Operational Reliability Assessment of a Remotely-controlled Siphon System for Draining Shallow Storage Ponds

Linlong Bian[1], Vivek Verma[2], Aditia Rojiali[3], Sumit R. Zanje[3], Dogukan Ozecik[4], and Arturo S. Leon[5]

[1]Department of Civil and Environmental Engineering, Florida International University; e-mail: lbian003@fiu.edu
[2]Department of Civil and Environmental Engineering, Florida International University; e-mail: vverm002@fiu.edu
[3]Department of Civil and Environmental Engineering, Florida International University; e-mail: aroja164@fiu.edu
[4]Department of Civil and Environmental Engineering, Florida International University; e-mail: dozec001@fiu.edu
[5]Department of Civil and Environmental Engineering, Florida International University; e-mail: arleon@fiu.edu

ABSTRACT

This paper presents the operational reliability assessment of a remotely controlled siphon system. The siphon system consists of water level switches, air vents, bilge pumps, etc. In this study, the reliability block diagram (RBD) model based on the ExtendSim software is applied to assess the operational reliability of a remotely-controlled siphon system. The Monte-Carlo simulation results from the RBD model demonstrate that the operational availability of the non-repairable siphon system can be enhanced from 0.683 to 0.855 within a 1-year life cycle by increasing the redundancy for the vulnerable components, such as the water level switch and the air vent. The value can increase to 0.999 when adopting an on-site maintenance strategy. Based on the analysis of multiple scenarios and maintenance strategies, a suitable architecture of the siphon system is proposed herein.

INTRODUCTION

Operational reliability can be defined as the mean of the probability that a system is functioning adequately over any given time (Chen 2013). It is also defined as the average availability of a system, which reflects the system ability to operate continuously (Trivedi 2012). The operational reliability index is widely used to optimize system design, performance, and operational strategy. The simulation approach is often employed to evaluate the operational reliability of the system (Raje 2000).

Qin et al. (2019) proposed an architecture of a self-operating and remotely-controlled siphon system. The proposed siphon system involves multiple components including water level switches (LS), air vent (AV), actuated butterfly valve (ABV), and a small capacity bilge pump (BP) for priming the siphon pipe only. As shown in Figure 1, all the components are connected physically with a Programmable Logic Controller (PLC). By linking with the VPN router (VPN), PLC can access 3G/4G cellular networks and send the current operation state to and receive operation orders from the control center. The PLC in turn will turn the specific components of the siphon on or off based on the received orders.

