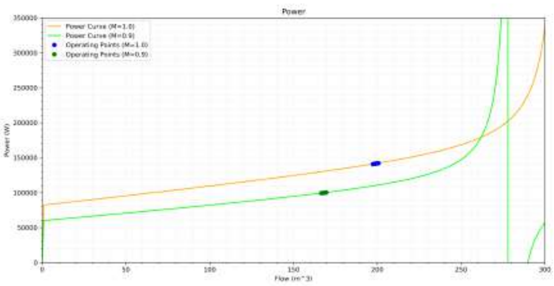
Analyzing the results, it can be seen that the average pump efficiency is practically unchanged, going from 0.661 to 0.660 but there is already a reduction of the average pump power around 27 percent. It also appears that less energy is needed to pump one cubic meter of water, dropping from 29,618 to 23,968 kWh/m^3. This reduction in energy consumed is reduced by 19,066 percent in the price for each cubic meter of water pumped. This scenario then helps us to conclude that for relatively small and oversized systems the use of VSDs can be relatively straightforward and intuitive, to a certain extent. Figure 5.2 presents the results for case 1, scenario B - AL.



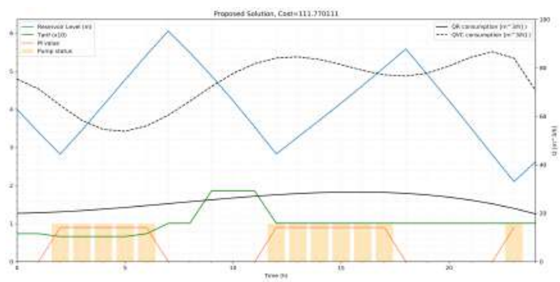
(a) Head Curve, Case 1 - Scenario B - AL



(b) Performance Curve, Case 1 - Scenario B - AL



(c) Power Curve, Case 1 - Scenario B - AL



(d) Resume, Case 1 - Scenario B - AL

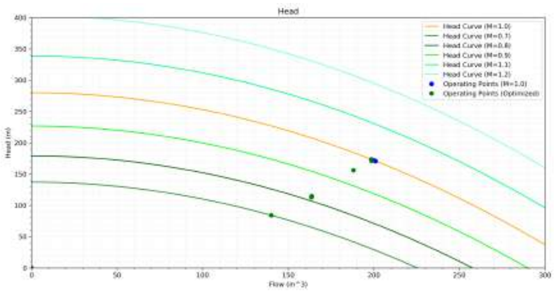
Figure 5.2: Case 1 - Scenario B - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

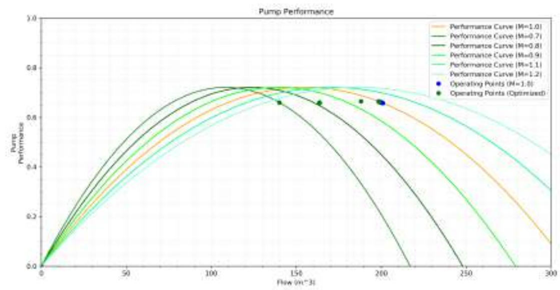
Case 1 - Scenario C - AL

Scenario C for case 1 is created to study how variable speed drives can be used to their maximum potential, using an algorithm to minimize the speed of rotation of the pump throughout the day. Here, as in the previous case, the pump's operating time is kept unchanged so that only the results from manipulating the pump's rotation speed are observed.

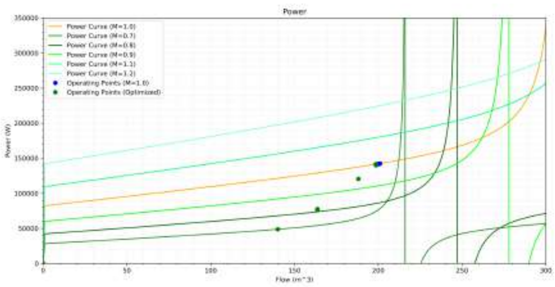
In this scenario, even though punctual values of higher energy consumption are reached with the maximum value being 141165.372 kWh, the average value is lower due to the fact that the pump rotation can be changed depending on the energy tariff throughout the day. This results in savings of around 25 percent in the price for one cubic meter of water pumped. Figure 5.3 presents the results for case 1, scenario C - AL.



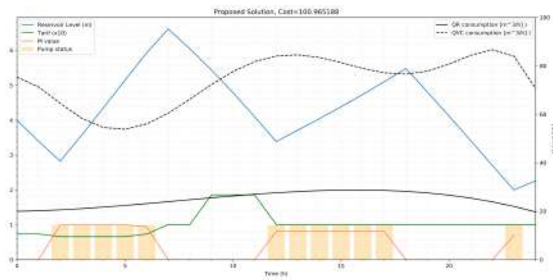
(a) Head Curve, Case 1 - Scenario C - AL



(b) Performance Curve, Case 1 - Scenario C - AL



(c) Power Curve, Case 1 - Scenario C - AL



(d) Resume, Case 1 - Scenario C - AL

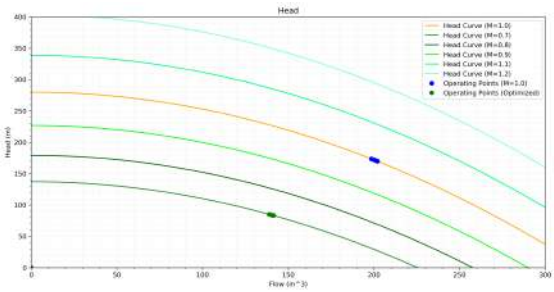
Figure 5.3: Case 1 - Scenario C - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

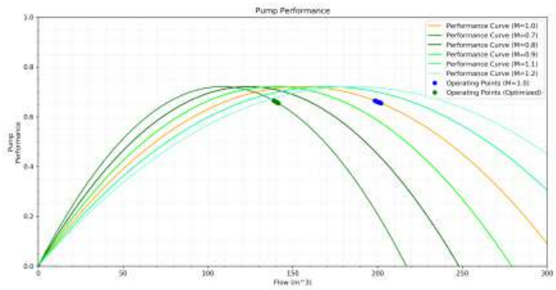
Case 1 - Scenario D - AL

Scenario D is created to show the theoretically most effective case, to optimize the speed of rotation and also the operating time. Although this case is the one with the best results, these results are misleading because in reality constantly turning the pump on and off is not a viable option.

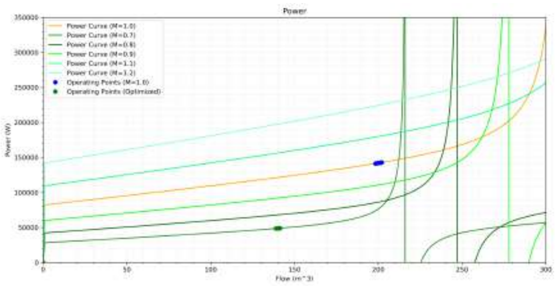
In this "perfect" case, the energy savings figures show savings results of around 50 percent in kWh/m^3. Figure 5.4 presents the results for case 1, scenario D - AL.



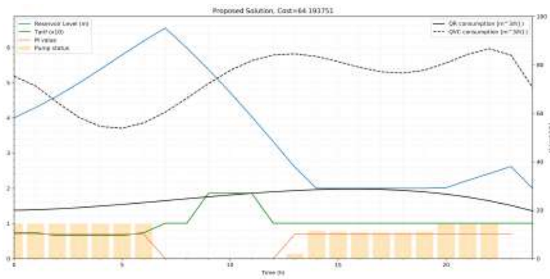
(a) Head Curve, Case 1 - Scenario D - AL



(b) Performance Curve, Case 1 - Scenario D - AL



(c) Power Curve, Case 1 - Scenario D - AL



(d) Resume, Case 1 - Scenario D - AL

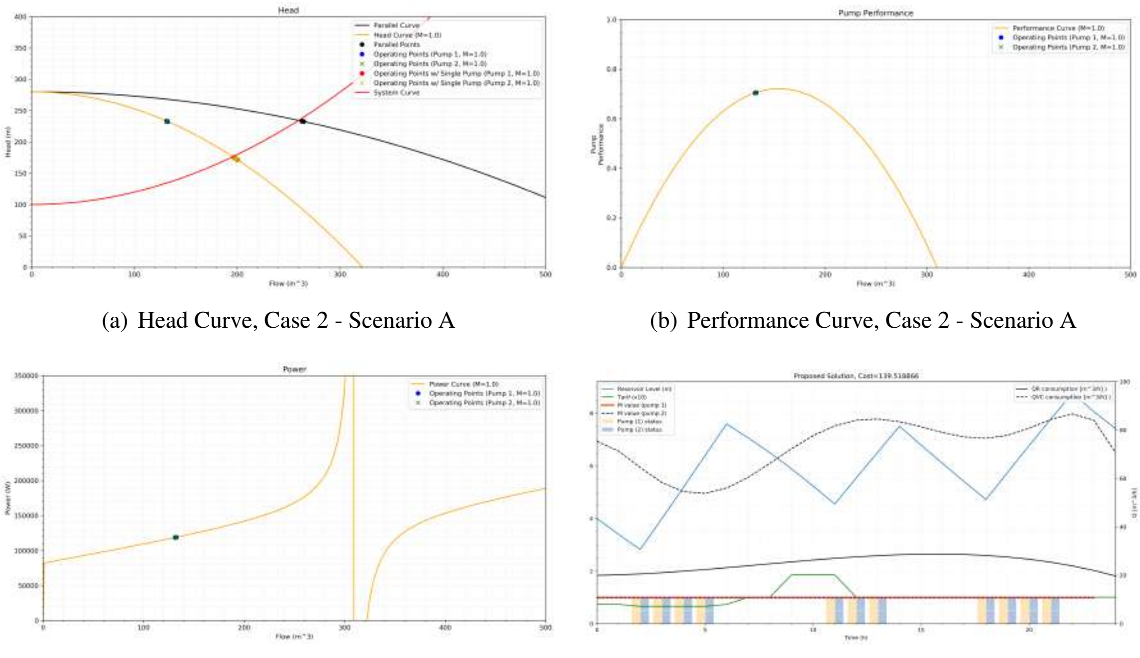
Figure 5.4: Case 1 - Scenario D - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

Case 2 - Scenario A

For case 2, a new pump is added, so we have two identical pumps in operation. This case is added to be able to observe the changes that can be obtained by changing the rotation speed of 2 pumps simultaneously. In order to try to conclude whether the use of VSDs is also beneficial for these cases.

This scenario is created with the objective of being a reference case for the remaining scenarios created for this case. The system in this scenario works with two identical pumps at the same time, both operating at their original speed, using start-stop during the day, being switched off at the hours of the day where there is less consumption. In this scenario the price per cubic meter is 4.806 €$\times$ 10^{-2} and the final cost is 139.519 €. Figure 5.5 presents the results for case 2, scenario A.



(a) Head Curve, Case 2 - Scenario A

(b) Performance Curve, Case 2 - Scenario A

(c) Power Curve, Case 2 - Scenario A

(d) Resume, Case 2 - Scenario A

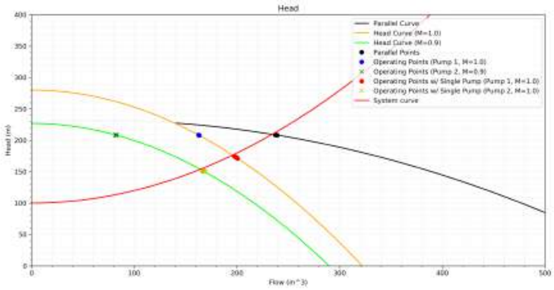
Figure 5.5: Case 2 - Scenario A

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

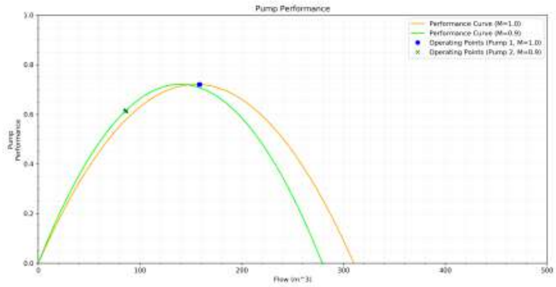
Case 2 - Scenario B - AL

Scenario B for case 2 is created in order to simulate the manual introduction of the VSD by establishing a rotation speed equal to 0.9 of the original for only one of the pumps. The operating time of the pumps is kept unchanged and in the same time spaces in order to become comparable to scenario A, with only the rotation speed being changed.

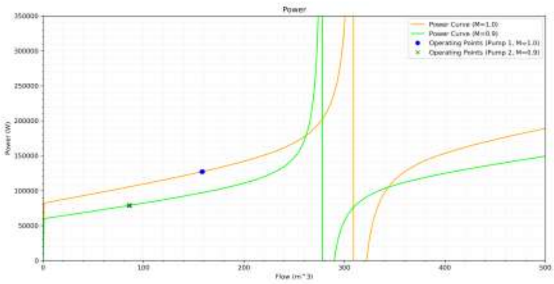
This scenario leads to a small reduction in energy consumption going from 37,531 from scenario A to 35,128 kWh/m^3, resulting in 6 percent savings in the price for m^3. Figure 5.6 presents the results for case 2, scenario B - AL.



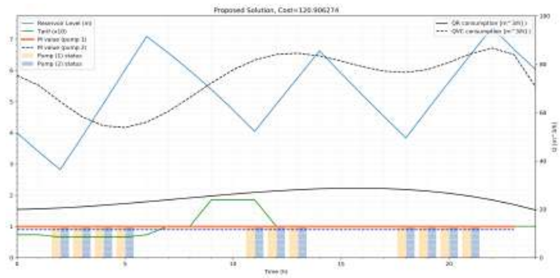
(a) Head Curve, Case 2 - Scenario B - AL



(b) Performance Curve, Case 2 - Scenario B - AL



(c) Power Curve, Case 2 - Scenario B - AL



(d) Resume, Case 2 - Scenario B - AL

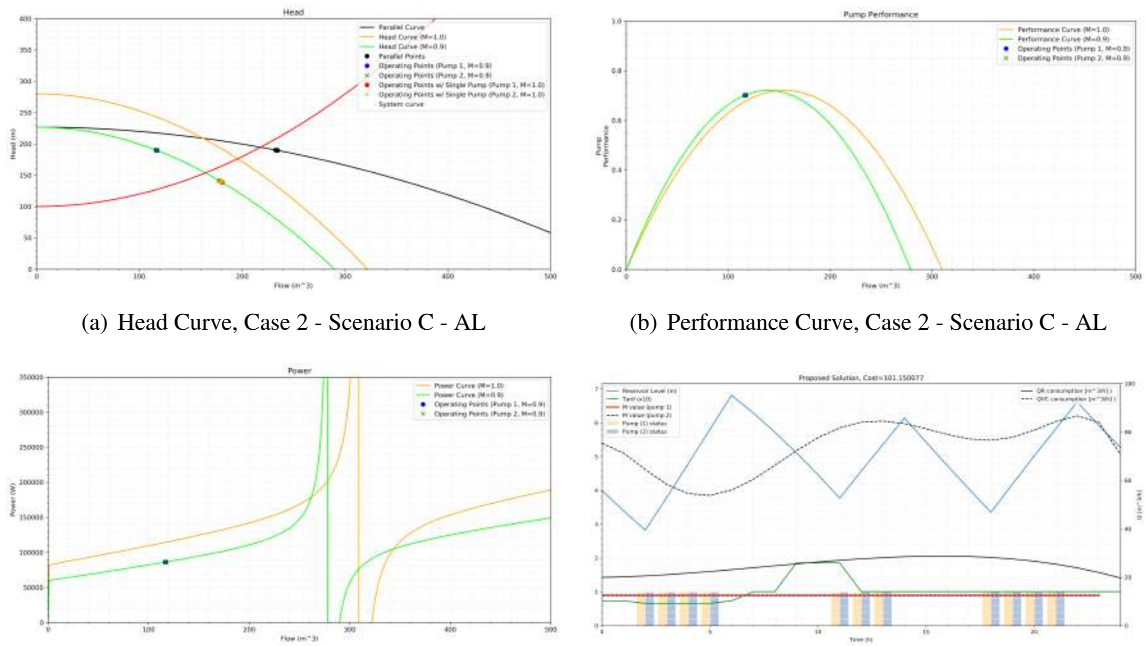
Figure 5.6: Case 2 - Scenario B - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

Case 2 - Scenario C - AL

Scenario C for case 2 is created in order to simulate the rotation speed equal to 0.9 of the original for both pumps. Here it's possible to see the difference between just varying the speed of a pump or both.

Significant reduction in the average pump power for both pumps are achieved, which results in savings of 18,109 % in the price for each cubic meter pumped, savings in energy are 18,109%. Figure 5.7 presents the results for case 2, scenario C - AL.



(a) Head Curve, Case 2 - Scenario C - AL

(b) Performance Curve, Case 2 - Scenario C - AL

(c) Power Curve, Case 2 - Scenario C - AL

(d) Resume, Case 2 - Scenario C - AL

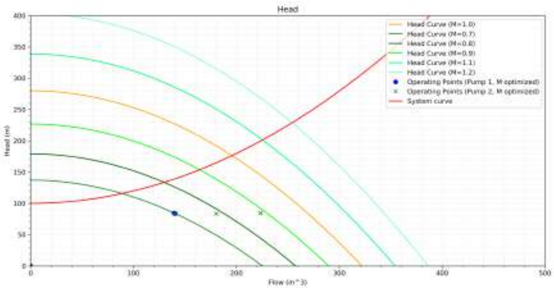
Figure 5.7: Case 2 - Scenario C - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

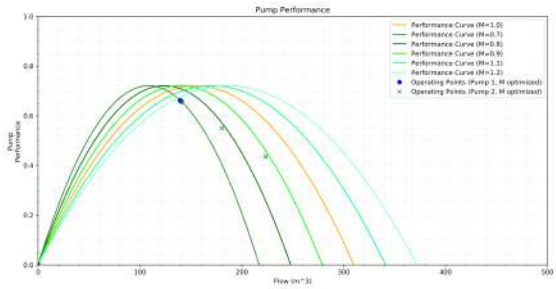
Case 2 - Scenario D - AL

Scenario D for case 2 is created to study how variable speed drives can be used to their maximum potential with operation of 2 pumps in parallel, using an algorithm to minimize the rotation speed of both pumps throughout the day. Here, as in the previous case, the pump's operating time is kept unchanged so that only the results from manipulating the pump's rotation speed are observed.

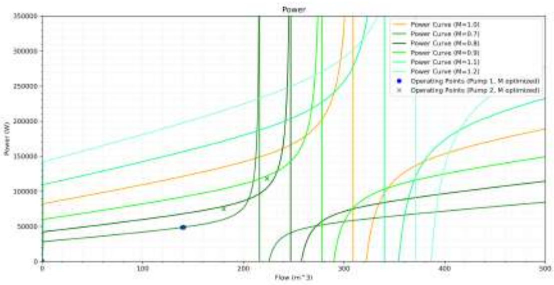
In this case, we see that the optimization resulted in having one of the pumps operating at a higher speed of rotation than the other pump, showing the flexibility of the system. Here, a reduction of about 60 percent of the price per m^3 of water pumped is achieved, while the savings in % kWh/m^3 are 55,479. Figure 5.8 presents the results for case 2, scenario D - AL.



