Membrane Bioreactor Life-Cycle Cost Assessment Simulation: Digital Game-Based Learning

Dave Kinnear[1*], Ingmar Nopens[2], Marie-Laure Pellegrin[1], Thomas Maere[2], Daniel Nolasco[3], Richard Glassen[1], Guclu Insel[4], Youri Amerlink[5], Erika Bailey[1], Evangelia Belia[6], Imre Takacs[7], Dwight Houweling[7], Paul Causey[8], Rick Giardina[9], Sudhir Murthy[10], Peter Vanrolleghem[11], James Barnard[12], Henryk Melcer[13], Paul Krauth[14], Rod Reardon[15], JB Neethling[1]

* Corresponding Author: HDR Engineering; 440 S. Church St., Suite 1000, Charlotte, NC 28202.
dkinnear@hdrinc.com

1. HDR Engineering, Inc; Charlotte, NC.
2. Biomath, Gent University; Gent, Belgium.
3. Nolasco & Associates; Buenos Aires, Argentina.
4. Istanbul Technical University; Istanbul, Turkey.
5. MostforWater; Kortrijk, Belgium.
6. Primodal US, Inc.; Kalamazoo, MI.
7. Envirosim Associates; Bordeaux, France.
8. Causey Consulting; Tiburon Sanitation District, CA.
9. Red Oak Consulting; Denver, CO.
10. DCWASA, Washington, DC.
11. Laval University; Québec City, Canada.
12. Black and Veatch; Kansas City, KS.
13. Brown and Caldwell; Seattle, WA.
14. Dept. of Env. Quality, Salt Lake City, Utah
15. Carollo Engineering, Orlando, FL

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Abstract

WEFTEC.09 preconference workshops included a new approach to training in the wastewater industry entitled Membrane Bioreactor (MBR) Life-Cycle Cost Assessment (LCA) Simulation: Digital Game-Based Learning. The workshop provided an interactive format for teams of participants to compare the design and operation of alternative MBR configurations. This paper presents a description of the workshop, the results, and suggestions for future game-based training through future Water Environment Federation (WEF) and Member Association (MA) Conferences.

Introduction

WEFTEC.09 preconference workshops included a new approach to training in the wastewater industry entitled Membrane Bioreactor (MBR) Life-Cycle Cost Assessment (LCA) Simulation: Digital Game-Based Learning. The workshop provided an interactive format for teams of participants to compare the design and operation of alternative MBR configurations. This paper presents a description of the workshop, the results, and suggestions for future game-based training through future Water Environment Federation (WEF) and Member Association (MA) Conferences.

A repetition of the workshop occurred at the WEF Membrane Specialty Conference in Anaheim, CA in June 2010. Revised design problem workshops scheduled for the International Water Association (IWA) World Water Conference 2010 and WEFTEC 2010 include nutrient removal upgrade problems. The workshop team plans to conduct similar workshops to improve the methodology for both training and to experiment with different design alternatives.

Workshop formats vary at professional conferences, but few offer the direct informal interaction between groups and experts that the digital game-based learning format does. Figure 1 presents two photographs of the workshop in action, demonstrating how the teams used computer simulations, easels, and scratch paper to debate the best wastewater design that would allow their team to produce the system with the lowest simulated life-cycle cost – the game objective.

Figure 1. Digital Game-Based Learning Interaction

Digital Game-Based Learning Methodology

The Digital Game-Based learning workshops conducted thus far divide the workshop into two segments: the morning design phase and the afternoon operating phase. Other formats will be developed in the future. During the design phase, participants develop a design detailed for which capital cost estimating occurs during the lunch break. Following the lunch break, a bid opening occurs and the participants learn the capital cost and financial terms for competing designs. The afternoon operations phase uses mathematical models of the developed designs using popular software packages to model the designed treatment facilities and develop annual operating costs. The following paragraphs provide more detail.