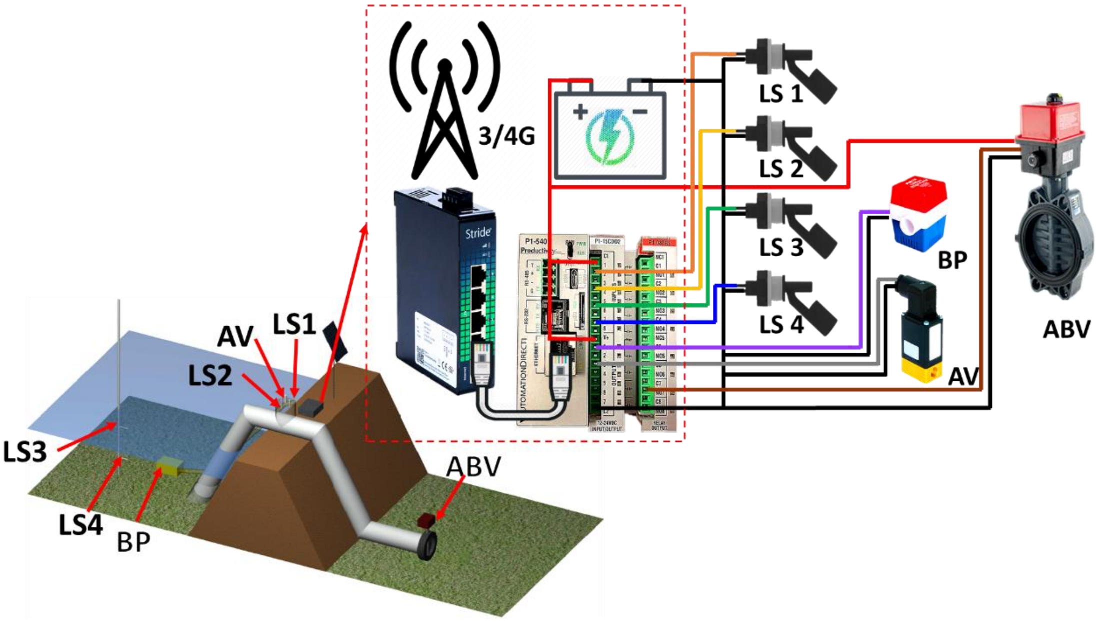


Figure 1. The architecture of our remotely controlled siphon system

The siphon flow can only start or stop when all the components work in a certain sequence. Any component of the siphon system fails to perform its function can lead to discharge water from the water storage units, insufficiently or excessively. The undesirable water discharge volume will cause the water storage units either there is no abundant storage capacity for flood mitigation, or there is no suitable water volume to maintain the aquatic life. Either the abovementioned scenarios will threaten the safety of human life and their property, and damage the ecological environment. Therefore, in view of these serious consequences, it is necessary to design a durable and reliable siphon system. However, most of the components are exposed in the natural environment in the realistic application, thereby facing threats caused by plenty of uncertainties and unknown factors, such as short circuits, animal and insect bites, and chemical corrosion, etc. These hazards are likely to cause the malfunction of the siphon components. Therefore, it is significant to understand the operational reliability of the siphon within the life cycle, comprehensively. Based on the evaluation of the operational reliability of the remotely controlled siphon system, this study will help to identify the vulnerable components, propose the optimized architecture of the siphon system, as well as suggest the reasonable maintenance strategies under the different working scenarios.

METHODOLOGY

RBD model based on ExtendSim

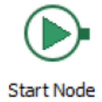
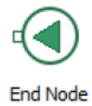
Many methods have been developed to analyze the reliability of a system and each method has its own advantages and disadvantages. Traditional approaches, such as the Markov model (Trivedi 2001, Veeraraghavan 1994, <<<<<) and Petri nets (PNs) (Malhotra 1995) (Bobbio 2003), are based on an analytic solution. These approaches need stringent assumptions about the system, such as the lifetime distribution of the components in the system has to obey an exponential distribution and the failure probability has to be independent for all the components. However, in reality many systems can hardly meet these strict conditions. Therefore, the scope of the above analytic approaches is limited in the case of complex systems since the model is hard to obtain directly from the specifications or descriptions of a system (Distefano 2009)

(Chen 2012). Such inconvenience led to the development of the Reliability Block Diagram (RBD), Fault Trees (FTs), and Reliability Graphs (RGs), which are more user-friendly.

RBD as an efficient tool has been widely used in reliability engineering for many years (Guo 2007). When evaluating the operational reliability of a complex system, the significant advantage of RBD is that it describes a system, graphically. All the components in the system can be connected by graphic blocks in accordance with their functional logic or operational relationship. Therefore, a complex system becomes intuitive and easy to build and read in the form of RBD (Wang 2004) (Distefano 2006) (Guo 2007). However, RBD is only used for non-repairable systems (Distefano 2007) (Rausand 2004).

Because ofthis limitation, the Reliability Module based on ExtendSim software has been developed by the Imagine That Company to achieve the application of RBD for both repairable and non-repairable systems. On ExtendSIM software, a reliability model is built by different functional blocks stored in the Reliability Library. In addition to its intuitive and user-friendly advantage, the ExtendSim RBD can simulate the maintenance process in complex systems. By applying the Monte Carlo method to repeat simulations thousands of times, the ExtendSim RBD model can provide accurate results of component reliability, the mean time to failure, and the operational reliability of both non-repairable and repairable systems. The function of the main blocks used to develop a RBD model is described in Table 1(Krahl 2014).

Table 1. The declaration of RBD functional blocks

Block	Library/Name	Block Function
	Reliability Start Node	Performs the RBD's important tasks, manages the RBD's behavior over time, and can be thought of as the brain of the RBD. Can alternate between up and down states due to event cycles that have been defined in the Event Builder.
	Reliability Component	Represents the component in the system. Over time, components alternate between up and down states due to event cycles that have been defined in the Event Builder.
	Reliability End Node	End the RBD and reports its status.
	Reliability Event Builder	Creates classes of event cycles for use by the Start Node and Component blocks to model and RBD's up and down states over time.
	Reliability Distribution Builder	Creates, stores, and provides statistical distribution definitions for time-between-downs (TBD), time-to-down (TTD), and time-to-up (TTU) to be used in the Event Builder block
	Item Executive	Manages the events that have been scheduled by the Start Node.

