The Application of Fuzzy Sets to the Evaluation of Artificial Lift Systems for Petroleum Production

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***Abstract* – The evaluation of artificial lift systems for a given oilfield operation is an important step in the management of petroleum production. The evaluation must consider the specific advantages and disadvantages for each of the available technologies, covering a number of different attributes, such as well design, equipment installation and reliability, capital costs, operation and maintenance best-practices. The selection of an artificial lift system demands research and method to account for the information from the petroleum reservoir, the fluids within and the well design. The present work aims to develop a methodology for the evaluation of artificial lift, to simulate the expert knowledge using fuzzy sets and fuzzy logic theory.**

Keywords: Petroleum, Artificial Lift, Evaluation, Fuzzy Sets.

I. Introduction

Artificial lift systems are used to improve the production of petroleum from a well or from a group of wells, maximizing the profit of a production operation. As a petroleum reservoir is exploited, its pressure decreases; once it drops below the point were it is capable of driving the oil to the surface at a flow rate that offers financial return, the reservoir becomes a candidate to the installation of an artificial lift system in its wells. These lift systems are differentiated by the equipments that they employ to attend to specific field conditions. Some systems are mostly found in onshore wells while others are largely used offshore. The following systems are in operation on Brazilian oilfields: mechanical sucker rod pumps (SRP), progressive cavity pumps (PCP), centrifugal pumps (ESP), continuous gas lift (CGL) and intermittent gas lift (IGL) (Figure 1). So many options require a careful evaluation for the selection of the best alternative. The method of evaluation must examine lots of information regarding the oilfield and assess many parameters of the reservoir and its fluids, and the design of the well. Literature research and the advise of experts may help in the determination of which information is relevant and what criteria should be applied to the selection. The main objective of the present work is to gather and organize such knowledge, and to devise a decision process to aid the design engineer in his task of selecting an artificial lift system for a given job. Fuzzy logic was chosen to achieve this goal, because it provides the ability to deal with uncertainties and with non-deterministic description of attributes of quantitative and qualitative nature.

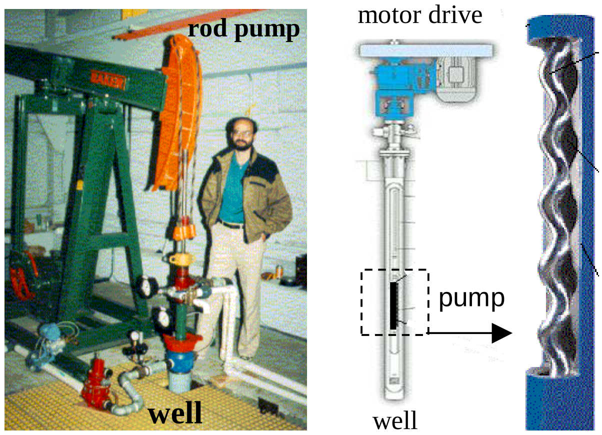

Figure 1a – Sucker Rod Pump (left) and Progressive Cavity Pump (right).

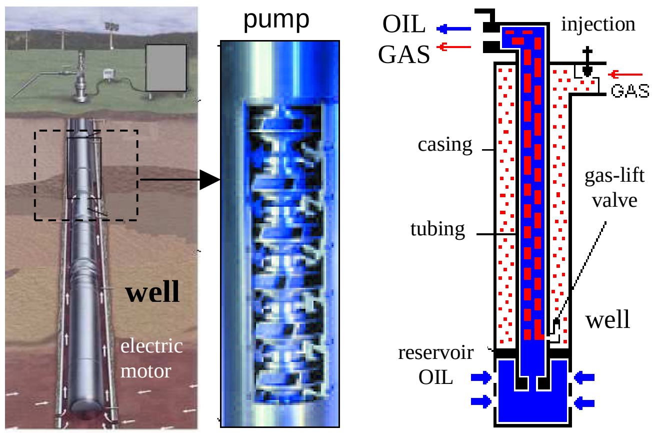

Figure 1b – Electric Submersible Centrifugal Pump (left) and Continuous Gas-lift (right).