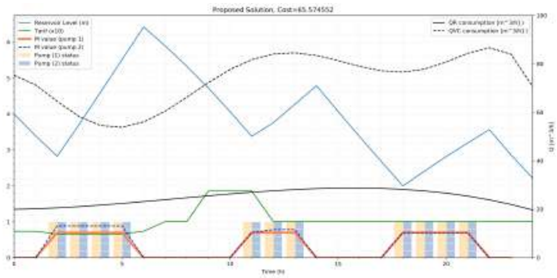
(a) Head Curve, Case 2 - Scenario D - AL



(b) Performance Curve, Case 2 - Scenario D - AL



(c) Power Curve, Case 2 - Scenario D - AL



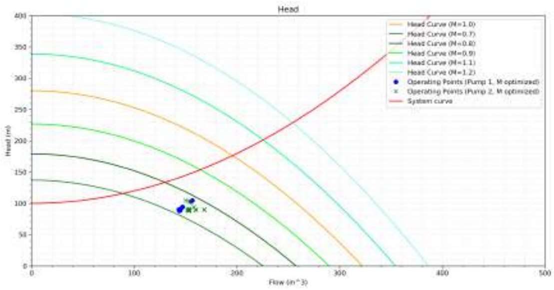
(d) Resume, Case 2 - Scenario D - AL

Figure 5.8: Case 2 - Scenario D - AL

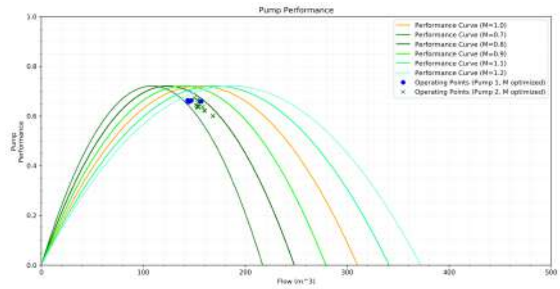
Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

Case 2 - Scenario E - AL

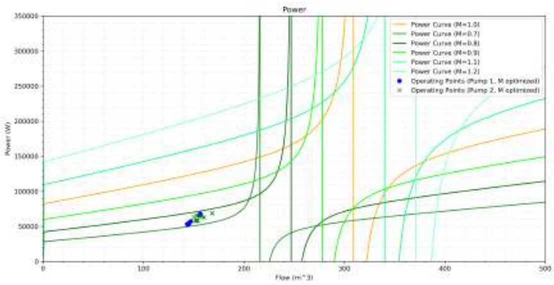
Scenario E is created to show the theoretically most effective case, to optimize the rotation speed and also the operating time of both pumps, as in scenario D of case 1.
It is interesting to see in this case, that with the possibility to also optimize the operation time, the M values decrease and are under 0.8 for all the operating points.
Here, there is a reduction of just over 60 percent of the price per m^3 of water pumped and 57,662% in % kWh/m^3, with no great advantage in relation to the case where the operating time is not optimized. Although this case is the one with the best results, these results are misleading because in reality constantly turning the pump on and off is not a viable option. Figure 5.9 presents the results for case 2, scenario E - AL.



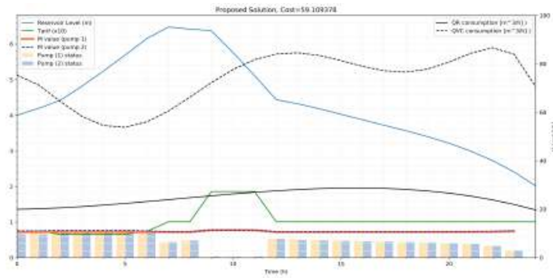
(a) Head Curve, Case 2 - Scenario E - AL



(b) Performance Curve, Case 2 - Scenario E - AL



(c) Power Curve, Case 2 - Scenario E - AL



(d) Resume, Case 2 - Scenario E - AL

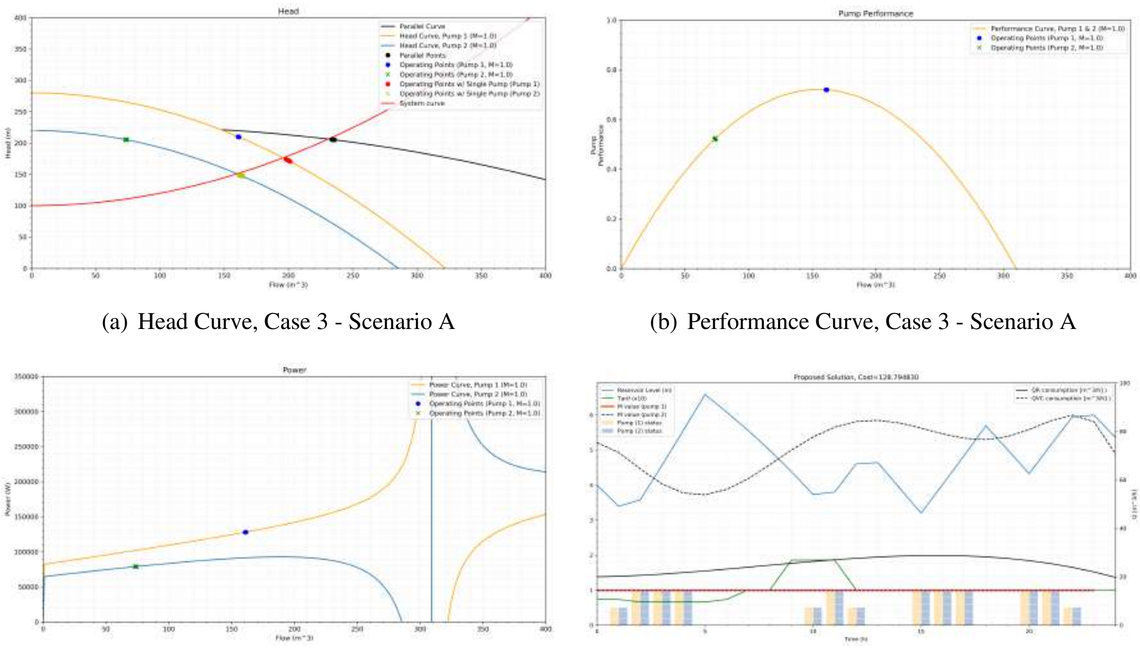
Figure 5.9: Case 2 - Scenario E - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

Case 3 - Scenario A

For case 3, two pumps are present, one larger than the other, in order to assess how energy savings vary in systems with different pumps in parallel. This scenario is created with the objective of being a reference case for the remaining scenarios created for this case. The system in this scenario works with the two pumps simultaneously, both operating at their original speed, using start-stop during the day, being switched off at the hours of the day where there is less consumption.

Having an average efficiency for pump 1 of 0.720 and 0.523 for pump 2 and a total cost of 128,795 €, this is the base scenario for case 3. This scenario has a cost per cubic meter of 4,985 $\times$ 10^{-2} and spends 36,725 kWh/m^3. Figure 5.10 presents the results for case 3, scenario A.



(a) Head Curve, Case 3 - Scenario A

(b) Performance Curve, Case 3 - Scenario A

(c) Power Curve, Case 3 - Scenario A

(d) Resume, Case 3 - Scenario A

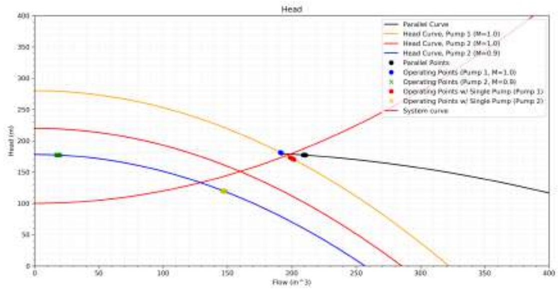
Figure 5.10: Case 3 - Scenario A

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

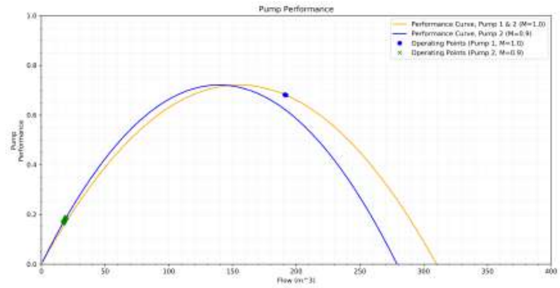
Case 3 - Scenario B - AL

Scenario B for case 3 is created in order to simulate the manual introduction of the VSD by establishing a rotation speed equal to 0.9 of the original for the smallest pump only. The operating time of the pumps is kept unchanged and in the same time spaces in order to become comparable to scenario A, with only the rotation speed being changed.

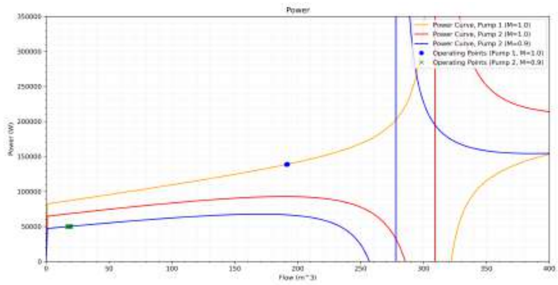
In this scenario, due to the reduction of rotation speed at the smallest pump, the pump reached very low values in efficiency, leading to a higher consumption of energy which sums up to a 1,978 % increase in the price per cubic meter. It does not present itself as a good option and demonstrates that sometimes less leads to more, hence the difficulty of applying VSDs and that it is best achieved using algorithms that adapt the speed over the time of operation. Figure 5.11 presents the results for case 3, scenario B - AL.



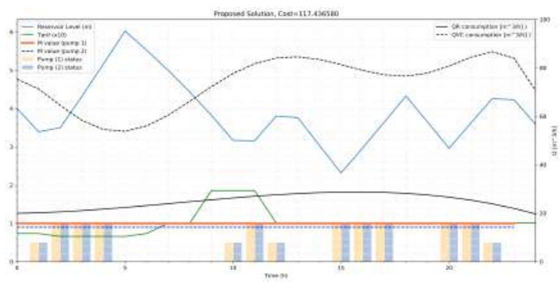
(a) Head Curve, Case 3 - Scenario B - AL



(b) Performance Curve, Case 3 - Scenario B - AL



(c) Power Curve, Case 3 - Scenario B - AL



(d) Resume, Case 3 - Scenario B - AL

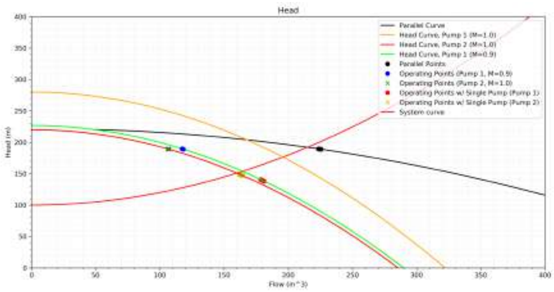
Figure 5.11: Case 3 - Scenario B - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

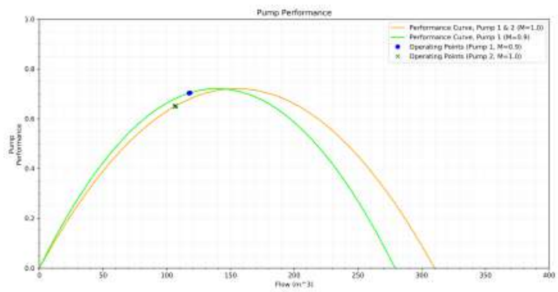
Case 3 - Scenario C - AL

Scenario C for case 3 is created in order to compare what is the difference between varying the rotation speed of the smallest or largest pump. This time, it is the largest pump that runs at 0.9 rotation speed, while the other pump runs at its original speed.

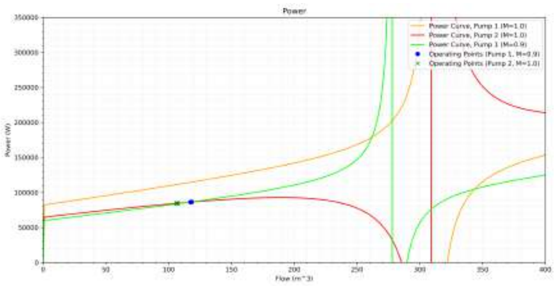
As in this case it is now the largest pump that is adjusted, the efficiency values are no longer as low as in the previous case. This case resulted in a 13,617 % reduction in the price per cubic meter. Figure 5.12 presents the results for case 3, scenario C - AL.



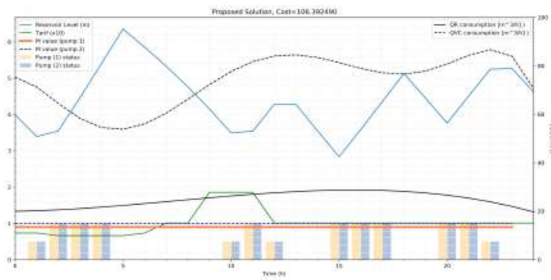
(a) Head Curve, Case 3 - Scenario C - ALA



(b) Performance Curve, Case 3 - Scenario C - AL



(c) Power Curve, Case 3 - Scenario C - AL



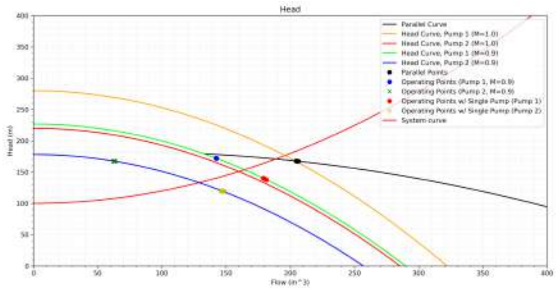
(d) Resume, Case 3 - Scenario C - AL

Figure 5.12: Case 3 - Scenario C - AL

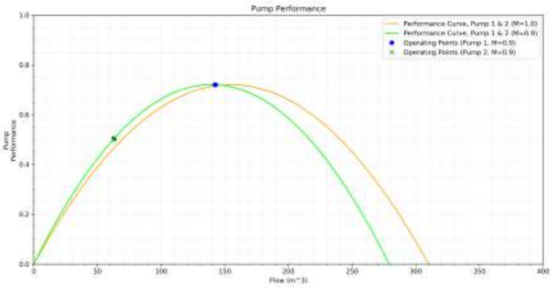
Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

Case 3 - Scenario D - AL

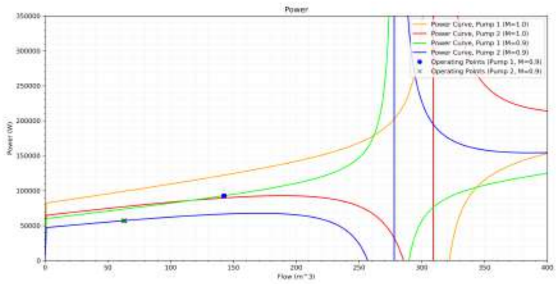
Scenario D for case 3 is created to study the use of both pumps with a changed speed of rotation set to 0.9. In this case, there is an improvement again, with both pumps operating with slightly higher efficiencies compared to scenario A. It presents savings of 17,350% in the price per cubic meter. Figure 5.13 presents the results for case 3, scenario D - AL.



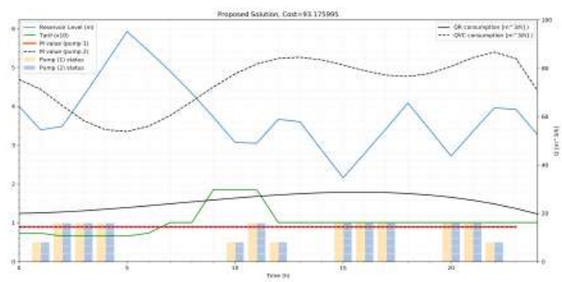
(a) Head Curve, Case 3 - Scenario D - AL



(b) Performance Curve, Case 3 - Scenario D - AL



(c) Power Curve, Case 3 - Scenario D - AL



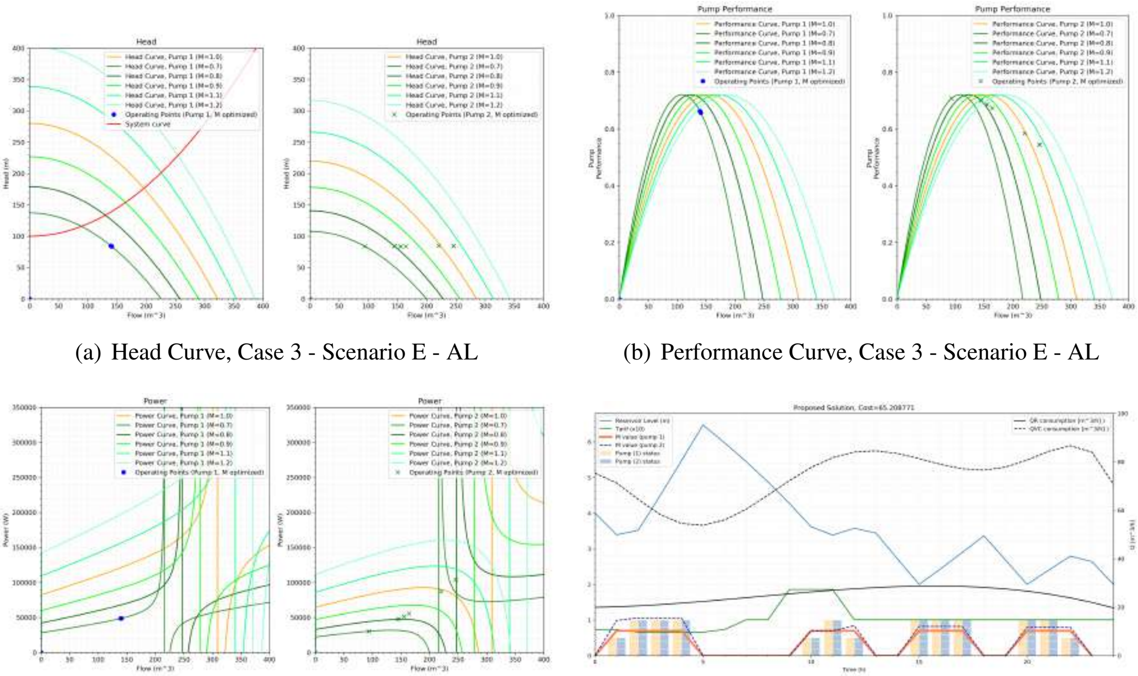
(d) Resume, Case 3 - Scenario D - AL

Figure 5.13: Case 3 - Scenario D - AL

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

Case 3 - Scenario E - AL

Scenario E for case 3 is the most viable case, since both pumps have rotation speed optimized by the algorithm. It is created to study how variable speed drives can be used to their maximum potential with the operation of 2 pumps in parallel, using an algorithm to minimize the rotation speed of both pumps throughout the day. Here, as in the previous case, the pump's operating time is kept unchanged so that only the results from manipulating the pump's rotation speed are observed. In this scenario the result that stands out most is the similarity in the average pump efficiency value between the pumps, which is very similar, showing that the variation in speed controlled by an algorithm can bring better results. With the speed of rotation optimized for both pumps, reductions of more than 17 % in kWh/m^3 are achieved. Figure 5.14 presents the results for case 3, scenario E - AL.



(a) Head Curve, Case 3 - Scenario E - AL

(b) Performance Curve, Case 3 - Scenario E - AL

(c) Power Curve, Case 3 - Scenario E - AL

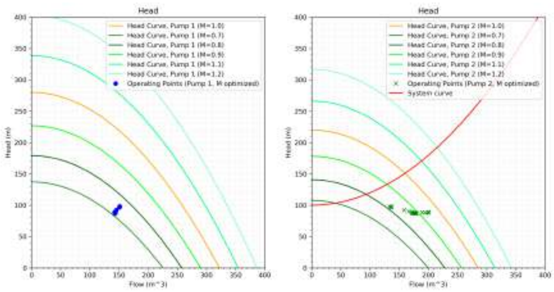
(d) Resume, Case 3 - Scenario E - AL

Figure 5.14: Case 3 - Scenario E - AL

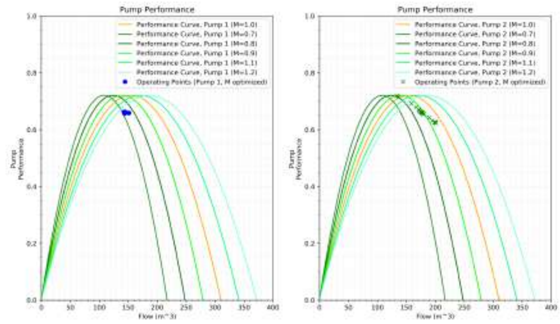
Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

Case 3 - Scenario F - AL

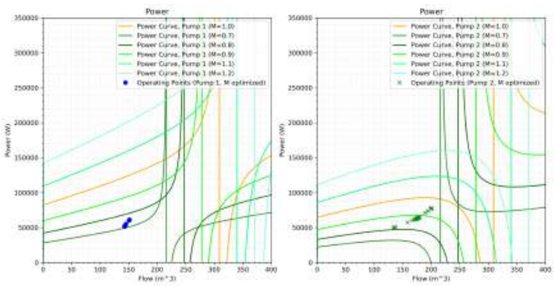
The last scenario created to show the theoretically most effective case, to optimize the rotation speed and also the operation time, for both pumps. Once again, the "perfect case" shows the best results with a price reduction per cubic meter of water of 64,133 %. Figure 5.15 presents the results for case 3, scenario F - AL.