Operational reliability

In the RBDs, each graphic block represents one physical component in the system with an associated mathematical function or a simulation model. There are only two possible working states for all the components, a functioning state (UP) and a failed state (DOWN), which can be described as equation (1).

$$\mathrm{X(t)} = \begin{cases} 1 & \text{if the component is functioning at time t} \\ 0 & \text{if the component is not functioning at time t} \end{cases} \tag{1}$$

The two-parameter Weibull distribution is applied in this study to simulate the lifetime distribution of all the components due to its flexibility and widespread application in the reliability engineering industry (Xie 1996, Zhang 2007, Fu 2019).

Assume that a component enters in operation at time t = 0 and the time to failure (TTF) T is continuously distributed with the probability density function of $t \sim \mathrm{Weibull}(\alpha, \frac{1}{\lambda})$, $\frac{1}{\lambda} = \beta$, where, α is the shape parameter, and β is a scale parameter, also called characteristic lifetime.

$$f(t) = \begin{cases} \alpha\lambda^{\alpha}t^{\alpha-1}e^{-(\lambda t)^{\alpha}} & for\ t > 0 \\ 0 & otherwise \end{cases} \tag{2}$$

The probability of the component to fail within the time interval (0,*t*) can be described by Equation (3). Thus, the reliability of the component can be described as Equation (4) and the mean time to fail (MTTF) can be denoted by Equation (5).

$$F(t) = Pr(T \leq t) = \int_0^t a\lambda^a x^{a-1} e^{-(\lambda t)^a} dx = 1 - e^{-(\lambda t)^a} \tag{3}$$

$$R(t) = 1 - F(t) = e^{-(\lambda t)^a} \tag{4}$$

$$\text{MTTF} = \int_0^\infty \text{R(t)}\, dt = \frac{1}{\lambda}\Gamma\left(\frac{1}{\alpha} + 1\right) \tag{5}$$

According to this definition, the operational reliability of a system can be expressed by Equation (6), where OT is the operational time or the life cycle time. For the reparable system, OT can be described by equation (7).

$$OR = \overline{\text{A}_V} = \min\left(\frac{MTTF}{OT}, 1\right) \tag{6}$$

$$\text{OT} = MTTF + MTTR \tag{7}$$

Where $MTTR$ indicates mean time to repair which also can be assumed as a Weibull distribution.

Generally, there are two main types of connections for the components in a system. The components can be configured in either series or parallel. It is necessary for all the series-connected components in a subsystem to be in a functioning state for the subsystem to function. On the contrary, the components connected in parallel indicate redundancy. To introduce redundancy, additional and identical components are connected in parallel with the vulnerable component. In system engineering, redundancy is often expressed as N+K where N is the minimum number of units required for system success and K is the number of backup units. In the proposed architecture of the remotely controlled siphon system, only one of the parallel components is required for the subsystem to function. Therefore, N is always equals to 1 and K could be either 0 or 1. By applying this approach, any complex system can be expressed as a parallel-series system.

The subsystem reliability for all the non-repairable components with series connection is given by

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{8}$$

The subsystem reliability for all non-repairable components with parallel connection is given by

$$R_s(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t)) \tag{9}$$

The above analysis shows that the system operational reliability depends on: 1) the reliability of the components of the system; 2) the configuration or topology (series or parallel); and 3) the system maintenance strategy (MTTR).

VALIDITY OF RBD MODEL ON EXTENDSIM

In order to demonstrate the validity of the RBD model based on ExtendSim, this paper takes the series-parallel model which can be solved by the analytic method as an example. As shown in Figure 2, assume that the structure of a system can be expressed as two components connected in parallel with the series connection of another. The assumptions for all the components are,

- All the components cannot be repaired.
- The probability of TTF are independent for all the components.
- The lifetime of all the components has the distribution of $T \sim \text{Weibull}(\alpha, \frac{1}{\lambda})$.
- Simulation time t is 60 minutes, ExtendSim RBD simulates 1,000 times.