II. Evaluation of Artificial Lift Systems

Matsatsinis et al (1997) [12] stresses that the definition of an evaluation model starts with the acquisition of expert knowledge, which entails the investigation and systemization of the information available in the literature, and is also derived from direct interviews with expert professionals. Comparative studies of different lift systems are presented in the works of Brown (1980) [3], Neely et al (1981) [14], Clegg et al (1992) [6], Bucaram et al (1994) [4], Campbell et al (1989) [5], Hein (1986) [7], Lea et al (1994) [10,11], Kunkel (2000) [9] and Jayasekera et al (2000) [8]. From a review of these papers, one may learn about the operational characteristics of the lift systems, and the recommended range of application for each system. Also, one may determine a list of parameters that would influence the choice of system to be employed under different field conditions – well completion, field location, productivity index, reservoir pressure, desired flow rate, well trajectory, well depth, gas-oil ratio, oil viscosity, sand production, paraffin precipitation, casing diameter, availability of electrical energy, availability of gas, operational challenges, well intervention issues etc. Besides, the authors of these papers acknowledge that geo-economic conditions and environment regulations may restrict the application of some methods. Another aspect of the selection process is that the engineer is prone to choose a system that is most familiar to him and to the field workers on whom the charge of operation will rest upon. This is a natural behavior concerning the issue of confidence on a well-proven system, and on the experience of the operation crew to respond correctly and quickly to everyday problems, and to keep the system working at its top efficiency. Nevertheless, this well-known system may not be the most adequate for the case at hand. In such instances, the training of the personnel will become a significant parameter.

In any case, the proper selection of a lift system is of paramount importance for production, because it has a long lasting effect on the life of an oilfield, and, moreover, because once a choice is made and a system is bought and installed, it will hardly ever be substituted; which means that the first choice ought to be the right one.

III. A Model for Evaluation of Artificial Lift Systems

The present work is restricted to onshore oilfields and to reservoirs of low static head – insufficient to bring the oil to the surface. This represents only the first step in the development of the evaluation methodology. In this stage, the aim was to validate the use of the fuzzy tools when applied to real life cases. The domain of study was determined by a partnership with the petroleum industry, due to the easiness and readiness of data acquisition through the company's channels. Another assumption, intrinsic to this first phase, is the availability of driving energy for the lift systems, might that be electric power lines, fuel, or a stable supply of compressed gas.

To build the evaluation model, the main parameters that describe an oilfield, its reservoirs and wells, were defined by a literature research and interviews with experts, as mentioned before. The model is flexible, therefore, the list of parameters may be changed as needed, and may not be considered as definite. Although this implies a certain amount of subjectivity, it must be remembered that it was based on the accumulated knowledge of experienced professionals and authors.

Once the parameters were chosen, they were treated as linguistic variables with fuzzy values; then, the operational characteristics of the lift systems were indicated by their response to these parameters – a qualitative attribute, to which fuzzy values were assigned. Next, the evaluation criteria were defined and organized as modules of fuzzy rules, attempting to simulate the thought process of the experts. Then, the model was tested to check if it would differentiate the various lift systems on the basis of the field conditions. Finally, the model was applied to real cases to validate its results.

Two general criteria were established for the evaluation model: the *technical viability* and the *economic viability*. These represent the major hurdles for any system performance. The *technical viability* answers the question "is it fit for the job?"; **if not**, the system is discarded, **otherwise**, it is a potential candidate, **but** still one may ask "how well does it do the job?", in order to rank the candidates according to their performance. In essence, these questions deal with the concept of effectiveness – "is it effective?" and "how effective is it?". Obviously, both answers are not strictly deterministic (although they may be treated as so) – they may be expressed by degrees, in terms of fuzzy values, thus defining the *efficacy*.