The morning design phase begins by the participant breaking into teams with each team assigned experts in mathematical modeling of wastewater treatment processes to develop computer simulations of the design concepts ‘on the fly’ as development occurred. The teams then received the following information regarding identical design problems:

1. A greenfield MBR needs to be constructed,
2. A site plan showing the space available,
3. Base year permit and hypothetical future permit conditions,
4. Wastewater flows (7.0 mgd base year) and loads and hypothetical projections,
5. Wastewater characterization to define wastewater strength and modeling parameters,
6. Unit capital and operating cost information.

In most cases, ambiguous information defined the problem, as often occurs in real-life problems. Participants assumed nitrogen and phosphorus effluent limits would become more stringent even as the population increased but did not know either how low the limits would go or how rapidly the population would increase. Both required educated guesses for future conditions. Teams spent the morning debating strategies to phase construction, balance capital and operating costs, and accommodating operating challenges.

Experts offered advice and discussion on the developed design alternatives interactively as the teams organized, defined their problem, and debated alternative solutions. By the time the participants left for lunch, they each submitted a Preliminary Engineering Report, which defined the details of their designs.

Teams adopted similar strategies in some respects and very different strategies in other respects to meet their effluent requirement. This allows the comparison of the success of different strategies at the conclusion of the workshop. For example, during the WEFTEC.10 workshop, one team selected enhanced biological phosphorus removal (EBPR) with chemical backup while the other team selected pure chemical phosphorus removal (CPR). Each team selected a four-stage biological nitrogen removal process (for the nitrogen removal portion); however, basin volumes differed between the teams depending on the strategy to minimize capital cost (concrete) or minimize operating cost (external carbon in future years to meet low effluent total nitrogen).

The workshop team goes to work during the lunch break estimating the capital cost of each design with a contractor and working financial terms to issue 20-year bonds with a banker. Upon returning from lunch, bids were opened and bonds sold to a fictitious financial market.
The afternoon operations phase when the participants learned of a $10.4 M or 17.5% difference in capital costs. The operations phase consisted of the mathematical models of the alternative treatment processes subjected to a series of “challenges” designed to stress the treatment designs and determine the performance under conditions such as:

1. Annual average flow steady-state conditions,
2. Diurnal transient flow conditions,
3. Peak flow transient conditions,
4. Low temperature steady-state conditions,
5. Bioreactor out of service steady-state conditions.

For WEFTEC.10, the output of each simulation above allowed a composite annual effluent quality for total nitrogen and total phosphorus to be calculated. For MEMBRANE.10, each group conducted fewer simulations to represent a complete year and a computer randomly chose the simulations required to represent each year. Balancing the computational time required to simulate a year’s life-cycle cost and still represent challenging design conditions in the life cycle proved challenging. Future workshops should include improvements to this aspect of the game.

Permits allowed a total annual mass to be discharged with nutrient permit violations accounted for through a market approach in which teams could either buy or sell nutrient credits based on the performance of their system. Each team strategized to sell credits during the early, low-flow, less-stringent operating years because they anticipated buying credits in subsequent years.

Operating costs simulations incorporated aspects of actual treatment facility budgets (courtesy of Charlotte Mecklenburg Utilities) for each year of the 20-year life cycle simulation. A simulated consumer price index (CPI) and RS Means index allowed projection of future year operations and expansion costs. Operations costs included the following categories:

A. Debt Service – Based on the capital cost and bond rate discussed above.
B. Capital Penalty Cost – This allowed teams that undersized equipment to pay a penalty and increase capacity in the following simulation year. Screens, membranes and blowers all needed adequate sizing for their intended services or severe, but realistic, penalties occurred.
C. Nutrient Market Costs – Nitrogen emissions opened at $8.61/lb while phosphorus opened at $4.74/lb. Trading ratios applied for buying and selling to balance point and non-point accounting (introduced into real markets). Both nutrient credits and trading ratios reflected realistic supply and demand as the game progressed in time.
D. Labor Cost – Teams requested operations and maintenance staff. Those with adequate staffing paid realistic salaries. Those understaffed paid overtime and increased operations costs until adequate staffing occurred.
E. General Operation Cost – Operations costs included repair materials, liability insurance, equipment, testing fees, landfill services, water, gas, and miscellaneous based on realistic budgets.
F. Effluent Market Costs – Teams could buy or sell nitrogen and phosphorus credits depending on how well their treatment plant performed compared to the permit requirements. The nitrogen price began at $8.61/lb and the phosphorus price began at $4.74/lb. A trading ratio between 1.0 and 3.0 applied when purchasing credits from the fictitious non-point source market compared to the point source credits being sold.
G. Sludge disposal costs – Based on a fixed fee (dependent on facility size) and a tipping fee. The game did not consider sludge processing operations.
H. Power Cost – Power included a demand charge opening at $10.79/kW and an energy charge of $0.09 per kWh. Both slightly outpaced the CPI in future years.
I. Greenhouse Gas Emission Cost – Greenhouse gas (GHG) emissions needed to be offset at $33/mt CO_{2e}, a value recommended by the US Department of Transportation in cost/benefit analysis. GHG costs did not significantly affect budgets.
J. Chemical Cost – Including methanol, sodium hydroxide, ferric chloride, aluminum sulfate, and magnesium hydroxide as required by the teams.

The operating phase progressed with challenges conducted in 5-year increments with teams permitted to expand facilities and change operating conditions prior to each challenge. During WEFTEC.10, time only permitted completion of a 10-year LCA. MEMBRANE.10 participants completed the full 20-year life cycle.

WEFTEC.10 Results

Table 1 presents the results of the project capitalization for the two teams participating in WEFTEC.10.

Table 1. Project Capitalization

Team/Model	Capital Cost, M$	Bond Rate, %
Team 1 EBPR	69.5	4.25
Team 2 - CPR	59.1	4.25

Table 2 presents abbreviated cash flows for each of the categories and net present worth for the two teams.

Table 2. Life-Cycle Cost Assessment Cash Flow, M$

Category	Team 1		Team 2	
	2010	2015	2010	2015
Debt Service	5.25	5.64	4.45	5.35
Nutrient Market	(0.44)	(0.42)	(0.40)	(0.08)
Labor	0.80	0.96	0.56	0.80
Operations	0.55	0.66	0.45	0.99
Sludge Disposal	0.15	0.21	0.15	0.21
Power	0.72	0.92	0.49	0.70
GHG Emissions	0.12	0.16	0.08	0.12
Chemicals	0.22	0.25	0.00	0.59
Total Annual	**7.37**	**8.38**	**5.78**	**8.68**
Present Value		**$72.89**		**$72.67**

In the ten-year LCA simulation, both the teams and the workshop developers were surprised to determine that only $205,000 (less than 1%) separate the two different designs and operating strategies, despite the $10.4 M separation in capital cost, different design concepts, and different operating strategies. Figures 2 and 3 presents a breakdown of the 2010 budgets for each team.