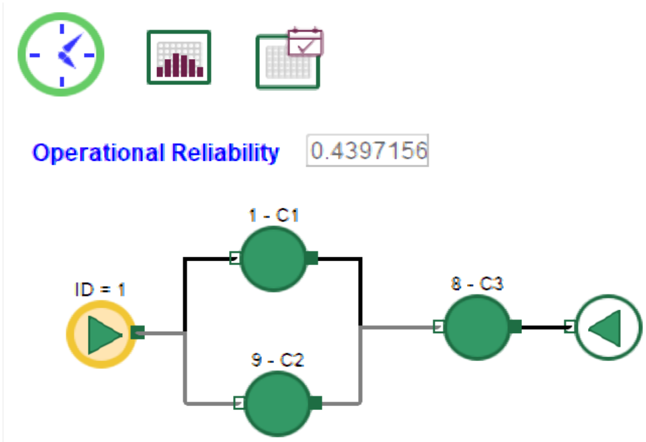


Figure 2. System structure for the validity of the RBD model based on ExtendSim

Applying the analytic method for the parallel structure of two components, according to Equation (9) gives

$$R_{sp}(t) = e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1+\lambda_2)t} \tag{10}$$

For the entire system, combining equation (8) and (10) gives

$$R_{ss}(t) = e^{-(\lambda_1+\lambda_3)t} + e^{-(\lambda_2+\lambda_3)t} - e^{-(\lambda_1+\lambda_2+\lambda_3)t} \tag{11}$$

Therefore, the MTTF can be obtained as follows:

$$\text{MTTF} = \int_0^\infty R_{ss}(t)\,dt = \frac{1}{\lambda_1+\lambda_3} + \frac{1}{\lambda_2+\lambda_3} - \frac{1}{\lambda_1+\lambda_2+\lambda_3} \tag{12}$$

Table 2. Comparison between the analytic and ExtendSim solutions

C_i	Weibull$(\alpha, 1/\lambda)$		Connection	Analytic Solution					ExtendSim RBD			
	α	λ		R_i	R_{Si}	R_S	MTTF	OR	R_i	R_S	MTTF	OR
1	1	0.050	Parallel	.050	.262				.041			
2	1	0.025		.223		.079	25.982	**.433**	.204	.072	26.564	**.444**
3	1	0.020	Series	.301	.301				.300			

As shown in Table 2, the operational reliability calculated by the analytic method and ExtendSim RBD is 0.433 and 0.444, respectively. The difference between them is only 2.5%.

According to the Monte Carlo theory, it has $R_S = \frac{1}{N_\infty}\sum_{j=1}^{N_\infty} X_S(j) \cong \frac{N_S}{N}$, where N_S is the number of successful simulations and N the total number of simulations. For a sufficiently large N, this method is guaranteed to converge to the actual expected value as a direct result of the law of large numbers (Hockenberry 2004). Considering the limitations of the trial number (1,000 times), the accuracy of the results is acceptable. Therefore, the results from ExtendSim RBD can be deemed reliable.

RBD MODEL FOR THE SIPHON SYTEM

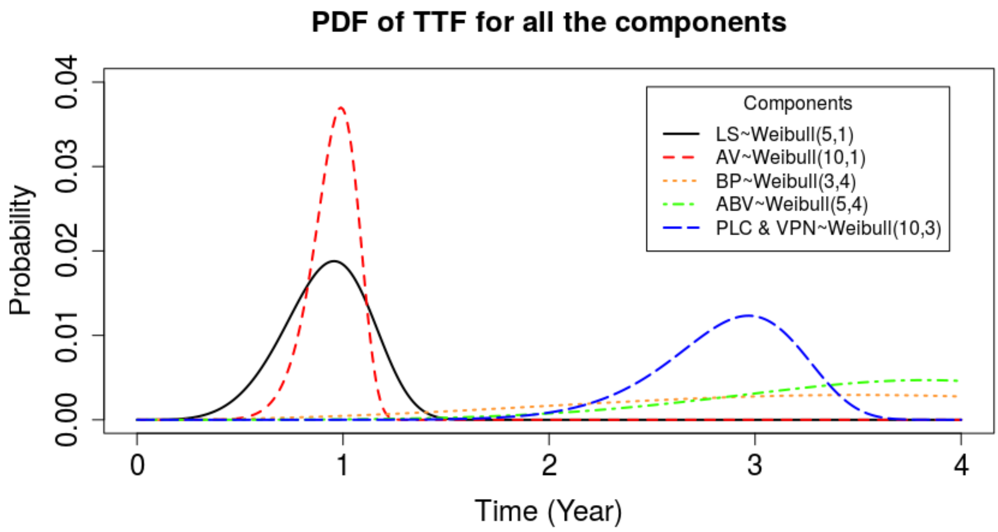
It is important to use a reliable data source to perform an accurate analysis of the operational reliability. If data is available from the facility or vendor, it is better to perform the analysis using these data. Unfortunately, most of the siphon component suppliers lack the required data. Therefore, the main purpose of this study is to evaluate the operational reliability of the siphon system based on different system architectures by assuming a failure probability for each of the components (Wang 2004).