Following a traditional quantitative approach, one might relate the efficacy to a single variable, the oil production for instance, then, define a scale based on a reference value, and compute the efficacy as the rate of the actual oil production to that reference value, using rational numbers. This method would be recommended as the final step of the design process, when the list of candidate systems would have been reduced to the most qualified systems. In the final stage of design, such complex calculations are justified. When first selecting the candidates, though, one employs a qualitative approach, which seems to run through decision-expressways based on expert experience – no numbers are used, the performance of the system is qualified as "low", "high" etc, which are linguistic values of a qualitative nature. Also, the efficacy is known to depend on many parameters, and the technical viability is not defined by a single variable. This is enough to motivate the investigation of the application of fuzzy sets and fuzzy logic to the selection of lift systems.

Furthermore, there is the issue of uncertainty, which appears in both quantitative and qualitative approaches. Although it is possible to deal with uncertainties, under a deterministic approach, using the concept of standard deviation and statistical tools, this procedure may become quite cumbersome, and again, would be recommended for the play-off. On the other hand, uncertainties are a natural feature of linguistic values and fuzzy sets, embedded intrinsically in the process. Uncertainties play a significant role in the resolution of the selection process, since they affect the ability to differentiate between systems; therefore, it is imperative to take uncertainties into account. Uncertainties are most important when two or more lift systems fare almost equally well. Sometimes, the difference between two systems actually means a technical tie, and does not warrant the declaration of a winner. However, fuzzy sets neatly account for that, providing a measure of the probability that one of the systems might outperform the other and vice-versa.

The *economic viability* is a backbreaker. Simplistically, it considers whether wagering on an artificial lift system will pay off. A lift system may technically be able to do a job, and even, do it well, but that is of no avail if the operation loses money. Many criteria may be used to qualify the profit: the Net Present Value (NPV), the Internal Rate of Return (IRR), schemes that combine both the NPV and the IRR, or other economic variables. The economics of petroleum production is affected by the location of the field, the availability of energy, the installation already present in the field, the efficiency of the system etc. At this point, economic constraints were not included in the evaluation, but they may me inserted as the work progresses. Again, the objective of this first stage was to test the applicability of fuzzy sets to an engineering problem that has been treated in a traditional manner. Once fuzzy sets are accepted as a tool for the technical analysis of artificial lift systems, the work should be extended to analyze the economic aspects of the decision process.

Partial criteria were defined to evaluate the *technical viability* – *well-adequacy*, *reservoir-adequacy*, *fluid-adequacy*. In the case of *fluid-adequacy*, the following issues were considered – fluidness, corrosiveness, abrasiveness (Figure 2).

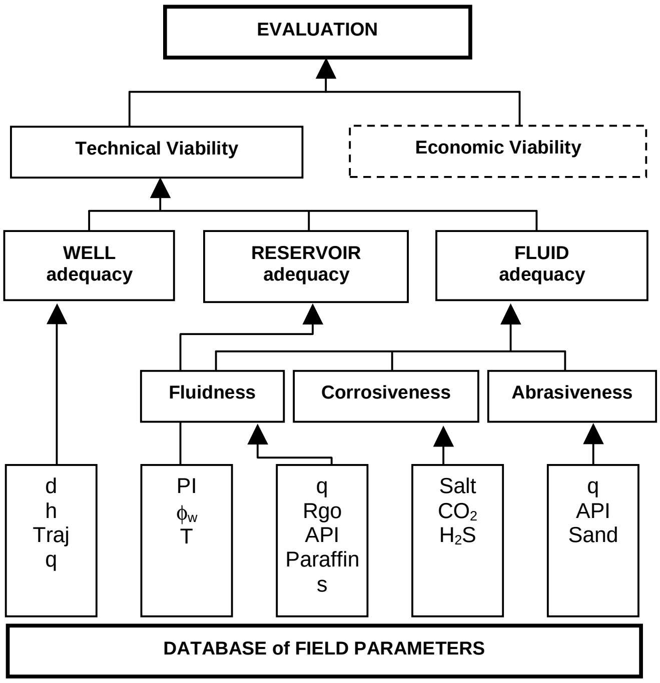

Figure 2 - Evaluation model.

Table 1 shows the parameters of the evaluation model. For the *technical viability*, one finds physical parameters that affect the mechanical performance, while, for the *economic viability*, parameters that have an impact on the financial profile are listed. The two lists are not dogmas, they may be modified as the model evolves.