Figure 2. Team 1 2010 Operating Budgets

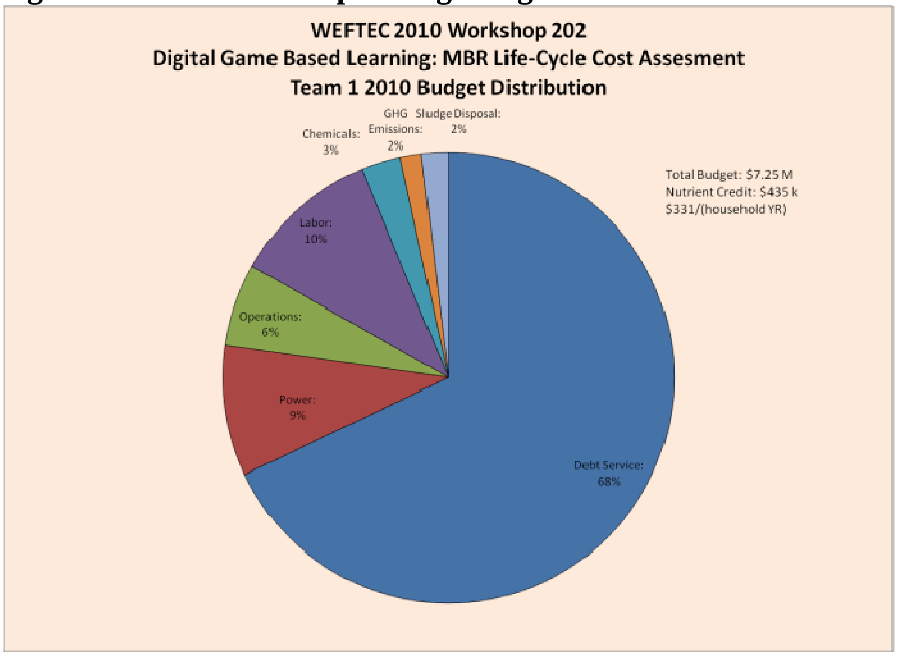
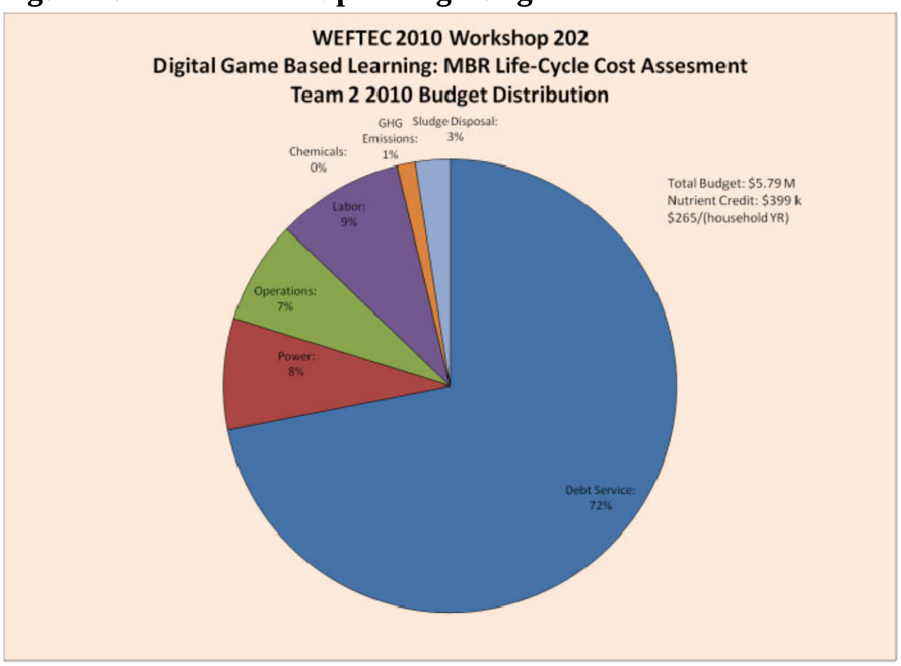


Figure 3. Team 2 2010 Operating Budgets



The figures indicated that debt service dominated the operating budgets of each facility. Although debt service can be a significant portion of a Utilities budget, the Greenfield nature of this project skewed these results to make debt service more significant. Debt service still remained at approximately 0.50% of an assumed median household income with per capita debt service in the $70 per person per year range and user charges of $300 per household per year, all realistic values.

Membrane.10 Results

Table 3 presents the results of the project capitalization for the two teams participating in MEMBRANE.10.

Table 3. Project Capitalization

Team/Strategy	Capital Cost, M$	Bond Rate, %
Team 1 - Biowin	119.8	4.25
Team 2 - WEST	110.0	4.25

Table 4 presents abbreviated cash flows for Team 1 for each of the categories as well as the net present worth.