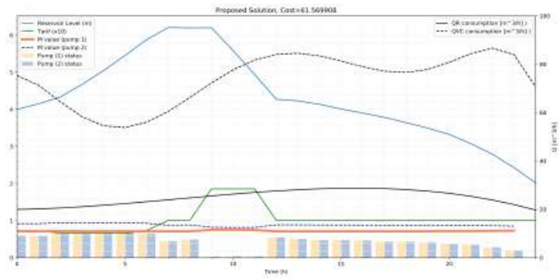
(a) Head Curve, Case 3 - Scenario F - AL



(b) Performance Curve, Case 3 - Scenario F - AL



(c) Power Curve, Case 3 - Scenario F - AL



(d) Resume, Case 3 - Scenario F - AL

Figure 5.15: Case 3 - Scenario F - AL

The results presented are only from the scenarios studied with AL application, eventhough AL, SB and CAC have been studied. The three different methods allow the reader to get to roughly the same conclusions, only difference being that SB and CAC methods theoretically are closer to reality.

Important note: after completing the dissertation and when introducing the system curves to the graphic results, a typo was discovered in the graphical representation of the operating points. The points represented in the figures seem to follow a wrong system curve (originating from point 0, instead of the 100m static head point), this is due to the fact that the points were represented using directly the affinity laws. It should be noted that despite the points being poorly represented here, the iterative cycle was calculated taking into account the flow rates of the correct operating points.

5.5 Overall Results

Table 5.5: Results Table for Single Pump Operation - Part 1

	Summary	Average Pump Efficiency	Average Pump Power (kW)
	A (**M** = 1.0)	0,661	141846,459
AL	B (**M** = 0.9)	0,660	103535,187
AL	C (**M** optimized)	0,660	103890,010
AL	D (**M** & **x** optimized)	0,659	53511,140
AL	B (**M** = 0.9)	0,656	104103,153
SB	C (**M** optimized)	0,656	104817,737
SB	D (**M** & **x** optimized)	0,648	54221,360
CAC	B (**M** = 0.9)	0,659	103638,826
CAC	C (**M** optimized)	0,658	103011,856
CAC	D (**M** & **x** optimized)	0,644	53749,737

In table 5.5 it is possible to verify that the use of the VSD's does not substantially contribute to a very significant change in the average efficiency of the hydraulic pump, however it is possible to verify the differences in the average pump efficiency between the three methods used. It is also important to mention the differences that can be seen in the average pump power, the simple manual introduction of variable speed drives with a reduction of only 10% of the nominal speed causes reductions of around one third in the average pump power.

Table 5.6: Results Table for Single Pump Operation - Part 2

	Summary	m^3	kWh (average)	kWh (max)
	A (**M** = 1.0)	2394,874	70930,389	142377,625
AL	B (**M** = 0.9)	2159,932	51769,510	103906,310
AL	C (**M** optimized)	2104,003	49771,506	141165,372
AL	D (**M** & **x** optimized)	2063,438	29913,050	48894,941
AL	B (**M** = 0.9)	2159,932	52053,558	104485,174
SB	C (**M** optimized)	2104,003	50104,166	142286,829
SB	D (**M** & **x** optimized)	2063,438	30484,136	49840,634
CAC	B (**M** = 0.9)	2159,932	51821,331	104010,321
CAC	C (**M** optimized)	2104,003	49799,306	138859,971
CAC	D (**M** & **x** optimized)	2063,459	30756,967	49883,663

In table 5.6, although there are differences in the cubic meters of water pumped, these values should not be taken into account for the analysis of the use of variable speed drives, since the level of the reservoir at the end of the 24-hour period may be different.
In the kWh average column there is clear the improvement with the reduction of the nominal speed of rotation. In scenario C with the optimized nominal speed of rotation it is seen that the maximum value of kWh is similar to the base case, yet the average during the day is lower, this is due to the fact that the system works in certain increments with relative speed of rotation close

to 1 but during the remaining increments it is possible to lower the nominal speed of rotation and thus the average power is lower.

Table 5.7: Results Table for Single Pump Operation - Part 3

	Summary	**kWh/m^3**	**€/m^3 ($\times$ 10^{-2})**	**€/kWh ($\times$ 10^{-2})**
	A (**M** = 1.0)	29,618	6,394	0,216
AL	B (**M** = 0.9)	23,968	5,175	0,216
AL	C (**M** optimized)	23,656	4,799	0,203
AL	D (**M** & **x** optimized)	14,497	3,111	0,215
AL	B (**M** = 0.9)	24,100	5,203	0,216
SB	C (**M** optimized)	23,814	4,829	0,203
SB	D (**M** & **x** optimized)	14,773	3,168	0,214
CAC	B (**M** = 0.9)	23,992	5,180	0,216
CAC	C (**M** optimized)	23,669	4,819	0,204
CAC	D (**M** & **x** optimized)	14,906	3,195	0,214

Table 5.7 shows that the use of variable speed drives contributes to a decrease in the energy required to pump each cubic meter of water, as well as the price to pump each cubic meter is also reduced. In scenario D where the nominal rotation speed and the nominal operating time of the hydraulic pump are optimized, there are even greater reductions than in the other scenarios, but it is necessary to take into account that this reduction is possible also due to the variation of the energy tariff, not only having to do with the application of variable speed drives.

Table 5.8: Results Table for Single Pump Operation - Part 4

	Summary	**Cost (€)**	**Savings (%)**	**Savings (% €/m^3)**	**Savings (%kWh/m^3)**
	A (**M** = 1.0)	153,121	-	-	
AL	B (**M** = 0.9)	111,770	27,005	19,066	19,076
AL	C (**M** optimized)	100,965	34,062	24,946	20,130
AL	D (**M** & **x** optimized)	64,194	58,076	51,343	51,053
AL	B (**M** = 0.9)	112,384	26,604	18,621	18,630
SB	C (**M** optimized)	101,608	33,642	24,468	19,596
SB	D (**M** & **x** optimized)	65,367	57,310	50,454	50,121
CAC	B (**M** = 0.9)	111,882	26,932	18,985	18.995
CAC	C (**M** optimized)	101,399	33,779	24,624	20,085
CAC	D (**M** & **x** optimized)	65,928	56,944	50,029	49,672

In table 5.8, although it is possible to see that the final costs are lower, this is also due to the lower amount of water pumped and not only to the use of variable speed drives, as stated earlier. It is interesting to verify the other price reduction columns, per cubic meter pumped, as well as the energy needed to pump each meter of water. It is possible to see reductions of approximately 20 % in energy needed to pump each cubic meter of water when using the VSD directly and reductions of approximately 50 % in the scenarios where optimization is performed, as would be expected according to the studied bibliography.

Table 5.9: Results Table for Parallel Operation with 2 Identical Pumps - Part 1

	Summary	Average Pump 1 Efficiency	Average Pump 2 Efficiency
	A (Both Pumps, **M** = 1.0)	0,705	0,705
AL	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	0,720	0,614
AL	C (Both Pumps **M** = 0.9)	0,702	0,702
AL	D (Both Pumps, **M** optimized)	0,660	0,613
AL	E (Both Pumps, **M** & **x** optimized)	0,660	0,633
SB	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	0,720	0,610
SB	C (Both Pumps **M** = 0.9)	0,699	0,699
SB	D (Both Pumps, **M** optimized)	0,652	0,607
SB	E (Both Pumps, **M** & **x** optimized)	0,649	0,623
CAC	B (Pump 1 **M** = 1.0, Pump 2 **M** = 0.9)	0,720	0,614
CAC	C (Both Pumps **M** = 0.9)	0,700	0,701
CAC	D (Both Pumps, **M** optimized)	0,651	0,609
CAC	E (Both Pumps, **M** & **x** optimized)	0,647	0,623

Table 5.10: Results Table for Parallel Operation with 2 Identical Pumps - Part 2

	Summary	Average Pump 1 Power (kW)	Average Pump 2 Power (kW)
	A	118862.705	118862.706
AL	B	127183.457	78829.367
AL	C	86174.228	86174.784
AL	D	79147.319	92903.668
AL	E	55170.742	61723.800
SB	B	127183.457	79356.841
SB	C	86564.013	86564.564
SB	D	77706.898	91732.723
SB	E	56315.160	62989.584
CAC	B	127183.457	78908.275
CAC	C	86260.489	86261.045
CAC	D	81054.793	94433.625
CAC	E	56578.997	63136.092

Table 5.11: Results Table for Parallel Operation with 2 Identical Pumps - Part 3

	Summary	**m^3 (Pump 1)**	**m^3 (Pump 2)**	**m^3 (Total)**
	A	1451.603	1451.603	2903.206
AL	B	1742.742	945.272	2688.014
AL	C	1285.104	1285.129	2570.233
AL	D	1540.441	1955.808	3496.250
AL	E	1647.617	1762.813	3410.430
SB	B	1742.742	945.272	2688.014
SB	C	1285.104	1285.129	2570.233
SB	D	1540.444	1955.806	3496.250
SB	E	1650.369	1761.063	3411.433
CAC	B	1742.742	945.271	2688.014
CAC	C	1285.104	11285.129	2570.233
CAC	D	1540.441	1955.809	3496.249
CAC	E	1644.660	1775.184	3419.844

Table 5.12: Results Table for Parallel Operation with 2 Identical Pumps - Part 4

	Summary	**kwh average - Pump 1**	**kwh average - Pump 2**
	A	54480.253	54480.254
AL	B	58293.649	36131.442
AL	C	39497.620	39497.874
AL	D	22332.064	36088.202
AL	E	25418.220	28773.289
SB	B	58293.649	36373.159
SB	C	3967.262	39676.514
SB	D	22758.231	36784.086
SB	E	25997.190	29367.403
CAC	B	58293.649	36167.610
CAC	C	39537.157	39537.412
CAC	D	22951.736	36436.725
CAC	E	25991.255	29562.591

Table 5.13: Results Table for Parallel Operation with 2 Identical Pumps - Part 5

	Summary	**kwh (max) - Pump 1**	**kwh (max) - Pump 2**
	A	118984.361	118984.362
AL	B	127282.757	78934.906
AL	C	86262.521	86263.051
AL	D	48831.222	118193.867
AL	E	42998.990	51355.558
SB	B	127282.757	79459.035
SB	C	86651.576	86652.100
SB	D	49771.859	121091.129
SB	E	43883.440	52985.852
CAC	B	127282.757	70913.919
CAC	C	86348.870	86349.400
CAC	D	50186.218	117892.412
CAC	E	44175.511	53569.772

Table 5.14: Results Table for Parallel Operation with 2 Identical Pumps - Part 6

	Summary	**kwh/m^3**	**€/m^3 ($\times$ 10^{-2})**	**€/kwh ($\times$ 10^{-2})**
	A	37.531	4.806	0,128
AL	B	35.128	4.498	0,128
AL	C	30.735	3.935	0,128
AL	D	16.709	1.876	0,112
AL	E	15,890	1,733	0,109
SB	B	35.218	4.509	0,128
SB	C	30.874	3.953	0,128
SB	D	17.030	1.910	0,112
SB	E	16,229	1,768	0,109
CAC	B	35.142	4.500	0,128
CAC	C	30.766	3.939	0,128
CAC	D	16.986	1.910	0,112
CAC	E	16,245	1,762	0,108

Table 5.15: Results Table for Parallel Operation with 2 Identical Pumps - Part 7

	Summary	Cost (€)	Savings (%)	Savings (% €/m^3)	Savings (%kWh/m^3)
	A	139.519	-	-	-
AL	B	120.906	13,341	6.403	6,402
AL	C	101.150	27,501	18.109	18,109
AL	D	65.575	53.000	60.972	55,479
AL	E	58,109	57.633	63.934	57,662
SB	B	121.215	13,119	6.164	6,163
SB	C	101.607	27.173	17.738	17,138
SB	D	66.764	52.147	60.264	54,623
SB	E	60.327	56.761	63.203	56,758
CAC	B	120.952	13,307	6.367	6,367
CAC	C	101.251	27.428	18,027	18,027
CAC	D	66.796	52.124	60.245	54,741
CAC	E	60,249	56.817	63.341	56,717

Table 5.15 shows greater reductions with direct use of variable speed drives compared to the first case where only one pump is used, showing that it pays to have a set of pumps available in parallel operation when compared to a single pump. It should also be noted that the savings differences between case D (with optimization of the nominal speed of rotation) and E (with optimization of the nominal speed of rotation and optimization of the nominal time of operation of the pumps) are very similar, showing the usefulness of using the variable speed drives.

Table 5.16: Results Table for Parallel Operation with 2 Dissimilar Pumps - Part 1

	Summary	Average Pump 1 Efficiency	Average Pump 2 Efficiency
	A (Both Pumps, **M**=1.0)	0,720	0,523
AL	B (Pump 1 **M**=1.0, Pump 2 **M**=0.9)	0,681	0,179
AL	C (Pump 1 **M**=0.9, Pump 2 **M**=1.0)	0,703	0,650
AL	D (Both Pumps, **M** = 0.9)	0,720	0,504
AL	E (Both Pumps, **M** optimized)	0,660	0,677
AL	F (Both Pumps, **M** & **x** optimized)	0,660	0,662
SB	B (Pump 1 **M**=1.0, Pump 2 **M**=0.9)	0,681	0,170
SB	C (Pump 1 **M**=0.9, Pump 2 **M**=1.0)	0,700	0,651
SB	D (Both Pumps, **M** = 0.9)	0,717	0,499
SB	E (Both Pumps, **M** optimized)	0,651	0,673
SB	F (Both Pumps, **M** & **x** optimized)	0,649	0,652
CAC	B (Pump 1 **M**=1.0, Pump 2 **M**=0.9)	0,681	0,179
CAC	C (Pump 1 **M**=0.9, Pump 2 **M**=1.0)	0,703	0,651
CAC	D (Both Pumps, **M** = 0.9)	0,720	0,504
CAC	E (Both Pumps, **M** optimized)	0,650	0,673
CAC	F (Both Pumps, **M** & **x** optimized)	0,646	0,655

In table 5.16, it is possible to see that the direct application of variable speed drives can be harmful. In case B, with the reduction of the nominal speed of rotation of the smallest hydraulic pump, its average efficiency throughout the day is greatly reduced, leading to average efficiency values below 0.20.

Table 5.17: Results Table for Parallel Operation with 2 Dissimilar Pumps - Part 2

	Summary	Average Pump 1 Power (kW)	Average Pump 2 Power (kW)
	A	128059,569	78934,720
AL	B	138690,225	50079,132
AL	C	86432,807	84557,967
AL	D	92692,348	57056,638
AL	E	77126,493	65493,421
AL	F	53353,328	64803,081
SB	B	138690,225	52644,757
SB	C	86820,526	84557,967
SB	D	93074,932	57656,976
SB	E	76786,711	64984,298
SB	F	54401,629	67542,885
CAC	B	138690,225	50129,261
CAC	C	86519,327	84557,967
CAC	D	92785,133	57113,751
CAC	E	76791,841	64976,827
CAC	F	54580,172	67140,248

Table 5.18: Results Table for Parallel Operation with 2 Dissimilar Pumps - Part 3

	Summary	**m^3 (Pump 1)**	**m^3 (Pump 2)**	**m^3 (Total)**
	A	1772,198	811,243	2583,441
AL	B	2105,178	204,732	2309,910
AL	C	1296,776	1173,720	2470,496
AL	D	1567,505	693,804	2261,309
AL	E	1540,571	1898,492	3439,063
AL	F	1508,947	1934,377	3443,323
SB	B	2105,178	204,732	2309,910
SB	C	1296,776	1173,720	2470,496
SB	D	1567,505	693,804	2261,309
SB	E	1540,571	1898,492	3439,063
SB	F	1490,247	1950,291	3440,538
CAC	B	2105,178	204,732	2309,910
CAC	C	1296,776	1173,720	2470,496
CAC	D	1567,505	693,804	2261,309
CAC	E	1540,571	1898,492	3439,063
CAC	F	1493,254	1948,769	3442,023

Table 5.19: Results Table for Parallel Operation with 2 Dissimilar Pumps - Part 4

	Summary	**kWh (average) - Pump 1**	**kWh (average) - Pump 2**
	A	58696,071	36180,420
AL	B	63563,674	22956,819
AL	C	39617,005	38757,094
AL	D	42485,462	26152,465
AL	E	22333,125	29298,820
AL	F	22919,765	29928,182
SB	B	63563,674	24129,322
SB	C	39794,695	38757,094
SB	D	42660,821	26427,498
SB	E	22759,286	29411,428
SB	F	23106,980	30715,638
CAC	B	63563,674	22979,799
CAC	C	39656,662	38757,094
CAC	D	42527,990	26178,644
CAC	E	22952,852	29421,381
CAC	F	23336,231	30594,421

Table 5.20: Results Table for Parallel Operation with 2 Dissimilar Pumps - Part 5

	Summary	kWh (max) - Pump 1	kWh (max) - Pump 2
	A	128166,623	79037,311
AL	B	138873,516	50282,179
AL	C	86533,228	84627,400
AL	D	92767,147	57133,645
AL	E	48845,406	104231,236
AL	F	36310,072	53856,359
SB	B	138873,516	52658,861
SB	C	86920,179	84627,400
SB	D	93150,161	57727,671
SB	E	49787,385	104718,453
SB	F	35979,873	54019,723
CAC	B	138873,516	50332,511
CAC	C	86619,848	84627,400
CAC	D	92860,007	57190,835
CAC	E	50200,830	104138,389
CAC	F	36676,872	53817,551

Table 5.21: Results Table for Parallel Operation with 2 Dissimilar Pumps - Part 6

	Summary	**kWh/m^3**	**€/m^3 ($\times$ 10^{-2})**	**€/kWh ($\times$ 10^{-2})**
	A	36,725	4,985	0,136
AL	B	37,456	5,084	0,136
AL	C	31,724	4,307	0,136
AL	D	30,353	4,120	0,136
AL	E	15,013	1,896	0,126
AL	F	15,348	1,788	0,117
SB	B	37,964	5,152	0,136
SB	C	31,796	4,011	0,126
SB	D	30,552	4,147	0,136
SB	E	15,170	1,918	0,126
SB	F	15,644	1,832	0,117
CAC	B	37,466	5,085	0,136
CAC	C	31,740	4,004	0,126
CAC	D	30,384	4,125	0,136
CAC	E	15,229	1,927	0,127
CAC	F	15,668	1,835	0,117

Table 5.22: Results Table for Parallel Operation with 2 Dissimilar Pumps - Part 7

	Summary	**Cost (€)**	**Savings (%)**	**Savings (% €/m^3)**	**Savings (%kWh/m^3)**
	A	128,795	-	-	-
AL	B	117,437	8,819	-1,978	-1,991
AL	C	106,392	17,394	13,617	13,617
AL	D	93,176	27,655	17,350	17,350
AL	E	65,209	49,370	61,967	59,119
AL	F	61,570	52,195	64,133	58,208
SB	B	119,006	7,600	-3,342	-3,374
SB	C	99,099	23,057	19,539	13,421
SB	D	93,787	27,181	16,808	16,807
SB	E	65,959	48,787	61,529	58,693
SB	F	63,044	51,051	63,245	57,403
CAC	B	117,468	8,795	-2,006	-2.019
CAC	C	98,925	23,192	19,681	13,573
CAC	D	93,269	27,583	17,267	17,267
CAC	E	66,286	48,534	61,338	58,532
CAC	F	63,164	50,957	63,191	57,336

Table 5.22 shows that the low efficiency values in scenario B lead to an increase in energy

consumption, proving that the use of variable speed drives has to be done carefully in order to take advantage of their usefulness. It should also be noted that the energy savings figures in this case 3 are quite similar to those achieved in case 2, again reaching energy savings figures close to 60 %.

Intentionally blank page.