Furthermore, in order to make the assumption of TTF for each component reasonable, the shape parameter and characteristic life of Weibull distribution are assumed based on the broken events observing from the current field working period and the information gathered from the vendor. Table 3 shows the broken events that have been recorded from January to December in 2019. The warranty time is obtained from the vendors. Common sense is that the vendor does not expect their products broken within the warranty time. Therefore, the minimum characteristic life for the products can be assumed one year longer than the warranty time. Nonetheless, when a broken event is observed for a component, the minimum characteristic life for the component needs to be assumed one year since the period of broken events observation is only one year, currently. The maintenance time, or called time to up (TTU), is assumed according to the maintenance experience from the field working. Based on the above experience and assumptions, the assumed PDF of TTF and TTU for all the components is shown in Figure 3.

Table 3. The recordings of the broken components from January to December in 2019

Component	Price	Warranty	Broken Records	Assuming Parameter based on	Assumed characteristic lifetime
	USD	Year	Times	Source	Year
LS1	17.20	N/A	0	Field working experience	1
LS2	17.20	N/A	1	Field working experience	1
LS3	17.20	N/A	1	Field working experience	1
LS4	17.20	N/A	1	Field working experience	1
AV	10.49	1	1	Field working experience + Vendor Information	1
BP	36.34	3	0	Vendor Information	4
ABV	1400	3	0	Vendor Information	4
PLC	320	2	0	Vendor Information	3
VPN	640	2	0	Vendor Information	3

Currently, there are two architectures of the remotely controlled siphon system which are proposed in the study. One is assembled by using only one of each component as shown in Figure 4. That means the redundancy of the siphon architecture is N=1, and K=0. Therefore, it does not have any redundancy in the siphon system. Additionally, the other is designed, as shown in Figure 5, by duplicating an extra identical component for introducing the redundancy. Figure 5 shows the redundancy of the siphon architecture is N=1, and K=1. According to the architectures of the current siphon system, two RBD models (without redundancy, and with redundancy, respectively) were developed based on ExtendSim software to quantify the operational reliability of a remotely controlled siphon system over the life cycle from 1 year to 3 years. At the same time, the two RBD models follow two maintenance strategies, namely "no repair" and "repair". The designed simulation scenarios are listed in Table 4.



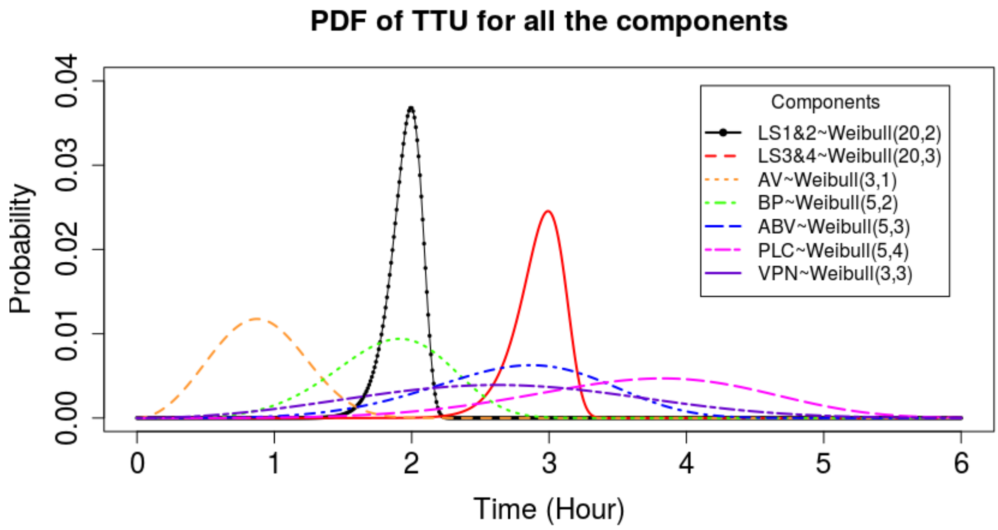


Figure 3. Weibull probability density distribution of TTF and TTU for all the components