Table 4. Team 1 Life-Cycle Cost Assessment Cash Flow, M$

Category	Team 1 - BIOWIN				
	2010	**2015**	**2020**	**2025**	**2030**
Debt Service	10.0	10.0	10.0	10.0	10.0
Nutrients*	(1.63)	(2.58)	(2.82)	(2.18)	(2.73)
Labor	0.48	0.77	1.20	1.65	2.54
Operations	0.68	0.99	1.43	1.82	2.54
Sludge Disposal	0.15	0.24	0.45	0.56	0.70
Power	1.36	1.81	2.45	3.07	3.44
GHG Emissions	0.22	0.32	0.36	0.32	0.27
Chemicals	0.00	0.00	0.45	0.00	0.00
Total Annual	**11.4**	**10.3**	**11.1**	**11.5**	**11.6**
Present Value					**$249.5**

*** Sold to market**

Table 5 presents abbreviated cash flows for Team 2 for each of the categories as well as the net present worth.

Table 5. Team 2 Life-Cycle Cost Assessment Cash Flow, M$

Category	Team 2 - WEST				
	2010	**2015**	**2020**	**2025**	**2030**
Debt Service	9.27	9.27	9.27	9.27	9.27
Nutrients*	(1.72)	(2.73)	(2.42)	(2.50)	(3.10)
Labor	0.67	0.93	1.32	1.61	2.50
Operations	0.68	0.99	1.43	1.82	2.54
Sludge Disposal	0.15	0.25	0.48	0.57	0.71
Power	1.11	1.58	2.00	2.67	2.98
GHG Emissions	0.18	0.27	0.29	0.28	0.23
Chemicals	0.00	0.00	0.00	0.30	0.33
Total Annual	**10.3**	**10.6**	**12.3**	**14.0**	**15.5**
Present Value					**$243.9**

*** Sold to market**

In the twenty-year LCA simulation, both the teams and the workshop developers were surprised to determine that only $5.6M (2.2%) separate the two different designs and operating strategies. In this case, one team chose larger reactors but smaller membrane surface area. Figures 4 and 5 presents a breakdown of the 2010 budgets for each team.