Chapter 6

Conclusion and Future Works

Variable speed drives have a great potential for energy savings, even for its wide variety of applications. Although VSD's application have been introduced into the industry for a long time now, VSD's are still not being used to their full potential, despite presenting to be a good alternative to constant speed control systems.
The present study tries to dispel the idea that VSD's are not a viable option for water pumping systems.
According to the literature studied, the proper application of VSD's can lead to savings in the range of 20 [6] to 63.3 % [5], values that were found to resemblance the results obtained, thus fulfilling what it promised. In spite of all this, it is also seen that the application of VSD's has to be well planned and executed according to each case.
The most important conclusion to be made after analyzing the results is that it is proven that VSD's, if used correctly, can, in fact, contribute to reduce the cost of water networks operation. This study presents cases in which the application of variable speed control leads to higher costs, proving that if not used properly, VSD's can increase energy consumption. Therefore, the conclusion is that raw results can be misleading when not carefully analyzed. Even so, whenever well applied, there are clear advantages to the use of VSD's but it is necessary to take into account that the reality is different from the theoretical. Other external factor have to be included when studying the feasibility of using VSD's. In this study, there are scenarios presented where both the speed of rotation (**M**) and the pump's operating time are optimized, these are the cases where theoretically it will be possible to take greater advantage of the VSD's application but it is necessary to take into account that in real operation it is not possible to constantly switching the pumps on and off, that would lead to higher pump energy consumption and, naturally, reducing the equipment remaining useful life expectation.
Therefore it is possible to conclude that despite leading to cost reduction, VSD's have limitations, it must be used with care and it is humanly impossible to be operated manually, forcing the use of software, whether developed by the user himself or from other sources.
In the future, in order to have a better understanding of the advantages to use VSD's in water supply systems, is advised to study more complex and larger networks and the use of other software, such as EPANET, also to test in a longer period of time thus increasing the data to be analyzed.

Intentionally blank page.

Bibliography

[1] Doe, Hi. (2001). Pump Life-Cycle costs: A Guide to LCC analysis for pumping systems, US Department of energy's Office of Industrial Technologies. Europump.
[2] R. Saidur, S. Mekhilef, M.B. Ali, A. Safari, H.A. Mohammed. (2012). Applications of variable speed drive (VSD) in electrical motor energy savings. Renewable and Sustainable Energy reviews, 15 (1), 543-550.
[3] Okaeme N. (2008). Automated robust control system design for variable speed drives. PhD thesis. UK: University of Nottingham.
[4] Tsutiya, M.T. (2004). Abastecimento de Água, 1ª ed. São Paulo: Departamento de Engenharia Hidráulica e Sanitária. Escola Politécnica, Universidade de São Paulo. 634p.
[5] Solomon S. (1999). Understanding variable speed drives (part 2).
[6] Al-Bahadly I. (2007). Energy saving with variable speed drives in industry applications. WSEAS Int.
[7] Saidur R. (2010). A review on electrical motors energy use and energy savings. Renewable and Sustainable Energy Reviews, 14 (3), 877-898.
[8] Saidur R, Mahlia TMI. (2010). Energy, economic and environmental benefits of using high efficiency motors to replace standard motors for the Malaysian industries. Energy Policy, 38 (8), 4617-4625.
[9] Sueker KH. (2005). Power electronics design: a practitioner's guide, first edition. Newnes.
[10] LLC. (2003). VFD fundamentals.
[11] Mays, L.W. (1999). Hydraulic design handbook, First Edition, McGraw.
[12] Saidur R, Rahim N, Hasanuzzaman M. (2009). A review on compressed-air energy use and energy savings. Renewable and Sustainable Energy Reviews, 14 (4), 1135-1153.
[13] Lucarelli, D.L; Brucoli, A.C; Souza, R.F. (1981). Bombeamento direto nas redes de abastecimento através de bombas de velocidade variável sem reservatório de distribuição. Revista DAE, v.38, n.118, p266.
[14] Altmann, D. (2005). Modulação da velocidade em bombas submersas para redução das perdas físicas e energéticas nos sistemas de distribuição.
[15] Sarbu, I. (2016). A Study of energy optimization of urban water distribuition systems using potentials elements. Water (Switzerland) 8(12): 593:1-19.
[16] Quintela, A. C. (1981). Hidráulica (2nd ed.). Lisbon: Fundação Calouste Gulbenkian.
[17] Rossman, L. A. (2000). EPANET 2: users manual. US Environmental Protection Agency. Office of Research and Development. National Risk Management Research Laboratory.
[18] Walski, T., Zimmerman, K., Dudinyak, M., Dileepkumar, P. (2003). Some surprises in estimating the efficiency of variable-speed pumps with the pump affinity laws. World Water Environmental Resources Congress 2003 (pp. 1-10).
[19] Sárbu, I., Borza, I. (1998). Energetic optimization of water pumping in distribution sys-

tems. Mechanical Engineering. 42(2), 141-152.
[20] Morton,W. R. (1975). Economics of AC adjustable speed drives on pumps. IEEE Transactions on Industry Applications, IA-11(3), 282-286.
[21] Gulich, J. F. (2003). Effect of Reynolds number and surface roughness on the efficiency of centrifugal pumps. Journal of Fluids Engineering, 125(4), 670-679.
[22] Simpson, A. R., Marchi, A. (2013). Evaluating the approximation of the affinity laws and improving the efficiency estimate for variable speed pumps. Journal of Hydraulic Engineering, 139(12), 1314-1317.
[23] Osterwalder, J., Hippe, L. (1984). Guidelines for efficiency scaling process of hydraulic turbomachines with different technical roughnesses of flow passages. Journal of Hydraulic Research, 22(2), 77-102.
[24] Bernardete Coelho, António G. Andrade-Campos. (2016). A new approach for the prediction of speed-adjusted pump efficiency curves, Journal of Hydraulic Research 54(5):1-8.
[25] Arun Shankar V.K., Umashankar S., Paramasivam S., Norbert H. (2017). Real time simulation of Variable Speed Parallel Pumping system, Energy Procedia, 142, 2102-2108.
[26] U.S. Department of Energy (2012). Adjustable Speed Drive Part-Load Efficiency, Motor Systems Tip Sheet #11 (Fact Sheet). United States. https://doi.org/10.2172/1056706.
[27] A. Andrade - Campos, J. Dias-de-Oliveira (2018). Benchmark 2018 : Operação eficiente de bombagem.

Appendix A

Python Code

```
def Benchmark2018(xt,iChart):
    nInc = int(len(xt)/4)
    x = xt[0:nInc]
    y = xt[3*nInc:4*nInc]
    M = xt[nInc:2*nInc]
    M = list(map(normalize,M))
    MM = xt[2*nInc:3*nInc]
    MM = list(map(normalize,MM))
    #M=[1.0 for i in range (0, nInc)]
    #MM=[0.9 for i in range (0, nInc)]
    #x=[0.0,0.0,1.0,1.0,1.0,1.0,0.0,0.0,0.0,0.0,0.0,1.0,1.0,1.0,0.0,0.0,0.0,0.0,1.0,1.0,1.0,1.0,0.0,0.0]
    #y=[0.0,0.0,1.0,1.0,1.0,1.0,0.0,0.0,0.0,0.0,0.0,1.0,1.0,1.0,0.0,0.0,0.0,0.0,1.0,1.0,1.0,1.0,0.0,0.0]

    # definicao dos dicionarios
    empty_timeIncrem = {
        'number': None,
        'startTime': None, 'duration': None,'endTime': None,
        'hFini': None, 'hFfin': None,};
    fObjRest = {'fObj': None, 'g1': [], 'g2': []}
    Sensibil = {'dCdx': [],'dg1dx': [[0 for j in range(nInc)]for i in range(nInc)],
                    'dg2dx': [[0 for j in range(nInc)]for i in range(nInc)]};


    # Calculo dos consumos em cada t
    def Caudal_VC(ti, tf):
        # definicao do polinomio
        a6 = -5.72800E-05; a5 = 3.9382E-03; a4=-9.8402E-02
        a3 = 1.0477; a2 = -3.8621; a1 = -1.1695; a0 = 7.53930E+01
        QVC = a6/7.*(tf**7.-ti**7.)+a5/6.*(tf**6.-ti**6.)+a4/5.*(tf**5.-ti**5.)+ a3/4.*(tf**4.-ti**4.)+a2/3.*(tf**3.-ti**3.)+a1/2.*(tf**2.-ti**2.)+a0*(tf-ti)
        return QVC

    def Caudal_R(ti, tf):
        # definicao do polinomio
        a3 = -0.004; a2 = 0.09; a1 = 0.1335; a0 = 20.0
        QR = a3/4.*(tf**4.-ti**4.)+a2/3.*(tf**3.-ti**3.)+a1/2.*(tf**2.-ti**2.)+a0*(tf-ti)
        return QR

    def tarifario(ti):
        # definicao do tarifario usando o tempo inicial do incremento
        tarifHora = [None]*7; tarifCusto = [None]*7;
        set(tarifHora)
        tarifHora[0]= 0; tarifCusto[0]= 0.0737
        tarifHora[1]=2; tarifCusto[1]= 0.06618
        tarifHora[2]=6; tarifCusto[2]=  0.0737
        tarifHora[3]=7; tarifCusto[3]=  0.10094
        tarifHora[4]=9; tarifCusto[4]=  0.18581
        tarifHora[5]=12; tarifCusto[5]= 0.10094
        tarifHora[6]=24; tarifCusto[6]= 0.10094
        tarifF = 0.
        for i in range(0, len(tarifHora)-1):
            if (ti >= tarifHora[i]) & (ti < tarifHora[i+1]):
                tarifF = tarifCusto[i]
                break
        if tarifF == 0.: print("Erro no tarifario",ti,i); quit()
        return tarifF

    # Dados gerais
    g = 9.81; densidade = 1000.0
    hmin =  2.0; hmax = 7.0; hFixo = 100.0
    AF = 155.0; V0 = 620.0; hF0 = 4.0; deltahF = 0.
    LPR = 3500; LRF = 6000
    f =  0.02; d =  0.3
    # Dados da bomba
    a1 = 280.; a2 = -0.0027; b1=-1*10**-15; b2=0.0093; b3=-3*10**-5; a11=280; a22 = -0.0027;b11=-1*10**-15; b22=0.0093; b33=-3*10**-5;
    # variaveis constantes
```

```
    f32gpi2d5 = 32.0*f/(g*math.pi**2.0*d**5.)
    sys=(f32gpi2d5*LPR + f32gpi2d5*LRF)*10**-7

    aRes2 =  - f32gpi2d5*LPR - f32gpi2d5*LRF
    aRes1= (a2*3600.**2.)
    aRes11=(a22*3600.**2.)


    for i in range(0, nInc):
        # definicao dos incrementos de tempo
        timeInc.append(empty_timeIncrem.copy())
        timeInc[i]['number'] = i + 1
        if i == 0:
            timeInc[i]['startTime'] = 0
            hF = hF0
            timeInc[i]['hFini'] = hF
        else:
            timeInc[i]['startTime'] = timeInc[i-1]['endTime']
            timeInc[i]['hFini'] = timeInc[i-1]['hFfin']
        timeInc[i]['duration'] = 24 / nInc
        timeInc[i]['endTime'] = timeInc[i]['startTime']+timeInc[i]['duration'];
        #print ("timeInc", timeInc[i]['number'],timeInc[i]['startTime'],timeInc[i]['duration'])
        #
        # Calculo dos volumes bombeados no incremento i
        QVC = Caudal_VC(timeInc[i]['startTime'], timeInc[i]['endTime'])
        QR = Caudal_R(timeInc[i]['startTime'], timeInc[i]['endTime']); QRmed= QR/timeInc[i]['duration']
        #
        # Ciclo iterativo de convergÃªncia (com tolerancia=1.E-5)
        iter = 1; hFini = hF; hFmed = hF; deltahFold = 0.; tol = 1.E-6; maxIter = 8
        bRes = 2.*f32gpi2d5*LRF*QRmed/3600.
        aRes = aRes1 + aRes2
        aRes22= aRes11 + aRes2

        while iter < maxIter:
            cRes = a1-hFixo -f32gpi2d5*LRF*(QRmed/3600)**2 - hFmed
            cRes2 = a11-hFixo -f32gpi2d5*LRF*(QRmed/3600)**2 - hFmed
            iter += 1

        #caudais para cada incremento (Q1):
        Qpaux1.append(estrutura.copy());
        Qpaux2.append(estrutura.copy());
        Qpaux1[i]= (-bRes - math.sqrt(bRes**2 - 4 * aRes * cRes))/(2*aRes) * 3600
        Qpaux2[i]= (-bRes - math.sqrt(bRes**2 - 4 * aRes22 * cRes2))/(2*aRes22) * 3600
        #caudais modificados pelas leis da afinidade para cada incremento (Q2):
        Qpauxal1.append(estrutura.copy());
        Qpauxal2.append(estrutura.copy());
        Qpauxal1[i]= ((-bRes - math.sqrt(bRes**2 - 4 * aRes * cRes))/(2*aRes) * 3600)*M[i]
        Qpauxal2[i]= ((-bRes - math.sqrt(bRes**2 - 4 * aRes22 * cRes2))/(2*aRes22) * 3600)*MM[i]
        # Calculo da energia utilizada
        #H1:
        haux1.append(estrutura.copy());
        haux2.append(estrutura.copy());
        haux1[i]=a1+a2*Qpaux1[i]**2.;
        haux2[i]=a11+a22*Qpaux2[i]**2.;
        #H2:
        hauxal1.append(estrutura.copy());
        hauxal2.append(estrutura.copy());
        hauxal1[i]=M[i]**2*a1+a2*Qpauxal1[i]**2.;
        hauxal2[i]=MM[i]**2*a11+a22*Qpauxal2[i]**2.;

        x_curva_par.append(estrutura.copy());
        y_curva_par.append(estrutura.copy());
        x_curva_par = [math.sqrt((a11*MM[i]*MM[i]-a1*M[i]*M[i])/a2-a22),math.sqrt((-a1*M[i]*M[i])/a2)+math.sqrt((-a11*MM[i]*MM[i])/a22),
        math.sqrt((100-a1*M[i]*M[i])/(a2)) +math.sqrt((100-a11*MM[i]*MM[i])/(a22)),
        math.sqrt((200-a1*M[i]*M[i])/(a2))+math.sqrt((200-a11*MM[i]*MM[i])/(a22))]
        y_curva_par = [a1*M[i]*M[i]+a2*math.sqrt((a11*MM[i]*MM[i]-a1*M[i]*M[i])/a2-a22)*math.sqrt((a11*MM[i]*MM[i]-a1)/a2-a22),0,100,200]
        p2 = np.polyfit(x_curva_par,y_curva_par,2)
        p2_1.append(estrutura.copy());
        p2_0.append(estrutura.copy());
        p2_2.append(estrutura.copy());
        p2_1[i]=p2[1]
        p2_0[i]=p2[0]
        p2_2[i]=p2[2]

    for i in range(0, nInc):
        # definicao dos incrementos de tempo
        timeInc.append(empty_timeIncrem.copy())
        timeInc[i]['number'] = i + 1
        if i == 0:
            timeInc[i]['startTime'] = 0
            hF = hF0
            timeInc[i]['hFini'] = hF
        else:
            timeInc[i]['startTime'] = timeInc[i-1]['endTime']
            timeInc[i]['hFini'] = timeInc[i-1]['hFfin']
        timeInc[i]['duration'] = 24 / nInc
        timeInc[i]['endTime'] = timeInc[i]['startTime']+timeInc[i]['duration'];

        # Calculo dos volumes bombeados no incremento i
        QVC = Caudal_VC(timeInc[i]['startTime'], timeInc[i]['endTime'])
```

```
        QR = Caudal_R(timeInc[i]['startTime'], timeInc[i]['endTime']); QRmed= QR/timeInc[i]['duration']
        #
        # Ciclo iterativo de convergÃªncia (com tolerancia=1.E-5)
        iter = 1; hFini = hF; hFmed = hF; deltahFold = 0.; tol = 1.E-6; maxIter = 8
        bRes = 2.*f32gpi2d5*LRF*QRmed/3600.
        aRes = aRes1 + aRes2


        QQQ = symbols('QQQ')
        hpar.append(estrutura.copy());
        Qpar.append(estrutura.copy());
        eq2 = Eq(sys*QQQ*QQQ +100 - (MM[i]**2*a11+a22*QQQ**2.))
        sol2 = solve(eq2)
        Qpar2.append(estrutura.copy());
        Qpar2[i] = sol2[1]
        eq3 = Eq(sys*QQQ*QQQ +100 - (M[i]**2*a1+a2*QQQ**2.))
        sol3 = solve(eq3)
        Qpar3.append(estrutura.copy());
        Qpar3[i] = sol3[1]
        eq4 = Eq(sys*QQQ*QQQ + 100 -p2_0[i]*QQQ*QQQ - p2_1[i]*QQQ - p2_2[i])
        sol4 = solve(eq4)
        Qpar4.append(estrutura.copy());
        Qpar4[i] = sol4[1]
        Qpar[i]= (((Qpauxal1[i]-Qpar3[i])+(Qpauxal2[i]-Qpar2[i]))/2)+Qpar4[i]

        def paralelo(Q,M):
            if Qpar[i]> Qpar2[i]:
                return p2_0[i]*Q*Q + p2_1[i]*Q + p2_2[i]
            else:
                return (M[i]**2*a1+a2*Q**2.)

        Qpauxal2[i]=math.sqrt((hpar[i]-(MM[i]*MM[i]*a11))/a22)
        Qpauxal1[i]=Qpar[i]-Qpauxal2[i]
        Qpaux1[i]=(Qpar[i]-Qpauxal2[i])/M[i]
        Qpaux2[i]=(math.sqrt((hpar[i]-(MM[i]*MM[i]*a11))/a22))/MM[i]
        hauxal1[i]=M[i]**2*a1+a2*Qpauxal1[i]**2.;
        hauxal2[i]=MM[i]**2*a11+a22*Qpauxal2[i]**2.;

        #eta1:
        etaPaux1.append(estrutura.copy());
        etaPaux1[i]=(b1+b2*Qpaux1[i]+b3*Qpaux1[i]**2)
        etaPaux2.append(estrutura.copy());
        etaPaux2[i]=(b11+b22*Qpaux2[i]+b33*Qpaux2[i]**2)
        etaPauxal1.append(estrutura.copy());
        etaPauxal1[i]=(g*densidade*Qpauxal1[i]*(M[i]**2*a1+a2*Qpauxal1[i]**2.))/((g*densidade/etaPaux1[i]*Qp        aux1[i]*(a1+a2*Qpaux1[i]**2.))*(M[i]**3.))
        etaPauxal2.append(estrutura.copy());
        etaPauxal2[i]=(g*densidade*Qpauxal2[i]*(MM[i]**2*a11+a22*Qpauxal2[i]**2.))/((g*densidade/etaPaux2[        i]*Qpaux2[i]*(a11+a22*Qpaux2[i]**2.))*(MM[i]**3

        #eta2:
        etaPSB1.append(estrutura.copy());
        etaPSB2.append(estrutura.copy());
        etaPSB1[i]=1-(1-(b1+b2*Qpaux1[i]+b3*Qpaux1[i]**2))*((1/M[i])**0.1)
        etaPSB2[i]=1-(1-(b11+b22*Qpaux2[i]+b33*Qpaux2[i]**2))*((1/MM[i])**0.1)
        etaPparSB[i]=(etaPSB1[i]+etaPSB1[i])/2
        #eta3:
        etaPCAC1.append(estrutura.copy());
        etaPCAC2.append(estrutura.copy());
        etaPCAC1[i]=(b1+b2*(Qpaux1[i])+b3*(Qpaux1[i])**2)*((M[i]-1)**3+1)
        etaPCAC2[i]=(b11+b22*(Qpaux2[i])+b33*(Qpaux2[i])**2)*((MM[i]-1)**3+1)
        #P1:
        WPaux1.append(estrutura.copy());
        WPaux1[i]=g*densidade/etaPaux1[i]*Qpaux1[i]/3600*(a1+a2*Qpaux1[i]**2.)
        WPaux2.append(estrutura.copy());
        WPaux2[i]=g*densidade/etaPaux2[i]*Qpaux2[i]/3600*(a11+a22*Qpaux2[i]**2.)
        #P2:
        WPauxal1.append(estrutura.copy());
        WPauxal2.append(estrutura.copy());
        WPauxal1[i]=(g*densidade/etaPauxal1[i]*Qpaux1[i]/3600*(a1+a2*Qpaux1[i]**2.))*(M[i]**3.)  #in W
        WPauxal2[i]=(g*densidade/etaPauxal2[i]*Qpaux2[i]/3600*(a11+a22*Qpaux2[i]**2.))*(MM[i]**3.)  #in W

        #calculo da eficiencia VSD
        efi_vsd1[i]= eficiencia_vsd1(WPauxal1[i])
        efi_vsd1[i]= efi_vsd1[i]*10**-2
        efi_vsd2[i]= eficiencia_vsd2(WPauxal2[i])
        efi_vsd2[i]= efi_vsd2[i]*10**-2

        while iter < maxIter:
            cRes = a1-hFixo -f32gpi2d5*LRF*(QRmed/3600)**2 - hFmed
            cRes2 = a11-hFixo -f32gpi2d5*LRF*(QRmed/3600)**2 - hFmed
            Qp1 = ((-bRes - math.sqrt(bRes**2 - 4 * aRes * cRes))/(2*aRes) * 3600)*M[i]
            Qp2 = ((-bRes - math.sqrt(bRes**2 - 4 * aRes22 * cRes2))/(2*aRes22) * 3600)*MM[i]
            if x[i]>0 and y[i]>0 and x[i]>y[i]:
                deltahFn = ((Qpar[i]*y[i]+Qp1*(x[i]-y[i]))*timeInc[i]['duration']-QVC-QR)/AF
            elif x[i]>0 and y[i]>0 and y[i]>x[i]:
                deltahFn = ((Qpar[i]*x[i]+Qp2*(y[i]-x[i]))*timeInc[i]['duration']-QVC-QR)/AF
            elif x[i]==y[i]:
                deltahFn = ((Qpar[i]*y[i])*timeInc[i]['duration']-QVC-QR)/AF
            elif x[i]==0 and y[i]>0:
                deltahFn = ((Qp1*x[i])*timeInc[i]['duration']-QVC-QR)/AF
            elif y[0]==0 and y[i]>0:
```

```
                deltahFn = ((Qp2*y[i])*timeInc[i]['duration']-QVC-QR)/AF

            hF = hFini + deltahFn
            hFmed = hFini + deltahFn / 2

            if math.fabs(deltahFn-deltahFold) > tol:
                deltahFold = deltahFn
            else:
                break
            iter += 1
        timeInc[i]['hFfin']= hF



        tarifInc = tarifario(timeInc[i]['startTime'])*timeInc[i]['duration']/1000. # in Euro/W
        Custo1.append(estrutura.copy());
        Custo2.append(estrutura.copy());
        Custo3.append(estrutura.copy());
        Custo4.append(estrutura.copy());
        Custo5.append(estrutura.copy());
        Custo1[i]=0
        Custo2[i]=0
        Custo3[i]=0
        Custo4[i]=0
        Custo5[i]=0

        if x[i]>0 and y[i]>0 and x[i]>y[i]:
            Custo1[i]=(((x[i]-y[i])*WPauxal1[i]*tarifInc)/efi_vsd1[i])+((y[i]*WPpar[i]*tarifInc)/efi_vsd2[i])
            #calculos c\ eqs. paralelo (x2) & calculos c\ eqs.bomba 1  (x3=x1-x2)
        elif x[i]>0 and y[i]>0 and y[i]>x[i]:
            Custo2[i]=(((y[i]-x[i])*WPauxal2[i]*tarifInc)/efi_vsd2[i])+((x[i]*WPpar[i]*tarifInc)/efi_vsd2[i])
            #calculos c\ eqs. paralelo (x1) & calculos c\ eqs.bomba 2  (x3=x2-x1)
        elif x[i]==y[i]:
            Custo3[i]=(((y[i])*WPauxal2[i]*tarifInc)/efi_vsd2[i])+(((x[i])*WPauxal1[i]*tarifInc)/efi_vsd1[i])
            #calculos c\ eqs. paralelo (x3=x1=x2)
        elif x[i]==0 and y[i]>0:
            Custo4[i]=(((y[i])*WPauxal2[i]*tarifInc)/efi_vsd2[i])
            #calculos c\ eqs. Bomba 2 (x3=x2)
        elif y[0]==0 and y[i]>0:
            Custo5[i]=(((x[i])*WPauxal1[i]*tarifInc)/efi_vsd1[i])
            #calculos c\ eqs. Bomba 1 (x3=x1)



        #Custo =  ((x[i]*WPauxal1[i]*tarifInc)/efi_vsd1[i])+((y[i]*WPauxal2[i]*tarifInc)/efi_vsd2[i])
        #CustoT += Custo
        fObjRest['g1'].append(hmin - hF); fObjRest['g2'].append(hF - hmax);



        # Calculo de sensibilidades (aproximadas, pois consideram que Qp e independente de x)
        Sensibil['dCdx'].append(WPauxal1[i]*tarifInc);
        dgP=(Qp1+Qp2)*timeInc[i]['duration']/(AF + 0.5*x[i]*timeInc[i]['duration']*(bRes**2-4.*aRes*cRes)**(-0.5))
        #
        # ciclo para cada dg1dx[i][j], onde i=alfa do x; j=inc. e j>=alfa
        for j in range (i, nInc): Sensibil['dg1dx'][i][j]=-dgP; Sensibil['dg2dx'][i][j]=dgP;

    CustoT=(sum(Custo1))+(sum(Custo2))+(sum(Custo3))+(sum(Custo4))+(sum(Custo5))

    # Guardar valores em Arrays
    fObjRest['fObj']=CustoT;

    return fObjRest, Sensibil;

# main program (driver)
#----------------------
nInc = 24 #96 #24
# Declaracao de solucao

xt=[0.4 for i in range (0, 4*nInc)]
# 0.0 M = 0.7 | 0.2 M = 0.8 |0.4 M = 0.9 |0.6 M = 1 |0.8 M = 1.1 |1.0 M = 1.2
fObjRest, Sensibil = Benchmark2018(xt,1)


def fun_obj(xt):
    res, sens = Benchmark2018(xt,0)
    cost = res['fObj']
    return cost

def fun_constr_1(xt):
    res, sens = Benchmark2018(xt,0)
    g1 = res['g1']
    return g1

def fun_constr_2(xt):
    res, sens = Benchmark2018(xt,0)
    g2 = res['g2']
    return g2
```