The technical parameters were described by linguistic variables, through the theory of fuzzy sets according to Zadeh (1965) [15], Azevedo (1995) [1], Bojadziev et al. (1995) [2] and Mohaghegh (2000) [13]. For instance, the *depth* is described as ***low, medium, high***. Also, this attribute is not defined deterministically; that is, its value is not defined exclusively, and it is not treated by a binary function (1 = yes, 0 = no). The attribute is defined by a continuous function that represents the degree to which the parameter belongs to the value set. The degree of pertinence (μ) is a rational number between zero and one. Therefore, one needs a vector with as many elements as the number of sets; in this example, three elements $\{\mu_L, \mu_M, \mu_H\}$ to express the pertinence to the three sets (low, medium, high). Figure 3 illustrates this example.

Table 1 - Model parameters.

Technical viability	*Economic viability*
Well diameter (d)	Initial investment
Well depth (h)	Efficiency
Well trajectory (Traj)	Availability
Reservoir productivity index (PI)	Operation costs
	Maintenance
Reservoir temperature (T)	Decommission
Oil production rate (q)	Surface layout
Gas-oil ratio (R_{go})	Well-bottom equipment
Water fraction (ϕ_w)	Flexibility of operation
Submergence (s)	Driving flexibility
Oil API (API)	Noise level
Sand/solids (Sand)	Monitoring conditions
Salinity (Salt)	Well testing
Paraffin	Mean time between failure
H_2S	
CO_2	Personnel training

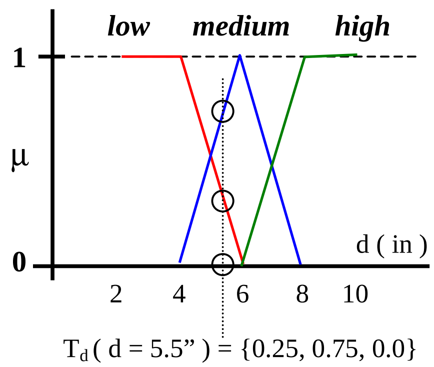

Figure 3 – Fuzzy Attributes.

When all the parameters are determined, the field and operation conditions become defined. Then, **rules** of inference, based on expert reasoning, are employed to reach a diagnosis regarding the application of each lift system. The evaluation is expressed by a linguistic variable, the *recommendation*, which has four sets: ***not recommended*** (NR)**,** ***recommended with restriction*** (RR)**,** ***recommended without restriction*** (RO)**,** ***strongly recommended*** (SR). Figure 4 represents the process. The total number of rules used for each evaluation module, *well-adequacy*, *reservoir-adequacy*, *fluid-adequacy*, are, respectively, 81, 27 and 108.

IV. Case Study – Evaluation of Real Wells.

The following is a report on the first case study to verify the consistency of the evaluation model. This collection of onshore wells was selected randomly, from groups of representative wells. The oil company collaborating with this research provided the data (Table 2). When comparing the recommendations from the model with the actual lift systems operating in the field, an agreement of almost 80% was observed (Table 3).

It must be remarked that this first case study does not cover a large variation on all the parameters, and the authors believe that further tests are required. Nevertheless, these first results are promising.