Table 4. The designed simulation scenarios and their abbreviations

The operational life cycle		1 year	2 year	3 year
N=1 & K=0	No Repair	N1K0NR1Y	N1K0NR2Y	N1K0NR3Y
	Repair	N1K0R1Y	N1K0R2Y	N1K0R3Y
N=1 & K=1	No Repair	N1K1NR1Y	N1K1NR2Y	N1K1R3Y
	Repair	N1K1R1Y	N1K1R2Y	N1K1R3Y
Optimized architecture	No repair	OANR1Y	OANR2Y	OANR3Y

Following we present the assumptions of the RBD system.

1. The aging process of all siphon components are ignored. Once a component is replaced, it is assumed "as good as new".
2. For the non-repairable system, there is no repair work within the life cycle. The broken components of a siphon system will be only replaced at the end of the life cycle.
3. For a repairable system, once a component is broken, the repair work begins immediately. A maintenance worker is required on-site during the life cycle.
4. The price of a maintenance worker is 55 USD per hour in both "No Repair" and "Repair" scenarios. The total maintenance price includes the price for a maintenance worker to replace all the broken components plus the total replaced component price.
5. All simulation scenarios are run 10,000 times.

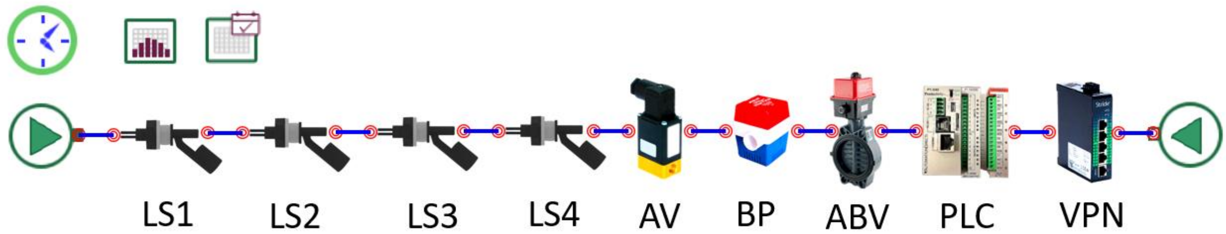


Figure 4. RBD model for the non/repairable siphon system of N1K0

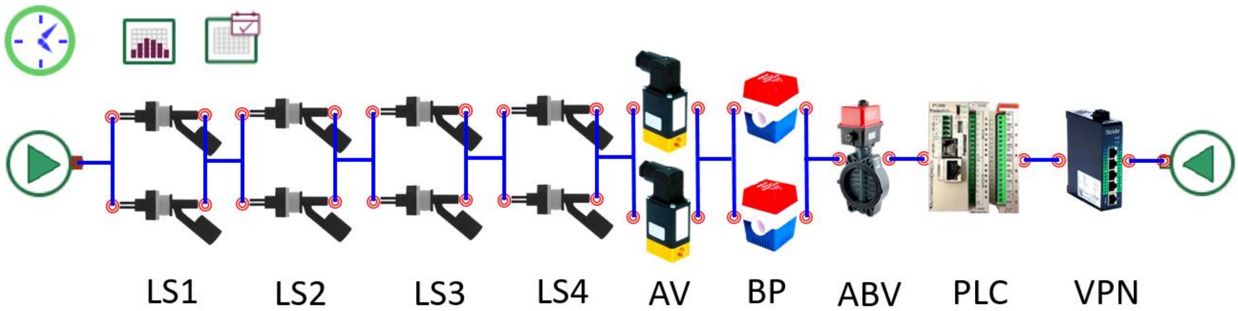


Figure 5. The RBD model for the non/repairable siphon system of N1K1

RESULTS

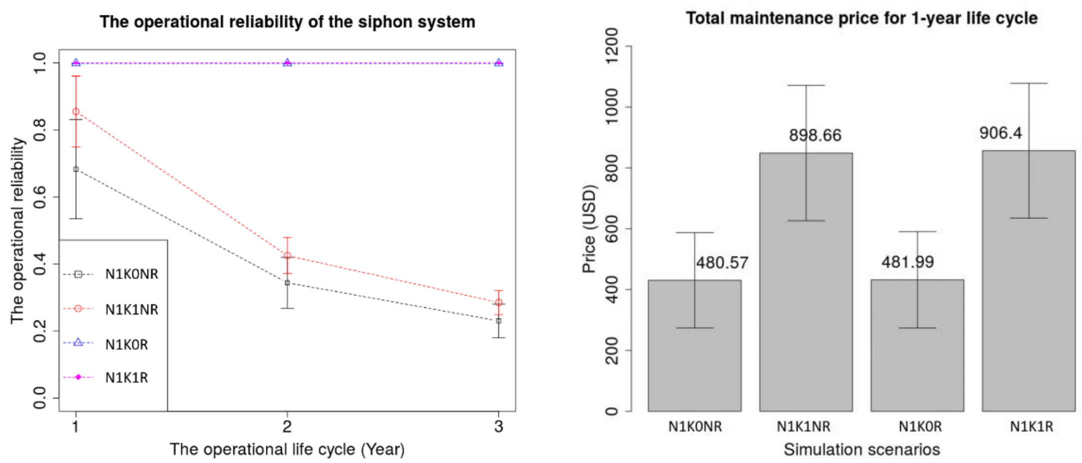


Figure 6. The operation reliability of the siphon system over 1-to-3-year life cycle and its maintenance price for 1-year life cycle