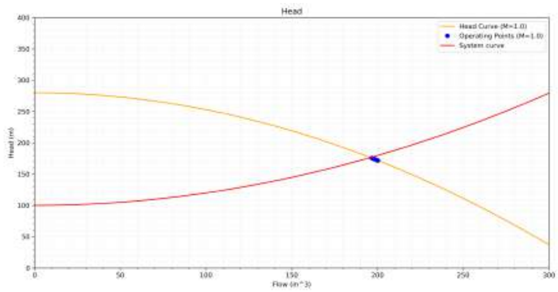
```
c1 = NonlinearConstraint(fun_constr_1, -9999999, 0, jac='2-point', hess=BFGS(), keep_feasible=False)
c2 = NonlinearConstraint(fun_constr_2, -9999999, 0, jac='2-point', hess=BFGS(), keep_feasible=False)
bounds = Bounds([0 for i in range(4*nInc)], [1 for i in range(4*nInc)], keep_feasible=False)
res = minimize(fun_obj, xt, args=(), method='trust-constr', jac='2-point', hess=BFGS(), constraints=[c1, c2],
                options={'verbose': 3}, bounds=bounds)

print("Solucao final: x=",[round(res.x[i], 3) for i in range(len(res.x))])

fObjRest, Sensibil = Benchmark2018(res.x,1)
print("CustoF=",fObjRest['fObj'], '\n')
```

Intentionally blank page.

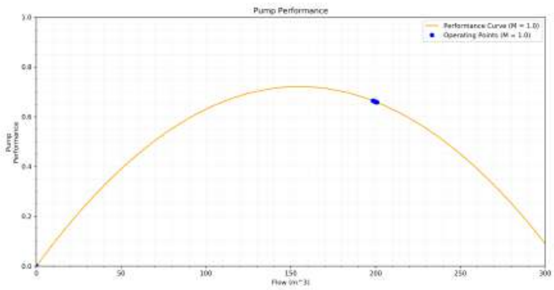
Appendix B

Results with SB

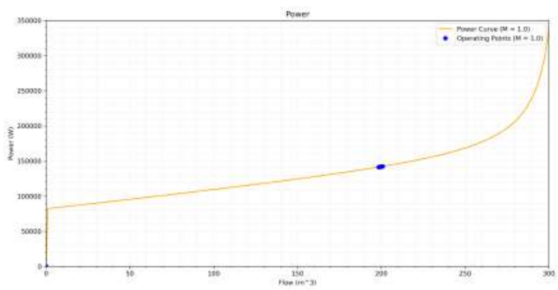
Case 1 - Scenario A



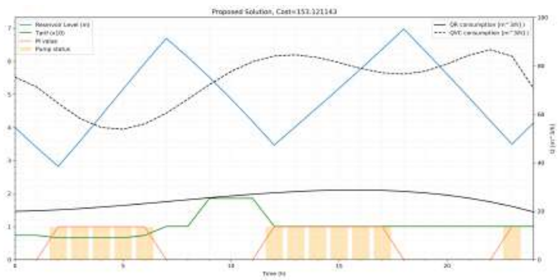
(a) Head Curve, Case 1 - Scenario A



(b) Performance Curve, Case 1 - Scenario A



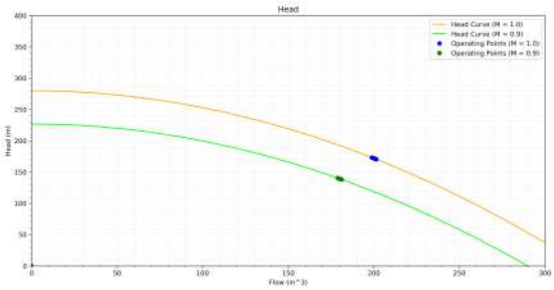
(c) Power Curve, Case 1 - Scenario A



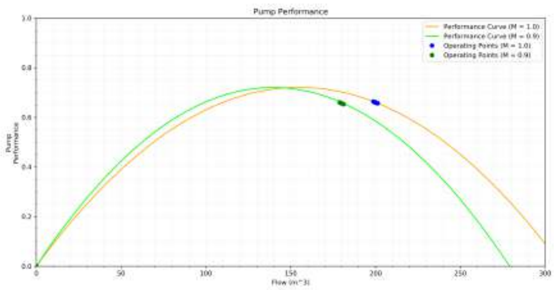
(d) Resume, Case 1 - Scenario A

Figure B.1: Case 1 - Scenario A

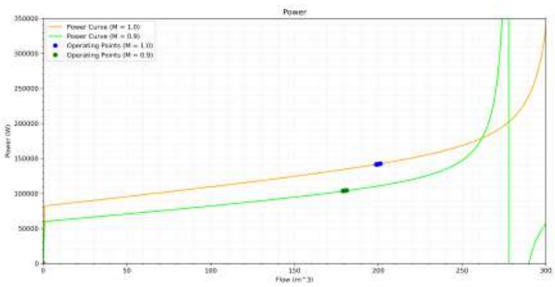
Case 1 - Scenario B - SB



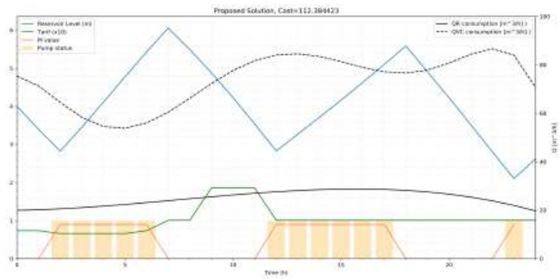
(a) Head Curve, Case 1 - Scenario B - SB



(b) Performance Curve, Case 1 - Scenario B - SB



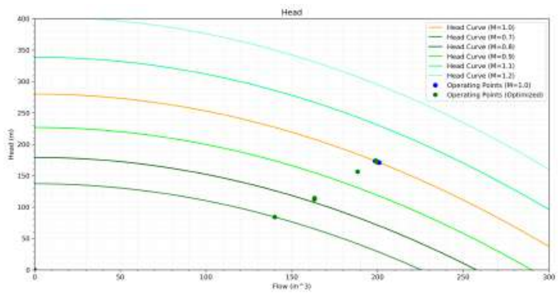
(c) Power Curve, Case 1 - Scenario B - SB



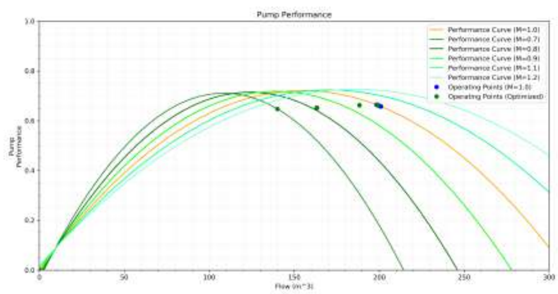
(d) Resume, Case 1 - Scenario B - SB

Figure B.2: Case 1 - Scenario B - SB

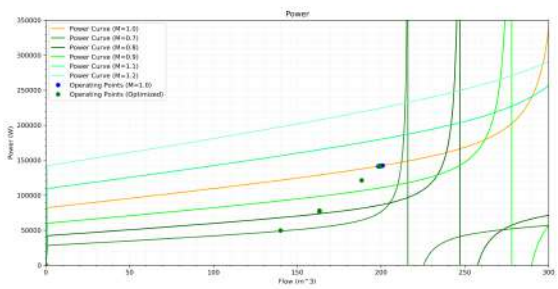
Case 1 - Scenario C - SB



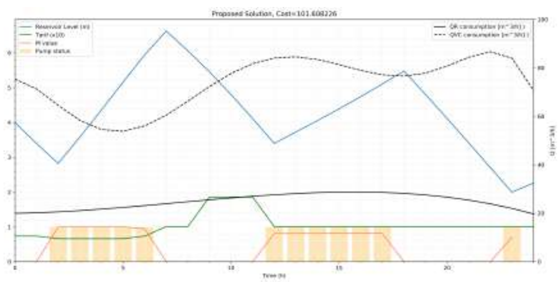
(a) Head Curve, Case 1 - Scenario C - SB



(b) Performance Curve, Case 1 - Scenario C - SB



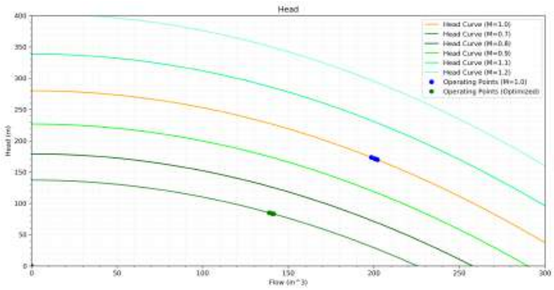
(c) Power Curve, Case 1 - Scenario C - SB



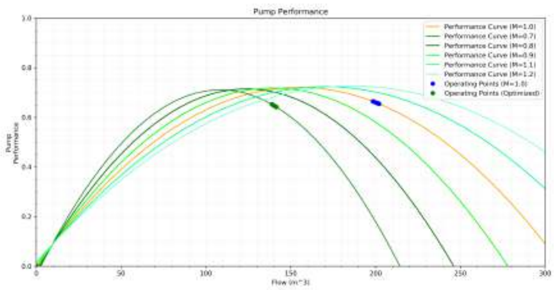
(d) Resume, Case 1 - Scenario C - SB

Figure B.3: Case 1 - Scenario C - SB

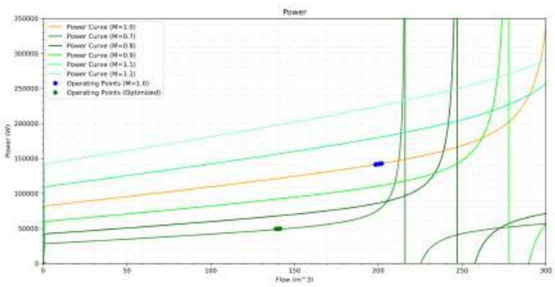
Case 1 - Scenario D - SB



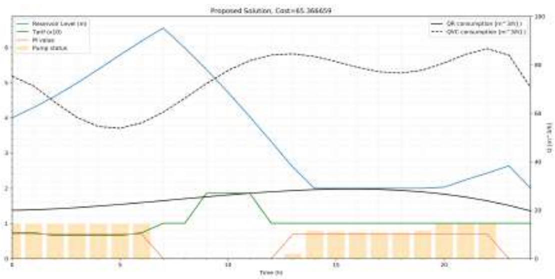
(a) Head Curve, Case 1 - Scenario D - SB



(b) Performance Curve, Case 1 - Scenario D - SB



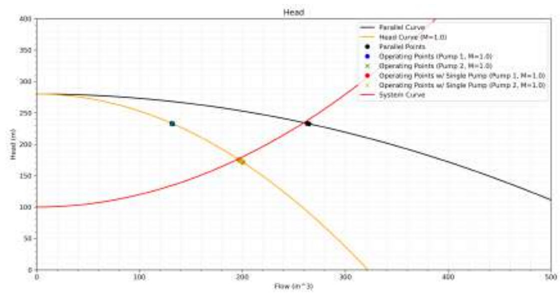
(c) Power Curve, Case 1 - Scenario D - SB



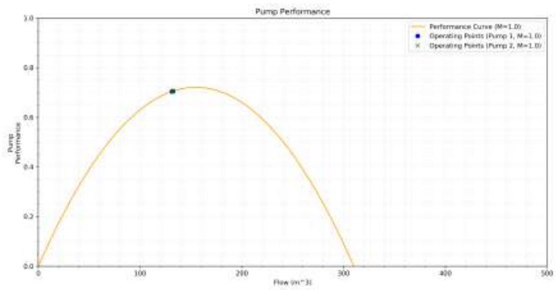
(d) Resume, Case 1 - Scenario D - SB

Figure B.4: Case 1 - Scenario D - SB

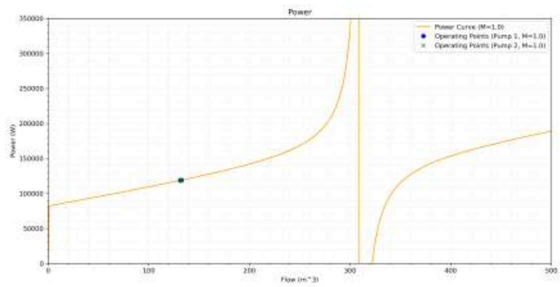
Case 2 - Scenario A



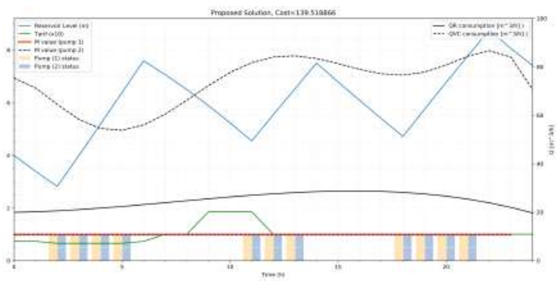
(a) Head Curve, Case 2 - Scenario A



(b) Performance Curve, Case 2 - Scenario A



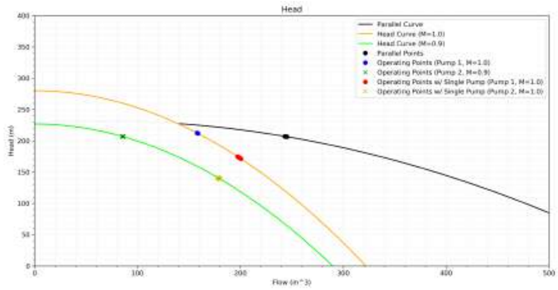
(c) Power Curve, Case 2 - Scenario A



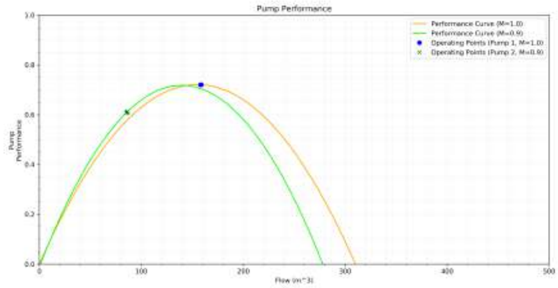
(d) Resume, Case 2 - Scenario A

Figure B.5: Case 2 - Scenario A

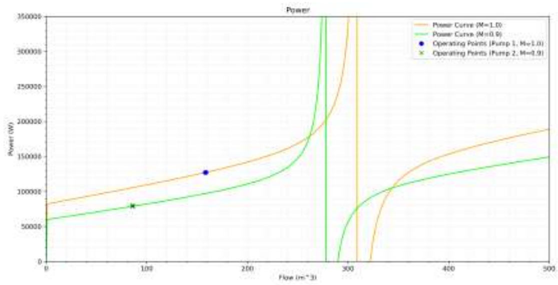
Case 2 - Scenario B - SB



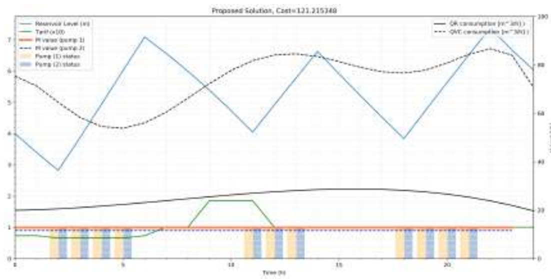
(a) Head Curve, Case 2 - Scenario B - SB