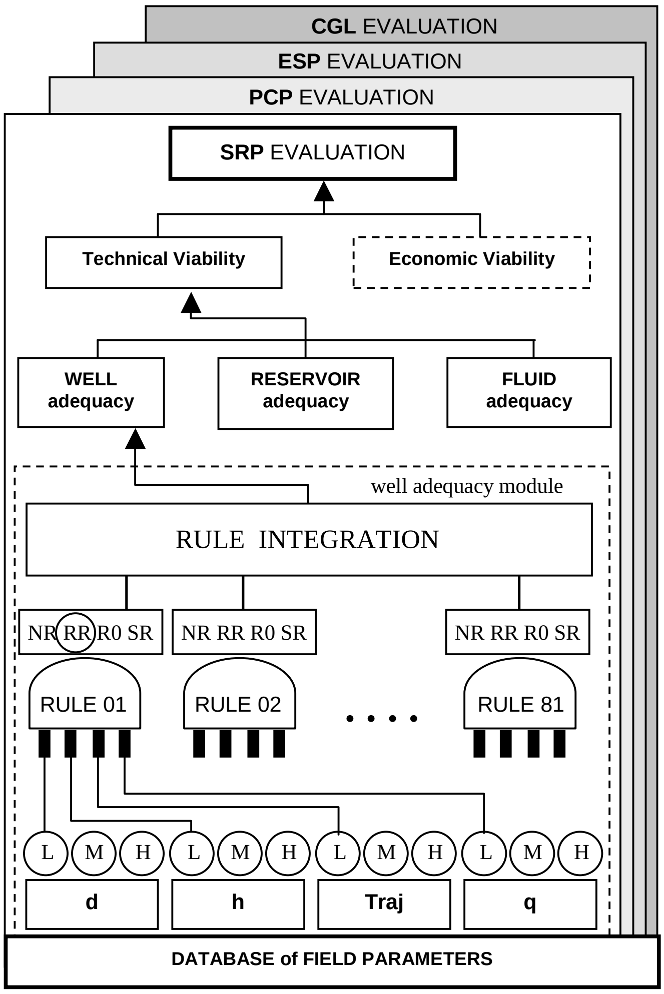

Figure 4 – Model wiring, depicting a detail of the well adequacy module

When investigating the cases were a disagreement occurred, it was found that the model underestimated the influence of free-gas on the performance of PCPs, for wells 01 and 02. This may be easily corrected. Also it was noted that the second option, for wells 01 and 02, is the ESP, but with such low flow rates, the revenue may not warrant that choice of lift system. At the same time, there is an ample supply of compressed gas in the field around those wells. Therefore, the CGL system is **economically** justified. Since the model does not account for economic parameters, at this time, it is not able to consider such arguments. This emphasize the need to attach the economic module to the evaluation procedure.

In the case of well 04, the physical conditions clearly favor the use of ESP or SRP, as indicated by the model, but the field operator installed a PCP because at the time of completion no other equipment was available. Consequently this decision was arbitrated by an **economic** factor – again, outside of the scope of the model.

Finally, in the case of well 09, it was a close run between the PCP and the ESP, almost a tie, and the operator decided to go with the ESP due to the high PI of the reservoir and other issues of an **economic** nature.

It is reasonable to conclude that the disagreements in all four cases could be mitigated by economic considerations, naturally beyond the technical viability.

All things considered, the proposed method is suitable for the selection of artificial lift systems, but it needs improvement.

V. Concluding Remarks

The fuzzy approach to the task of selecting artificial lift systems presented good convergence with the choices of oil production professionals. Although the first case study was restricted to a small sample of onshore wells, the results are encouraging.

The proposed model takes into account simultaneously many parameters that are important to the decision process, through fuzzy rules of inference. The parameters are represented by linguistic variables amenable to the description of attributes by expert knowledge, using fuzzy sets.

The model is flexible and may be improved without difficulty with regard to the computer coding. The main requirement for evolution is the accretion of knowledge, either from the literature or directly from interviews with experts. Suggestions for improvement may comprise the extension to offshore wells, heavy oils and other artificial lift systems.

Besides being useful for design purposes, the model may be employed in the training of young professionals, thus promoting the transfer of knowledge from one generation of employees to the next, inside a petroleum company, preserving the company's intelligence.

Acknowledgements

The authors are in debt to CAPES/MEC and PRH-ANP/MME-MCT for scholarships, PETROBRAS for well data, CEPETRO/UNICAMP and the Department of Petroleum Engineering/FEM/UNICAMP for material support and computer resources, and the Laboratory of Artificial Intelligence for Petroleum Production of DEP/FEM/ UNICAMP for sharing their knowledge. Special thanks are due to Dr. Manuel Barreto Filho (Petrobras) for invaluable advice.

Table 2 - Real well data.