1. The operational reliability for N1K0R and N1K1R is 0.999 and 1.000, respectively. As shown in Figure 6, the increase of the life cycle or the increase of the redundancy almost have no impact on the operational reliability for the reparable system. On the contrary, such impact is significant on the operational reliability for the non-repairable system. By increasing the redundancy, the operational reliability of the siphon system is increased from 0.683 to 0.855 for the 1-year life cycle. The overall increase rate is around 24% for the life cycle from 1 year up to 3 years.
2. The total average maintenance price and the standard deviation are close under the scenarios of the non-repairable and repairable system. The effect of the maintenance strategies for the non-repairable and repairable siphon system is the same. It should be notice that there is a maintenance worker onsite for the repairable system. In addition to the equipment maintenance expenditure, there will be the extra annual salary to pay for the maintenance worker. The total average maintenance price for the siphon system of redundancy of N=1 and K=1 is close to double the price for the siphon system without the redundancy.

Table 5. The failure time over 10,000 simulations for 1-year life cycle

Component	LS	AV	BP	ABV	PLC	VPN
Failure Time	6454	6500	155	0	0	0
Component Reliability	0.355	0.350	0.985	1	1	1

3. As shown in Table 5, during the 1-year life cycle, the level switch and the air vent are the major failure components of the siphon system. The bilge pump only fails 155 times within 10,000 simulations. Therefore, it is necessary to figure out what is the impact on the operational reliability of the non-repairable siphon system when a bilge pump is removed. This simulation scenario is named as the optimized architecture, which is shown in Table 4.