(b) Performance Curve, Case 2 - Scenario B - SB



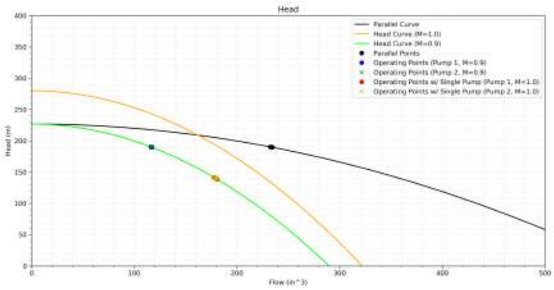
(c) Power Curve, Case 2 - Scenario B - SB



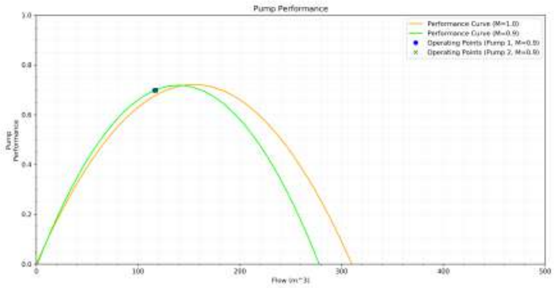
(d) Resume, Case 2 - Scenario B - SB

Figure B.6: Case 2 - Scenario B - SB

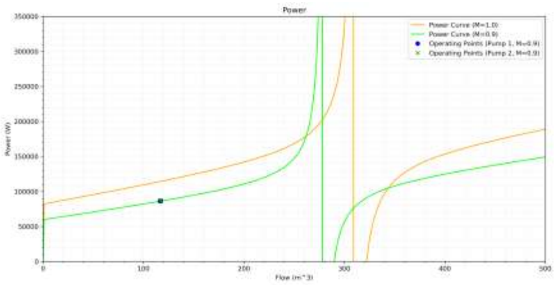
Case 2 - Scenario C - SB



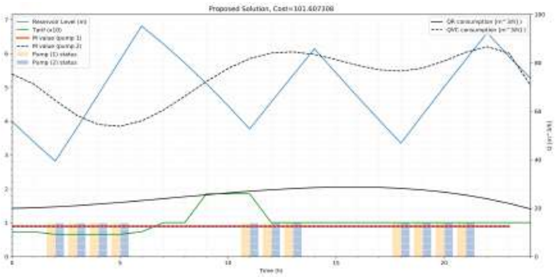
(a) Head Curve, Case 2 - Scenario C - SB



(b) Performance Curve, Case 2 - Scenario C - SB



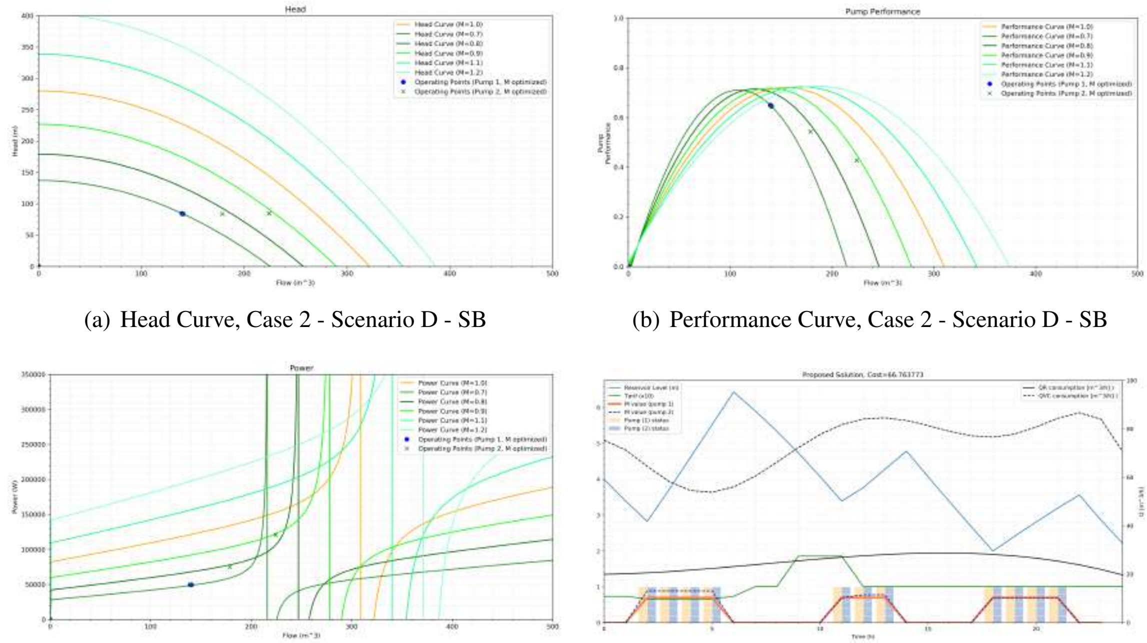
(c) Power Curve, Case 2 - Scenario C - SB



(d) Resume, Case 2 - Scenario C - SB

Figure B.7: Case 2 - Scenario C - SB

Case 2 - Scenario D - SB



(a) Head Curve, Case 2 - Scenario D - SB

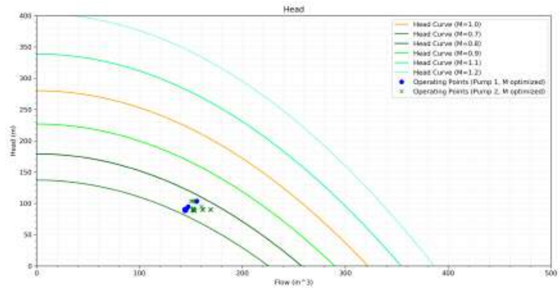
(b) Performance Curve, Case 2 - Scenario D - SB

(c) Power Curve, Case 2 - Scenario D - SB

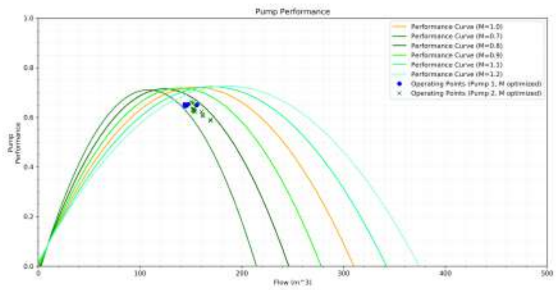
(d) Resume, Case 2 - Scenario D - SB

Figure B.8: Case 2 - Scenario D - SB

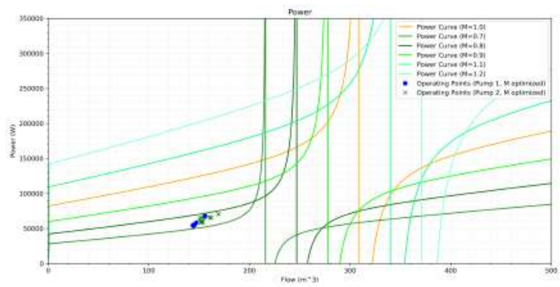
Case 2 - Scenario E - SB



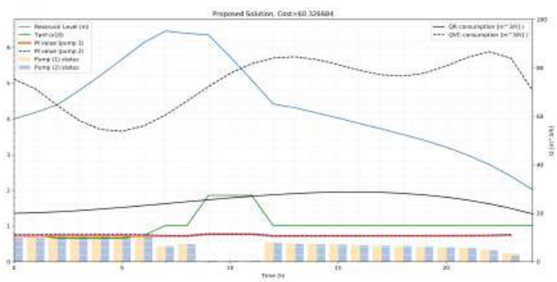
(a) Head Curve, Case 2 - Scenario E - SB



(b) Performance Curve, Case 2 - Scenario E - SB



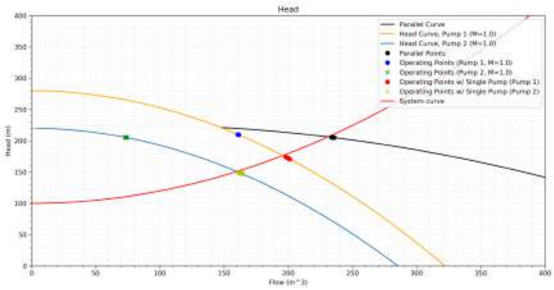
(c) Power Curve, Case 2 - Scenario E - SB



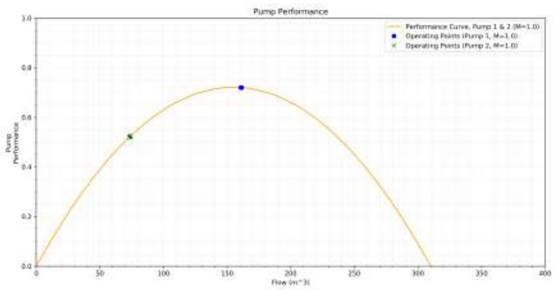
(d) Resume, Case 2 - Scenario E - SB

Figure B.9: Case 2 - Scenario E - SB

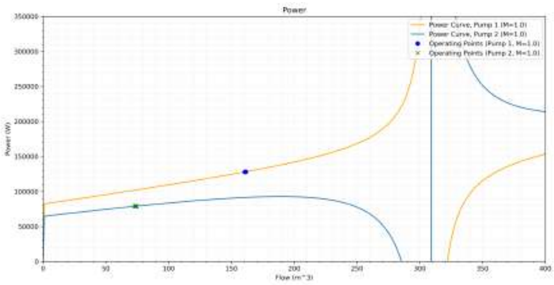
Case 3 - Scenario A



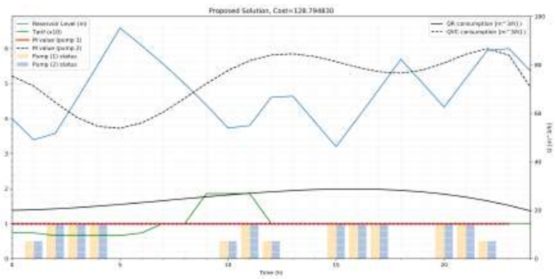
(a) Head Curve, Case 3 - Scenario A



(b) Performance Curve, Case 3 - Scenario A



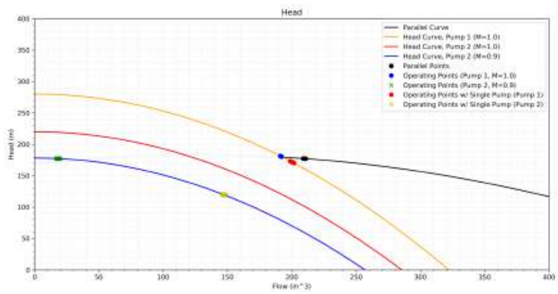
(c) Power Curve, Case 3 - Scenario A



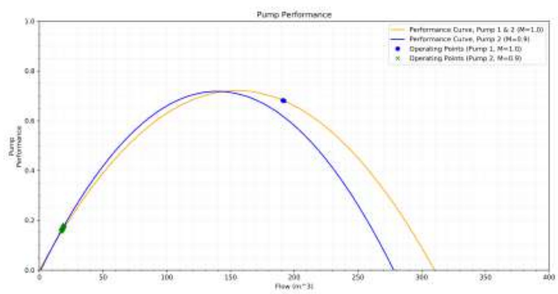
(d) Resume, Case 3 - Scenario A

Figure B.10: Case 3 - Scenario A

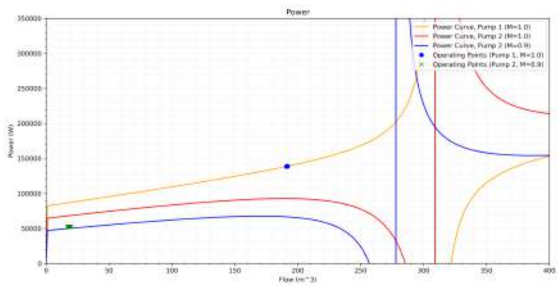
Case 3 - Scenario B - SB



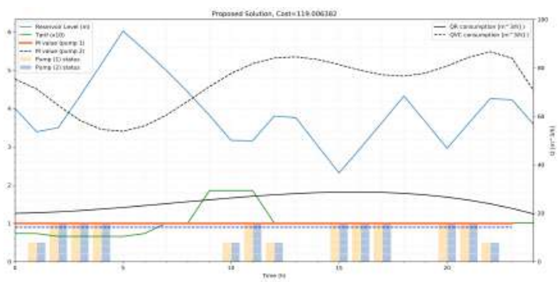
(a) Head Curve, Case 3 - Scenario B - SB



(b) Performance Curve, Case 3 - Scenario B - SB



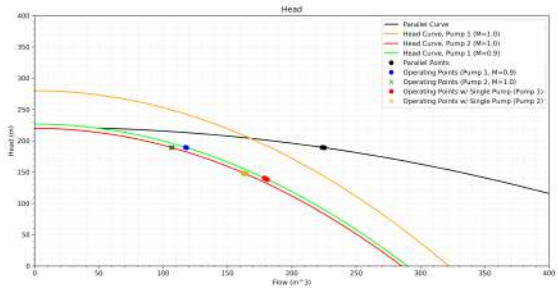
(c) Power Curve, Case 3 - Scenario B - SB



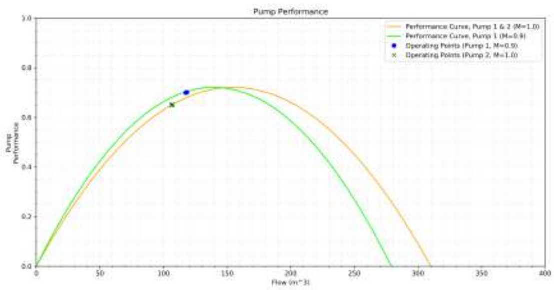
(d) Resume, Case 3 - Scenario B - SB

Figure B.11: Case 3 - Scenario B - SB

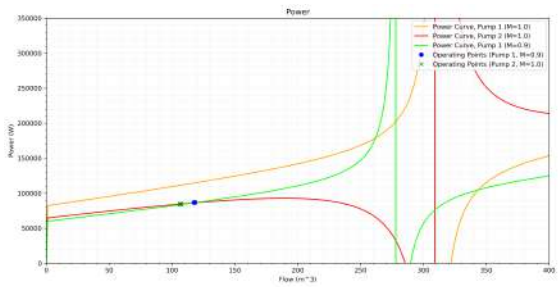
Case 3 - Scenario C - SB



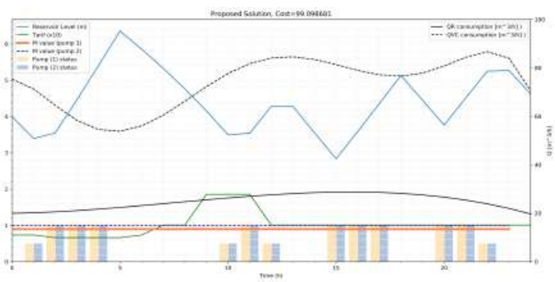
(a) Head Curve, Case 1 - Case 3 - Scenario C - SB



(b) Performance Curve, Case 3 - Scenario C - SB



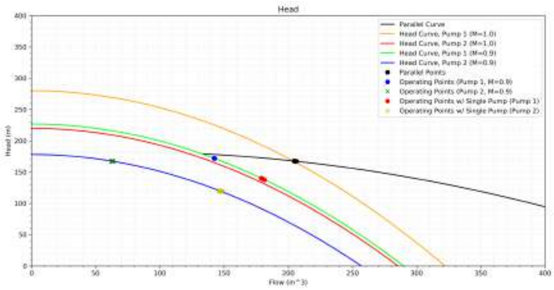
(c) Power Curve, Case 3 - Scenario C - SB



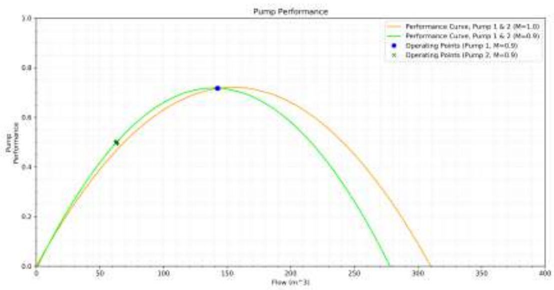
(d) Resume, Case 3 - Scenario C - SB

Figure B.12: Case 3 - Scenario C - SB

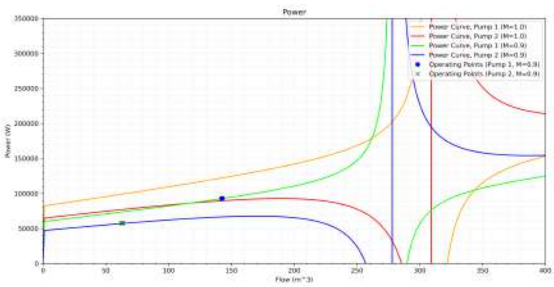
Case 3 - Scenario D - SB



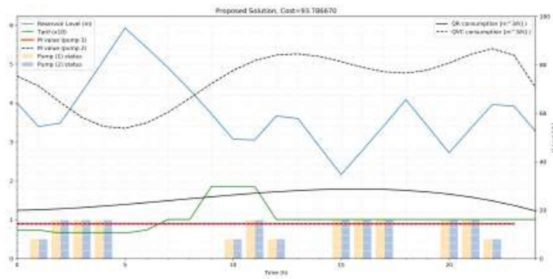
(a) Head Curve, Case 3 - Scenario D - SB



(b) Performance Curve, Case 3 - Scenario D - SB



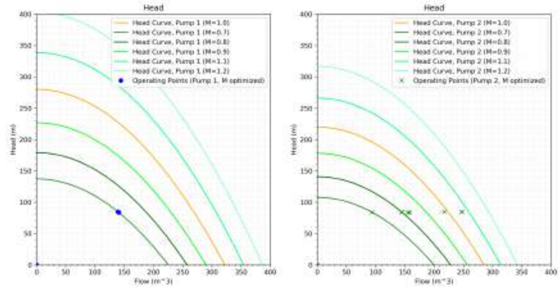
(c) Power Curve, Case 3 - Scenario D - SB



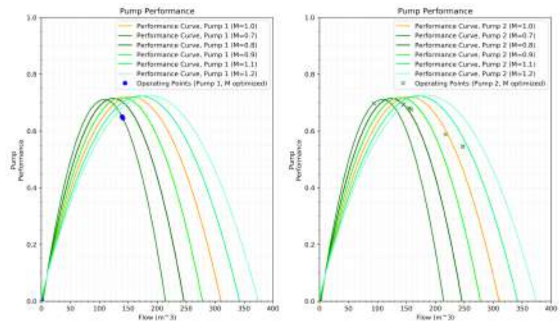
(d) Resume, Case 3 - Scenario D - SB

Figure B.13: Case 3 - Scenario D - SB

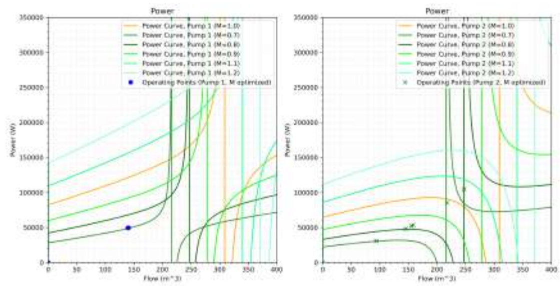
Case 3 - Scenario E - SB



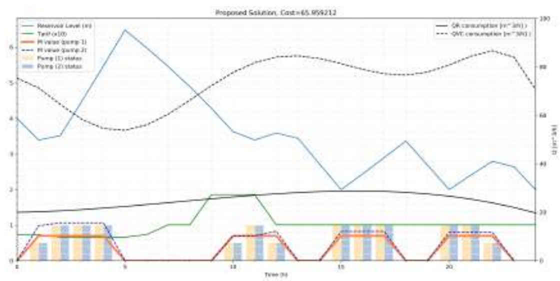
(a) Head Curve, Case 3 - Scenario E - SB