Well	d (in)	h (m)	T (^oF)	Traj.	q (m^3/d)	ϕ_w %	R_{go} (m^3/m^3)	PI ($m^3/d.bar$)	API	Salt	Paraffin	H_2S	$C0_2$	Sand
01	7	1600	163	V	52	94	250	1.0	36	H	N	N	N	N
02	5 ½	970	129	V	42	80	130	3.0	37	H	Y	Y	N	N
03	7	615	110	D	55	78	10	2.6	33	L	Y	N	N	Y
04	7	700	114	D	140	95	10	3.0	33	L	N	N	N	Y
05	5 ½	680	113	D	167	96	10	2.8	33	L	Y	Y	N	Y
06	5 ½	640	111	D	129	93	10	2.2	33	L	Y	N	N	Y
07	5 ½	650	112	V	128	95	10	2.2	33	L	N	Y	N	Y
08	7	620	110	D	300	96	10	31.	33	L	N	N	N	Y
09	5 ½	650	112	V	175	92	10	20.	33	L	N	N	N	Y
10	5 ½	665	112	V	7	0	100	0.7	33	L	Y	Y	Y	Y
11	5 ½	705	115	V	11	45	20	1.0	33	L	Y	Y	Y	Y
12	5 ½	690	114	V	7	18	40	2.4	33	L	Y	Y	Y	Y
13	5 ½	685	114	V	13	38	70	1.5	33	L	Y	Y	Y	Y
14	7	620	110	D	15	48	10	1.0	33	L	Y	N	N	Y
15	5 ½	650	112	V	7	12	100	0.8	33	L	Y	Y	Y	Y
16	5 ½	620	110	V	24	66	80	3.1	33	L	Y	Y	Y	Y
17	5 ½	560	107	V	19	66	10	4.1	33	L	Y	Y	N	Y
18	7	595	109	D	19	73	10	1.4	33	L	Y	N	N	Y
19	7	635	111	D	32	42	10	4.1	33	L	Y	N	N	Y

Legend: d = diameter, h = depth, T = temperature, Traj. = trajectory, q = production rate, ϕ_w = water fraction, R_{go} = gas-oil ratio, PI = productivity index, API = API degree, V = vertical, D = directional, H = high, L = low, Y = yes, N = No.

Table 3 - Results for the real wells (adequacy index).

Well	SRP	PCP	ESP	CGL	Model Recommendation	System Operating in the Field
01	0.4099	**0.5492**	0.5173	0.4932	**PCP**	**CGL**
02	0.4468	**0.5596**	0.5177	0.4753	**PCP**	**CGL**
03	0.4583	**0.5014**	0.4729	0.4276	PCP	PCP
04	0.4912	0.4664	**0.5356**	0.4787	**ESP**	**PCP**
05	0.4718	**0.4935**	0.4735	0.4779	PCP	PCP
06	0.5083	**0.5392**	0.4811	0.4785	PCP	PCP
07	0.4715	**0.5084**	0.4814	0.4786	PCP	PCP
08	0.3855	0.4343	**0.5284**	0.4887	ESP	ESP
09	0.4577	**0.5660**	0.5481	0.4777	**PCP**	**ESP**
10	**0.4640**	0.3990	0.3366	0.3069	SRP	SRP
11	**0.4723**	0.3888	0.4491	0.3195	SRP	SRP
12	**0.4640**	0.4117	0.3668	0.3142	SRP	SRP
13	**0.4829**	0.4785	0.4559	0.4619	SRP	SRP
14	**0.4749**	0.4321	0.4452	0.2922	SRP	SRP
15	**0.4751**	0.4127	0.3474	0.3029	SRP	SRP
16	**0.4842**	0.3986	0.4516	0.3285	SRP	SRP
17	**0.4550**	0.3936	0.4475	0.3175	SRP	SRP
18	**0.4481**	0.4217	0.4541	0.3849	SRP	SRP
19	**0.4810**	0.4445	0.4349	0.2986	SRP	SRP

Legend: SRP = (mechanical) Rod Pump, PCP = Progressive Cavity Pump, ESP = Electric Submersible (centrifugal) Pump, CGL = continuous gas-lift.

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