Figure 4. Team 1 2010 Operating Budgets

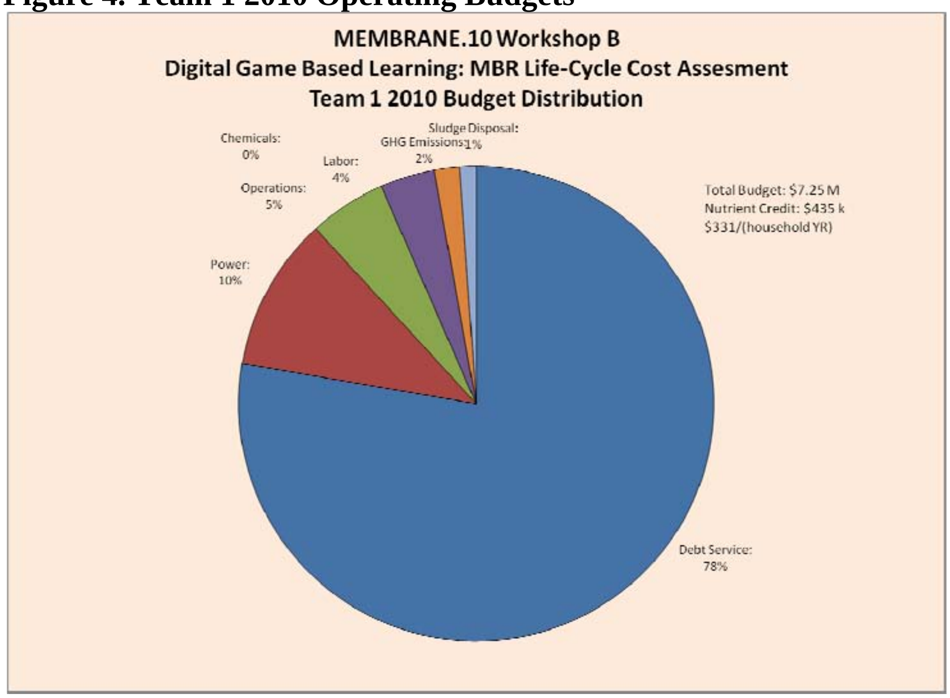
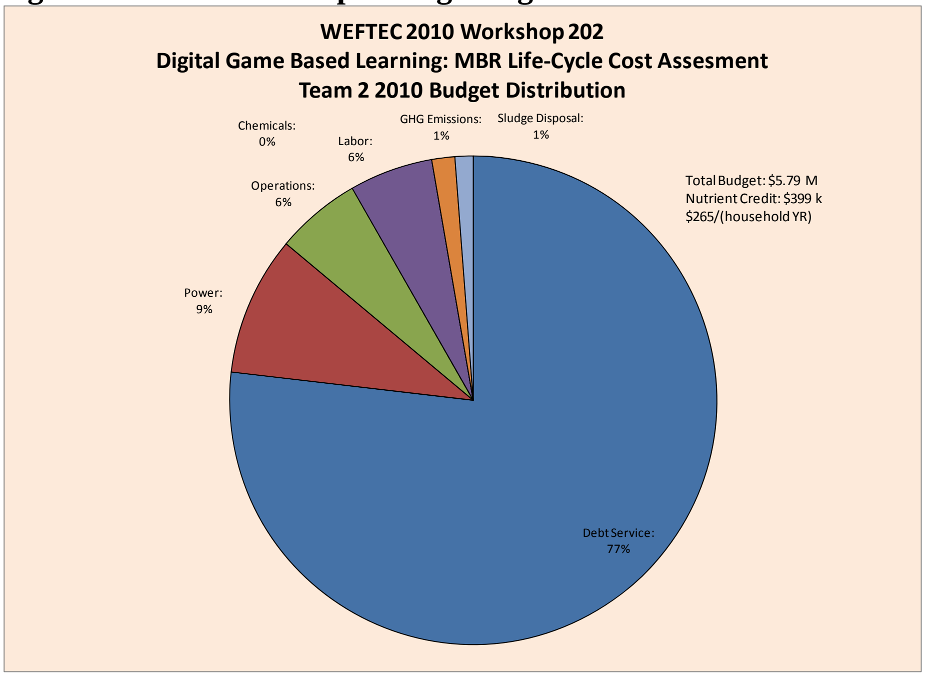


Figure 5. Team 2 2010 Operating Budgets



Again, the figures indicated that debt service dominated the operating budgets of each facility. Although debt service can be a significant portion of a Utilities budget, the Greenfield nature of this project skewed these results to make debt service more significant. Debt service still remained at approximately 0.25% - 0.75% of an assumed median household income with per capita debt service in the $111 per person per year range and user charges of $350 per household per year, all realistic values.

Conclusions

Conducting digital game-based simulations of a wastewater treatment plant design and operation provided many valuable lessons related to both real-world design and to conduct similar training sessions in the future, including:

1. The process is fun and educational and provides an opportunity for interactive learning for all who participate. The high-paced and competitive nature of the process reinforces the workshop objectives.
2. It provides the opportunity for young professionals to participate in a design process with more seasoned professional and learn through participation and observation the decision-making process.
3. It allows comparison of the performance of alternative design scenarios in a realistic, simulated environment – a condition that cannot occur in the real world.

The similarity in life cycle costs for each team at each of the workshops requires further consideration. One possibility, that that the design of the game lead to similar results needs to be compared to the possibility that teams which include experts instinctively develop solutions with comparable life-cycle costs. More than likely, both possibilities play a role. Making the game more competitive might

Future digital game-based learning concepts include combined sewer overflow mitigation, biosolids processes, sidestream treatment and existing facility expansion.

Digital game-based learning allows many other fields to compare alternative strategies and train decision makers without the high-stakes of many real-life situations. The workshop team believes digital-game based learning offers many advantages over traditional training and learning methods and plans to conduct additional workshops in the future. We invite interested people to both participate in the further development of this concept and to play the game whenever possible.