(b) Performance Curve, Case 3 - Scenario E - SB



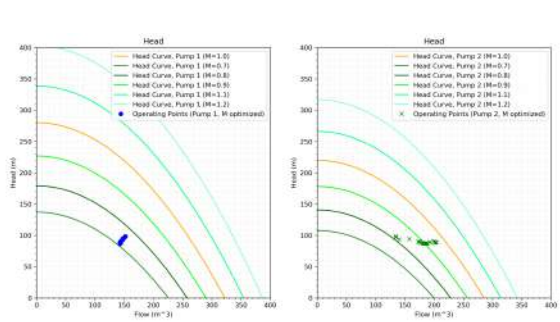
(c) Power Curve, Case 3 - Scenario E - SB



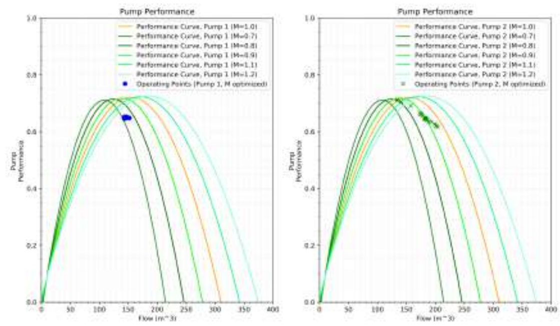
(d) Resume, Case 3 - Scenario E - SB

Figure B.14: Case 3 - Scenario E - SB

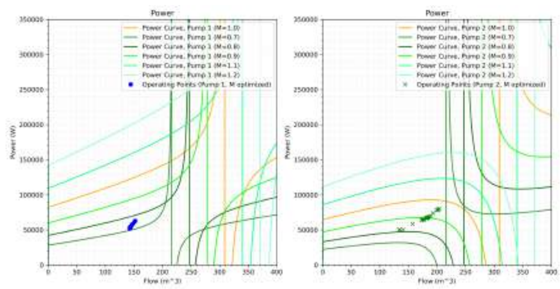
Case 3 - Scenario F - SB



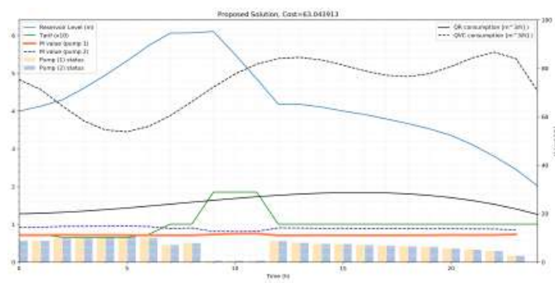
(a) Head Curve, Case 3 - Scenario F - SB



(b) PPerformance Curve, Case 3 - Scenario F - SB



(c) Power Curve, Case 3 - Scenario F - SB



(d) Resume, Case 3 - Scenario F - SB

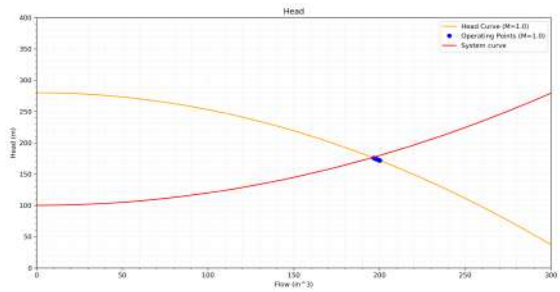
Figure B.15: Case 3 - Scenario F - SB

Intentionally blank page.

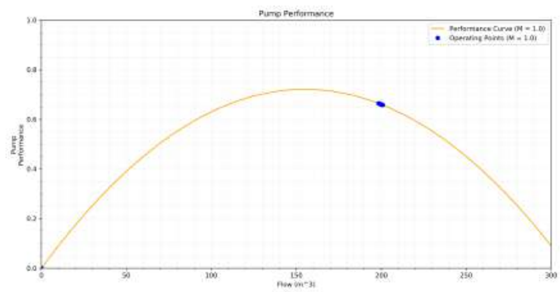
Appendix C

Results with CAC

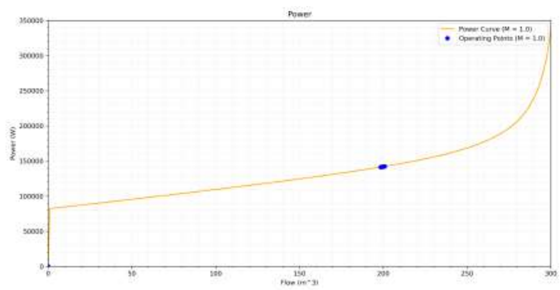
Case 1 - Scenario A



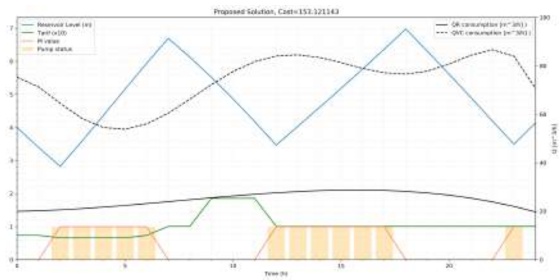
(a) Head Curve, Case 1 - Scenario A



(b) Performance Curve, Case 1 - Scenario A



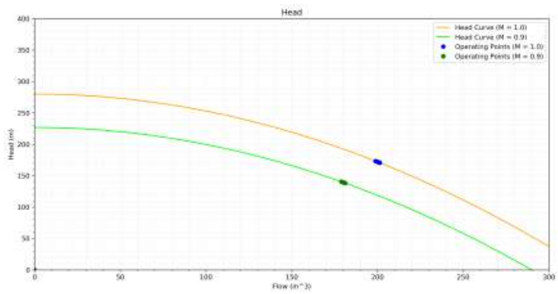
(c) Power Curve, Case 1 - Scenario A



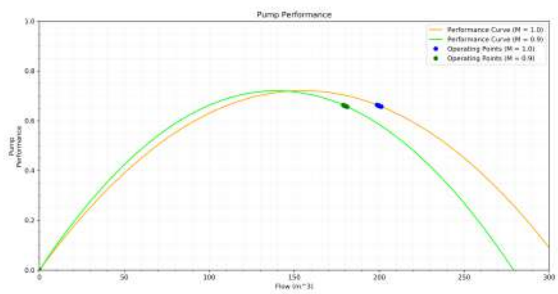
(d) Resume, Case 1 - Scenario A

Figure C.1: Case 1 - Scenario A

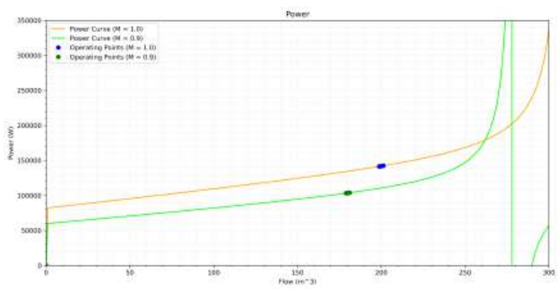
Case 1 - Scenario B - CAC



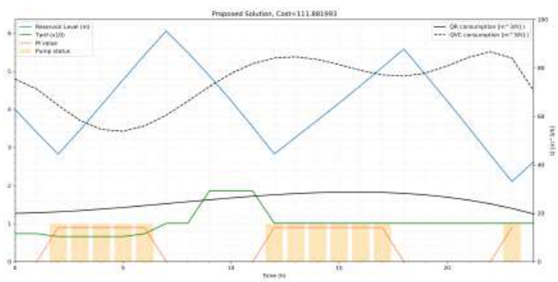
(a) Head Curve, Case 1 - Scenario B - CAC



(b) Performance Curve, Case 1 - Scenario B - CAC



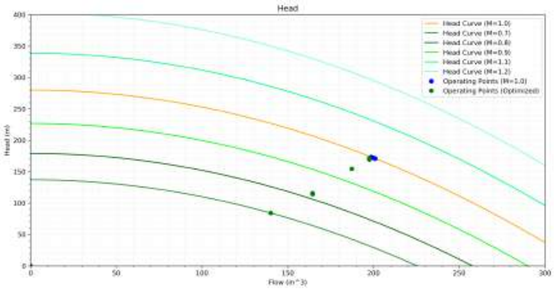
(c) Power Curve, Case 1 - Scenario B - CAC



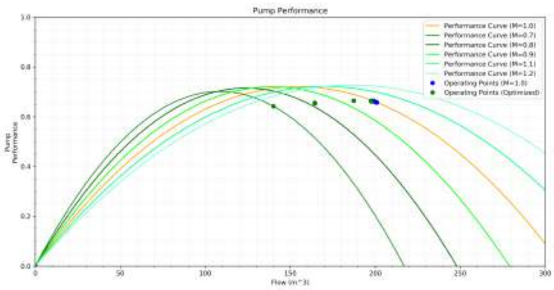
(d) Resume, Case 1 - Scenario B - CAC

Figure C.2: Case 1 - Scenario B - CAC

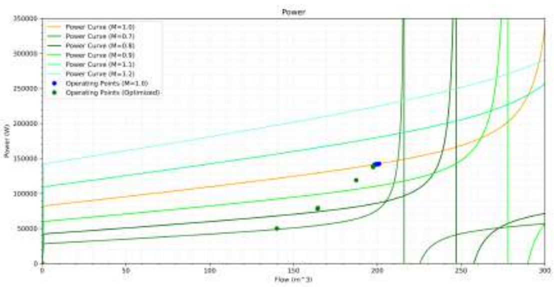
Case 1 - Scenario C - CAC



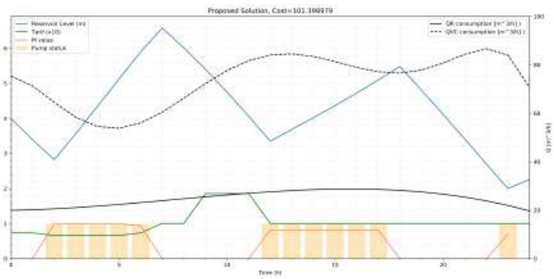
(a) Head Curve, Case 1 - Scenario C - CAC



(b) Performance Curve, Case 1 - Scenario C - CAC



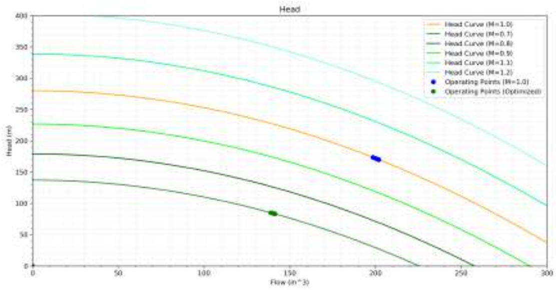
(c) Power Curve, Case 1 - Scenario C - CAC



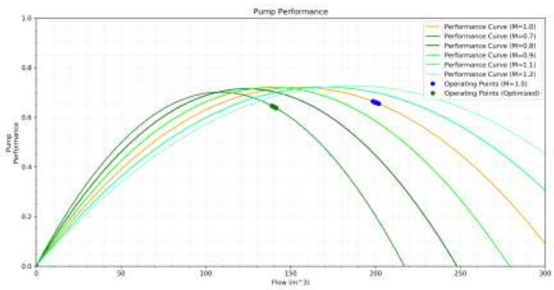
(d) Resume, Case 1 - Scenario C - CAC

Figure C.3: Case 1 - Scenario C - CAC

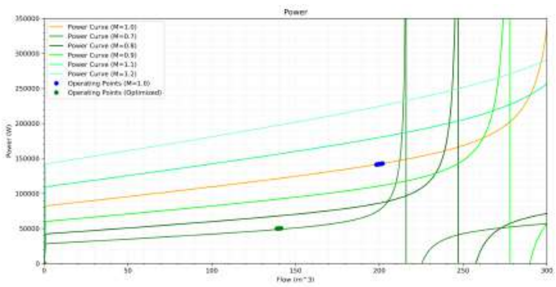
Case 1 - Scenario D - CAC



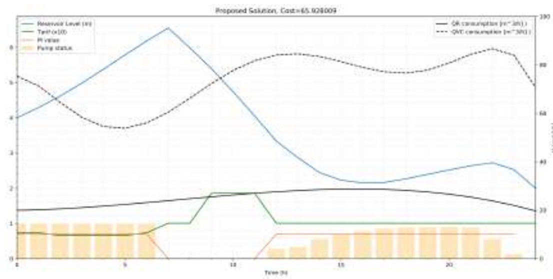
(a) Head Curve, Case 1 - Scenario D - CAC



(b) Performance Curve, Case 1 - Scenario D - CAC



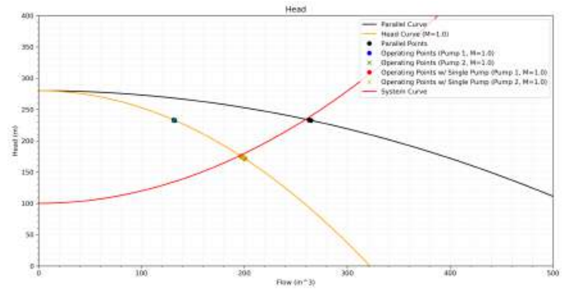
(c) Power Curve, Case 1 - Scenario D - CAC



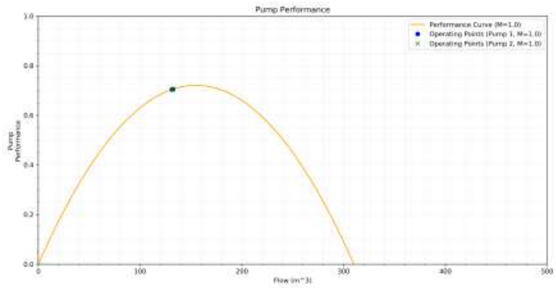
(d) Resume, Case 1 - Scenario D - CAC

Figure C.4: Case 1 - Scenario D - CAC

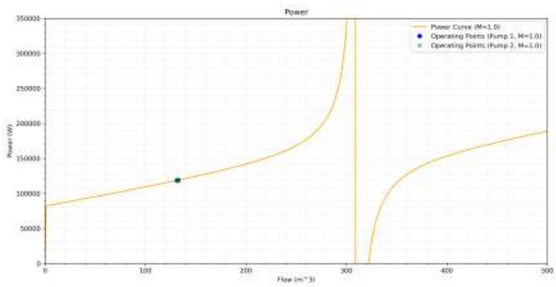
Case 2 - Scenario A



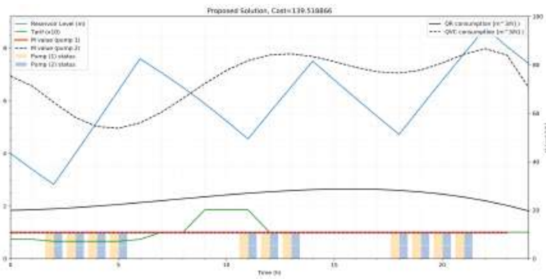
(a) Head Curve, Case 2 - Scenario A



(b) Performance Curve, Case 2 - Scenario A



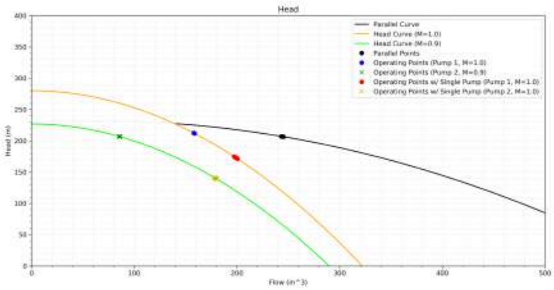
(c) Power Curve, Case 2 - Scenario A



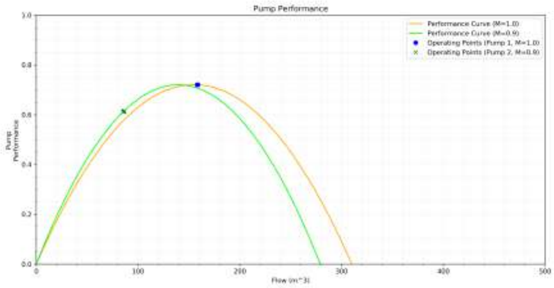
(d) Resume, Case 2 - Scenario A

Figure C.5: Case 2 - Scenario A

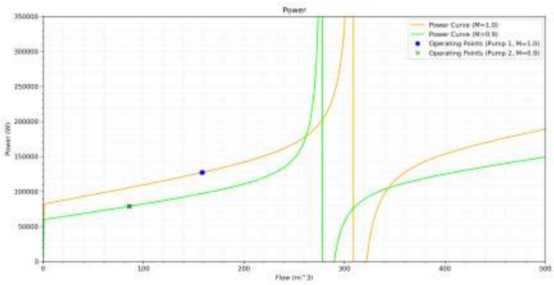
Case 2 - Scenario B - CAC



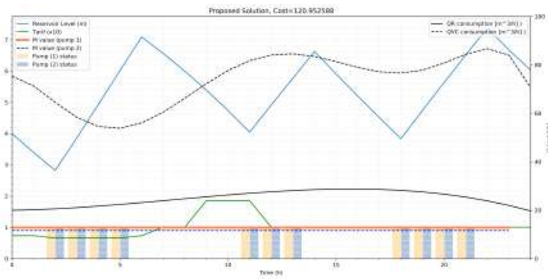
(a) Head Curve, Case 2 - Scenario B - CAC



(b) Performance Curve, Case 2 - Scenario B - CAC



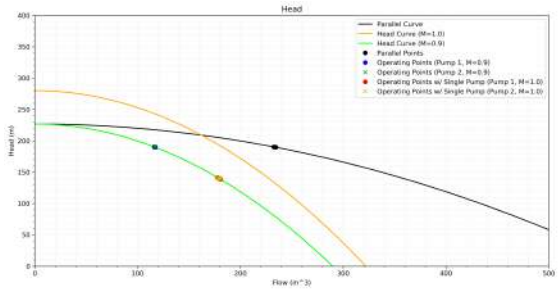
(c) PPower Curve, Case 2 - Scenario B - CAC



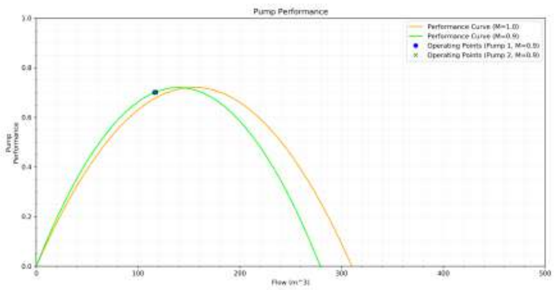
(d) Resume, Case 2 - Scenario B - CAC

Figure C.6: Case 2 - Scenario B - CAC

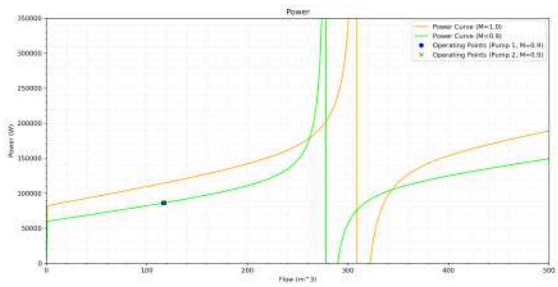
Case 2 - Scenario C - CAC



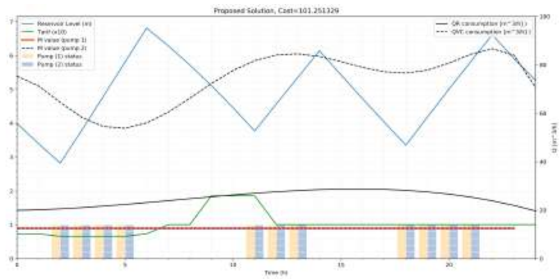
(a) Head Curve, Case 2 - Scenario C - CAC