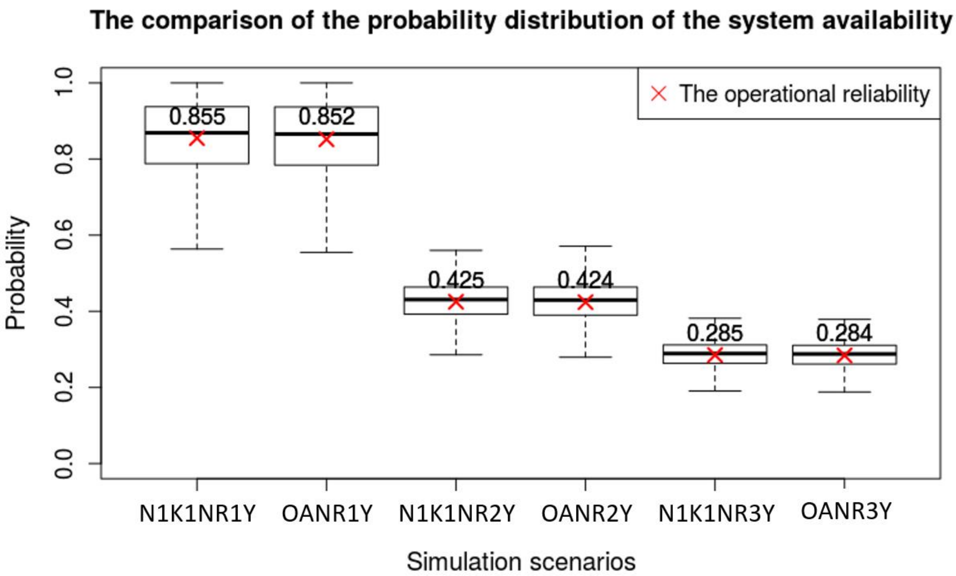


Figure 7. Comparison of the operational reliability distribution for the scenarios of SF2NR and OSFNR

4. According to the results in Figure 7, the optimized architecture of the remotely controlled siphon system is recommended to be used in the field since the redundancy

of the BP influences on the operational reliability, slightly. One-year operational life cycle can keep the operational reliability above 0.8 which meets the desired operational performance. If the annual salary for the onsite maintenance work is considered, the maintenance expenditure for non-repairable scenarios will be cheaper than the repairable scenarios. Therefore, the recommended maintenance strategy is to replace the broken components of the siphon system at the end of the 1-year operational life cycle.

CONCLUSION

1. Since the maintenance strategies in the assumption has no influence on the total average maintenance price for the non-repairable and reparable siphon system within the 1-year life cycle and the repairable siphon system always has a higher operation reliability (close to 1), in the perspective of the cost of construction and maintenance, the optimized architecture of a remotely controlled siphon system should apply and the maintenance strategy of the repairable system during 1-year life cycle. The operational reliability can remain 0.999 over 1 year. The total average maintenance price is $480.57 per year per siphon plus a maintenance worker annual salary.
2. Considering the situation that the remotely-controlled siphon system will be installed in the remote area where is hard to keep a maintenance worker, in order to ensure the higher operational reliability of the siphon system, the reasonable architecture should increase the redundancy of the level switch and the air vent. There is no need to introduce the redundancy of the bilge pump. The operational reliability for the reasonable architecture is 0.852 over 1 year. By applying the maintenance strategy of the non-repairable system, the total average cost should be lower than $898.66 per year per siphon.
3. The recommendation life cycle is 1 year to ensure the higher operational reliability when there is no maintenance worker on site.
4. The siphon flow will develop the negative pressure at the top of the siphon pipe. The maintenance work cannot perform once the siphon flow begins since replacing any components will cause air flowing into the siphon pipe, which leads to the decrease of the negative pressure until the siphon flow stops. Therefore, the results of N1K1R has no practical significance in the application. Therefore, applying the redundancy and the maintenance strategy of the repairable system is the most irrational choice.

SUMMARY AND FUTURE WORK

The RBD blocks developed by ExtendSim can quantify the operational reliability of the remotely controlled siphon system, successfully and efficiently. RBD as an efficient tool can decrease the difficulty of the modeling work, especially dealing with a complex system. Moreover, the powerful ExtendSim software can allow over 10,000 simulations to finish in a short time. Due to the flexibility and efficiency of ExtendSim software, the operational reliability of any complex system can be successfully evaluated.

The operational reliability of the remotely controlled siphon can be increased easily by introducing the redundancy for the vulnerable components such as level switches and air vents. Alternatively, it also can be increased by using components that are more durable. Considering the space limitation on the siphon cap, instead of installing two air vents, the recommended solution is to use a more durable one. Moreover, in the perspective of construction, level switch 3 and 4 is not easy to be installed in the wetland when they are using the architecture of redundancy. However, it is hard to find more durable level switches because of the uniformity of the product in the industry. Moreover, all the broken events in the study are obtained from 2 siphons in the experiment field, only. Therefore, the suggestion for the future work should be,

1. Explore more durable air vents and observe its performance and broken events during the siphon operation.
2. Design a protective shield to the level switch 3 and 4. For example, the level switch can be fixed inside a 4 inches PVC pipe with many pores on the pipe walls. The pipe wall can perform as a protective shield so that the level switches will not be wrapped by the plants or weeds in the wetlands and still can detect the accurate water level since the pores can allow water flow inside and outside the PVC pipe.
3. Build the more siphons, observe their working performance and record the broken events. This information will be used to change the parameters of Weibull distribution, which can help to improve the operational reliability results.

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