(b) Performance Curve, Case 2 - Scenario C - CAC



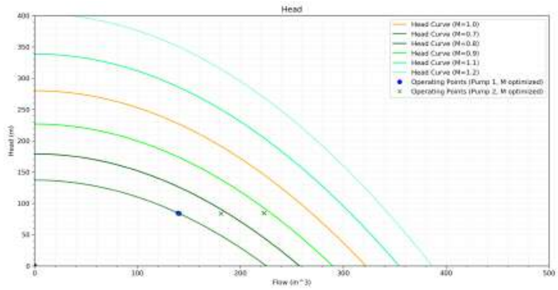
(c) Power Curve, Case 2 - Scenario C - CAC



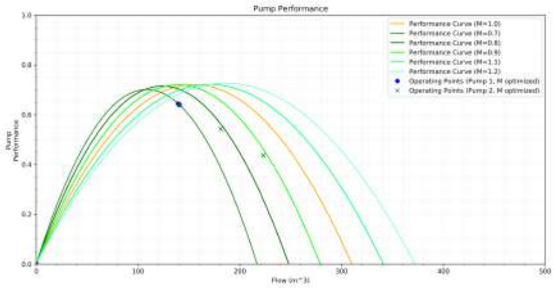
(d) Resume, Case 2 - Scenario C - CAC

Figure C.7: Case 2 - Scenario C - CAC

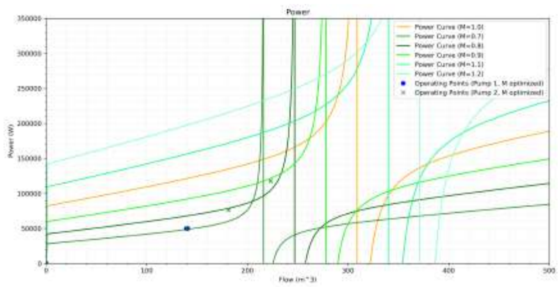
Case 2 - Scenario D - CAC



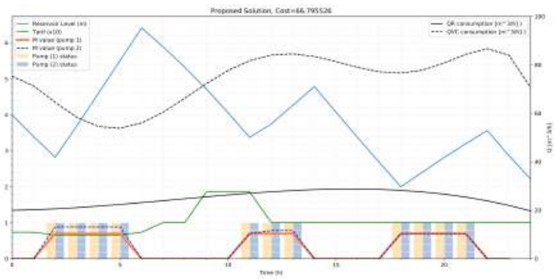
(a) Head Curve, Case 2 - Scenario D - CAC



(b) Performance Curve, Case 2 - Scenario D - CAC



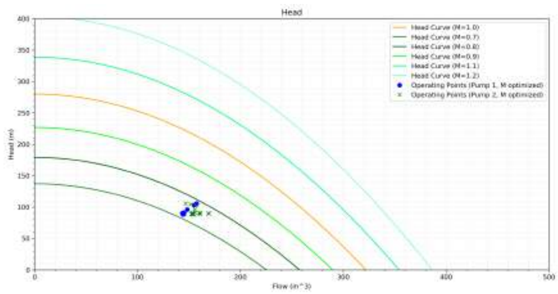
(c) Power Curve, Case 2 - Scenario D - CAC



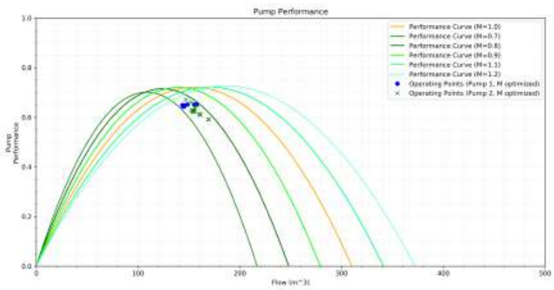
(d) Resume, Case 2 - Scenario D - CAC

Figure C.8: Case 2 - Scenario D - CAC

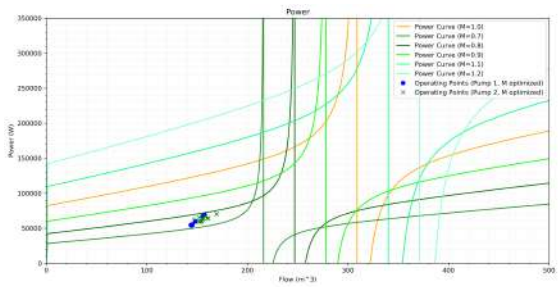
Case 2 - Scenario E - CAC



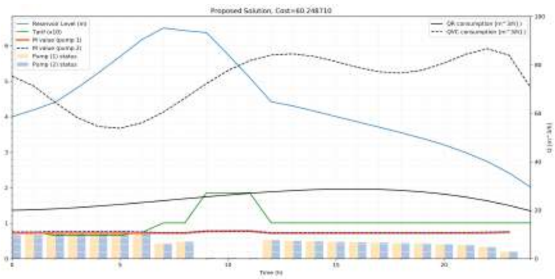
(a) Head Curve, Case 2 - Scenario E - CAC



(b) Performance Curve, Case 2 - Scenario E - CAC



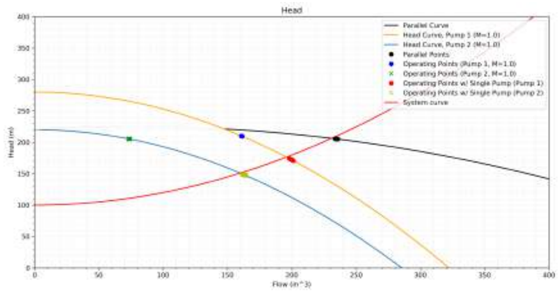
(c) Power Curve, Case 2 - Scenario E - CAC



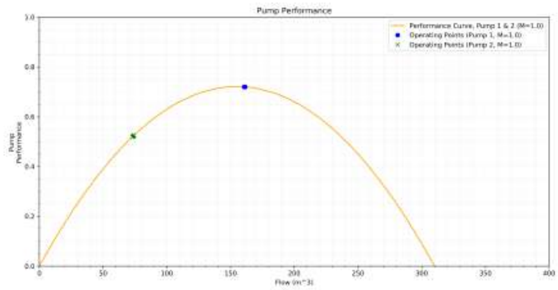
(d) Resume, Case 2 - Scenario E - CAC

Figure C.9: Case 2 - Scenario E - CAC

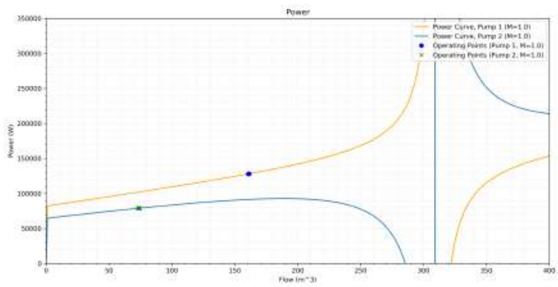
Case 3 - Scenario A



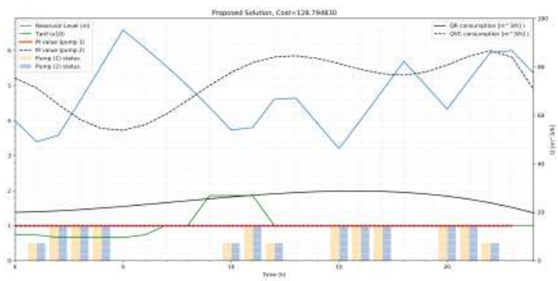
(a) Head Curve, Case 3 - Scenario A



(b) Performance Curve, Case 3 - Scenario A



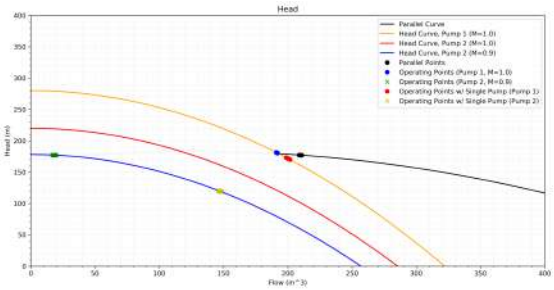
(c) Power Curve, Case 3 - Scenario A



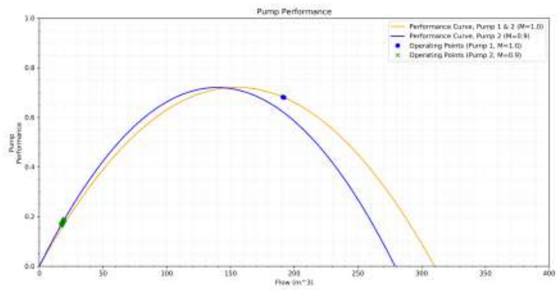
(d) Resume, Case 3 - Scenario A

Figure C.10: Case 3 - Scenario A

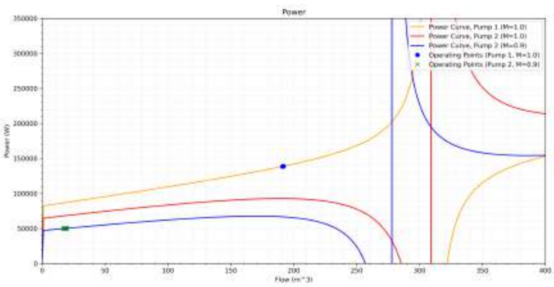
Case 3 - Scenario B - CAC



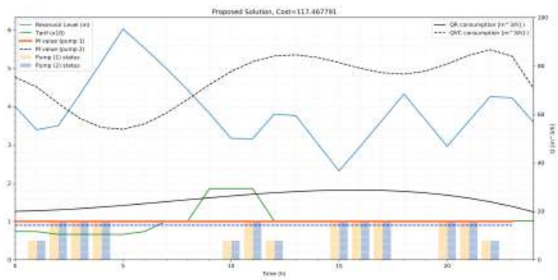
(a) Head Curve, Case 3 - Scenario B - CAC



(b) Performance Curve, Case 3 - Scenario B - CAC



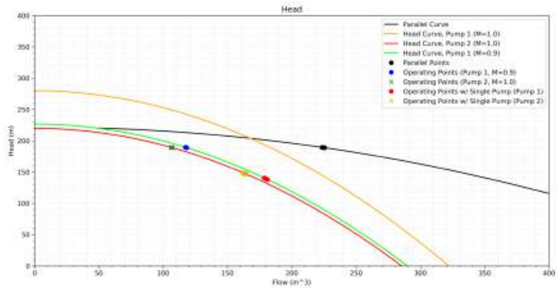
(c) Power Curve, Case 3 - Scenario B - CAC



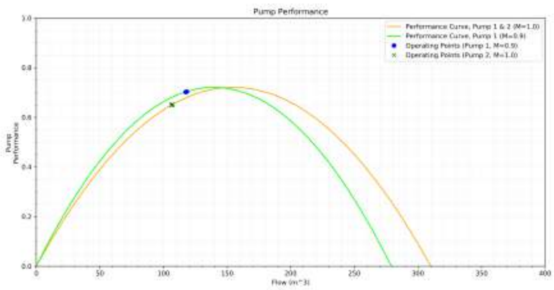
(d) Resume, Case 3 - Scenario B - CAC

Figure C.11: Case 3 - Scenario B - CAC

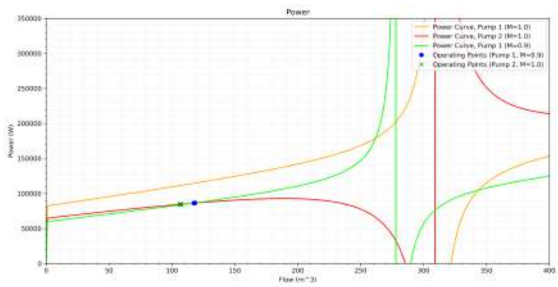
Case 3 - Scenario C - CAC



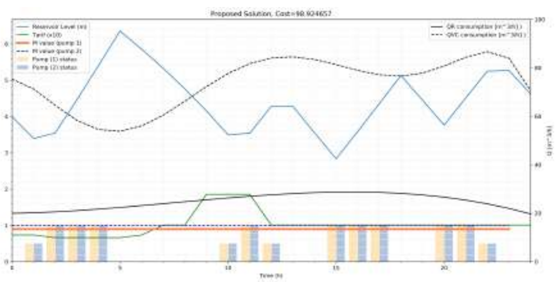
(a) Head Curve, Case 3 - Scenario C - CAC



(b) Performance Curve, Case 3 - Scenario C - CAC



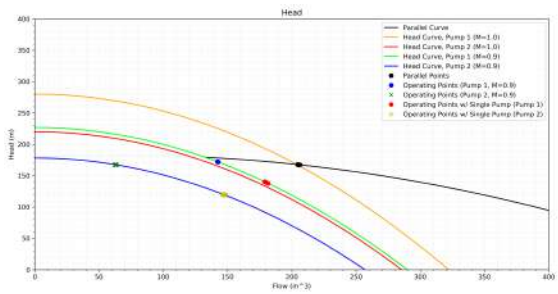
(c) Power Curve, Case 3 - Scenario C - CAC



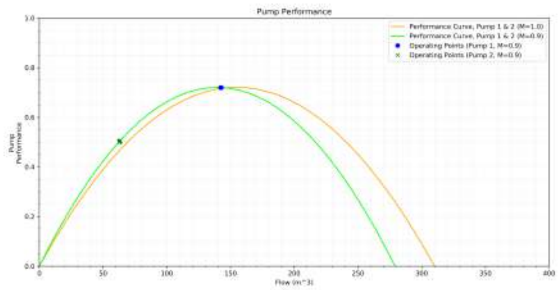
(d) Resume, Case 3 - Scenario C - CAC

Figure C.12: Case 3 - Scenario C - CAC

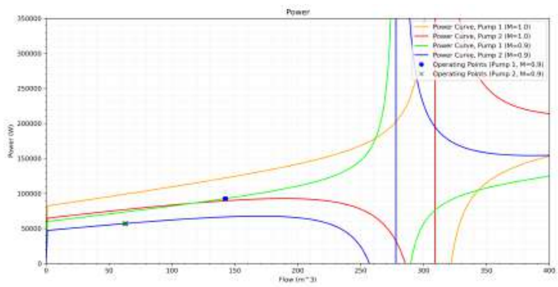
Case 3 - Scenario D - CAC



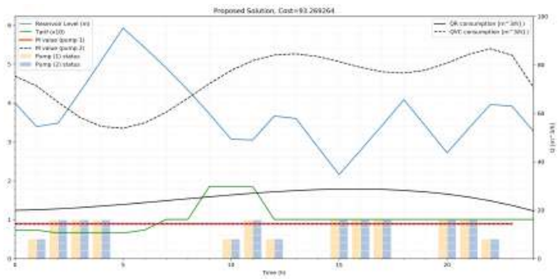
(a) Head Curve, Case 3 - Scenario D - CAC



(b) Performance Curve, Case 3 - Scenario D - CAC



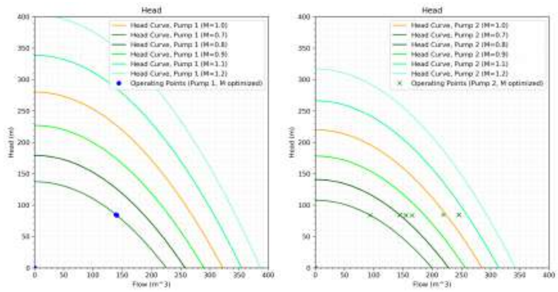
(c) Power Curve, Case 3 - Scenario D - CAC



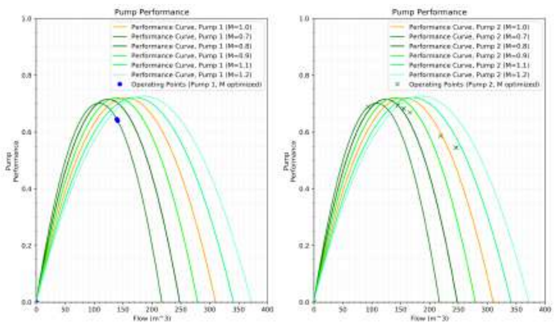
(d) Resume, Case 3 - Scenario D - CAC

Figure C.13: Case 3 - Scenario D - CAC

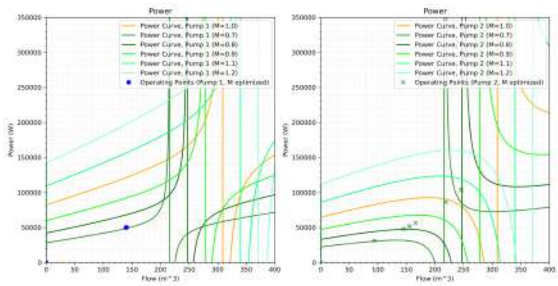
Case 3 - Scenario E - CAC



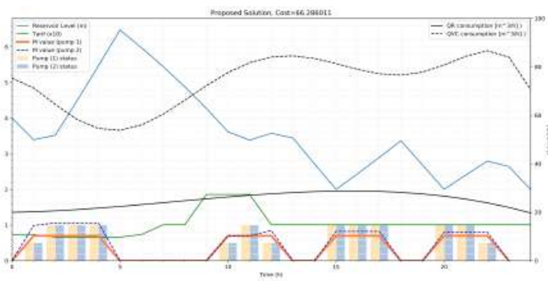
(a) Head Curve, Case 3 - Scenario E - CAC



(b) Performance Curve, Case 3 - Scenario E - CAC



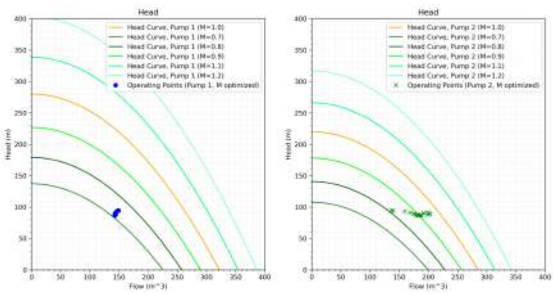
(c) Power Curve, Case 3 - Scenario E - CAC



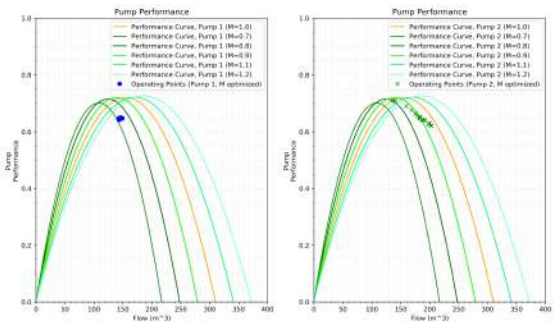
(d) Resume, Case 3 - Scenario E - CAC

Figure C.14: Case 3 - Scenario E - CAC

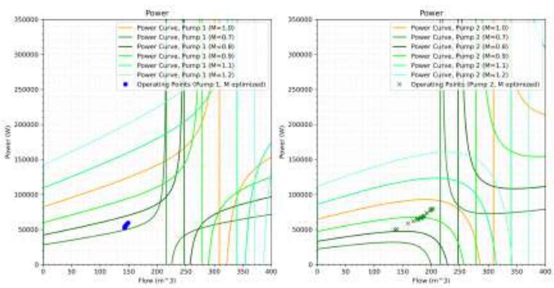
Case 3 - Scenario F - CAC



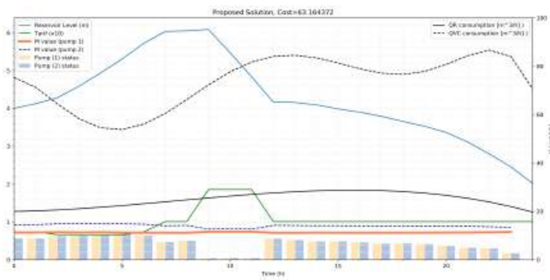
(a) Head Curve, Case 3 - Scenario F - CAC



(b) Performance Curve, Case 3 - Scenario F - CAC



(c) Power Curve, Case 3 - Scenario F - CAC



(d) Resume, Case 3 - Scenario F - CAC

Figure C.15: Case 3 - Scenario F - CAC