DISCRETE EVENT MODEL DEVELOPMENT OF PILOT PLANT SCALE MICROALGAE FACILITIES: AN ANALYSIS OF PRODUCTIVITY AND COSTS

A Thesis

by

JUSTIN WAYNE STEPP

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2011

Major Subject: Agricultural Systems Management

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Approved by:

Chair of Committee,	Ronald E. Lacey
Committee Members,	Calvin B. Parnell
	James W. Richardson
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ABSTRACT

Discrete Event Model Development of Pilot Plant Scale Microalgae Facilities: An Analysis of Productivity and Costs. (August 2011)

Justin Wayne Stepp, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Ronald E. Lacey

America's reliance on foreign oil has raised economic and national security issues, and in turn the U.S. has been active in reducing its dependence on foreign oil to mitigate these issues. Also, the U.S. Navy has been instrumental in driving bio-fuel research and production by setting an ambitious goal to purchase 336M gallons of bio-fuel by 2020. The production of microalgae biomass is a promising field which may be able to meet these demands. The utilization of microalgae for the production of bio-fuel requires the implementation of efficient culturing processes to maximize production and reduce costs. Therefore, three discrete rate event simulation models were developed to analyze different scaling scenarios and determine total costs associated with each scenario. Three scaling scenarios were identified by this analysis and included a stepwise, volume batching and intense culturing process. A base case and potential best case were considered in which the culturing duration, lipid content and lipid induction period were adjusted. A what-if analysis was conducted which identified and reduced capital and operational costs contributing greatly to total costs. An NPV analysis was performed for each scenario to identify the risk associated with future cash flows.

The research findings indicate that the intense culturing scaling scenario yielded the greatest model throughput and least total cost for both the base case and potential best case. However, this increased productivity and cost reduction were not significantly greater than the productivity generated by the stepwise scaling scenario, suggesting that the implementation of flat plate bio-reactors in the intense culturing process may be non-advantageous given the increased operational costs of these devices. The volume batching scenario yielded the greatest total cost L^{-1} of microalgae bio-oil for both, indicating an inefficient process. The scaling scenarios of the base case and potential best case yielded negative NPV’s while the stepwise and intense culturing scenarios of the what-if analysis generated positive NPV’s. The base case is based on current technological advances, biological limitations and costs of microalgae production therefore, a negative NPV suggests that utilizing microalgae for bio-fuel production is not an economically feasible project at this time.

DEDICATION

To

My Parents

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Ronald E. Lacey, for providing direction and entertaining any and all questions throughout this entire process. I would also like to thank my committee members, Dr. Parnell and Dr. Richardson, for their guidance and support throughout the course of this research.

I would also like to thank Texas AgriLIFE Research and General Atomics for making this research possible.

Thanks to Lou and Jola Brown for all of their generous support as well as the staff at the Texas AgriLIFE Research Facility in Pecos, TX. Also, thanks to Aga Pinowska of General Atomics for her assistance. Finally thank you to Jarrett Lassig, Taylor Morrison, Jared Murdock, Phillip Luedecke, Ryan Davis, Andrea Garzon, Rebekah Garcia, Ashley Williams, Eric Wood, Tyrell Love and Scott Emsoff for all of your help.

Thanks to my parents for their support and advice they have bestowed throughout my life.

A special thanks to Mrs. Terri Gehrmann, for teaching me to “leave my inhibitions at the door”. You were a very special person and are missed dearly.

Finally, I would like to extend a very special thanks to my fiancé for her love and support throughout this entire process.

NOMENCLATURE

ACT	Average Cycle Time
LEA	Lipid Extracted Algae
NPV	Net Present Value
R&D	Research and Development
TBA	Time Between Item arrival
TBI	Time Between Items

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CHAPTER I

INTRODUCTION

America’s energy demand is heavily dependent upon foreign oil, accounting for roughly 59% of America’s oil consumption. The total cost of foreign oil dependence to the U.S. economy in 2009 was $294 billion (EERE, 2010). The reliance on foreign oil has raised economic and national security issues and the U.S. has been active in promoting efforts to reduce dependence on foreign oil. Policies to accomplish this goal include: more efficient fuel economy standards, investments in hybrid and electric vehicles, development of natural gas-fueled heavy duty vehicles, and production of advanced bio-fuels (Beddor et al., 2009). The U.S. Navy has been instrumental in driving bio-fuel research and production by setting an ambitious goal to purchase 336M gallons of bio-fuel by 2020. The Navy’s Energy Strategy is a product of unstable oil prices which soared to a record high of $147 per barrel in 2008. In an effort to meet budgetary constraints, the U.S. Navy has recognized that domestically produced bio-fuel would provide insulation from the unpredictability of the oil market. Annual U.S. energy consumption is approximately 100 quads (quadrillion BTUs), of which 4% is acquired from renewable sources of biomass. However, the current use of commodity crops for bio-fuel production has proven to be unsustainable because of market implications caused by the utilization of low energy food crops for bio-fuel. Therefore, a renewable, sustainable feedstock that has minimal impact on other markets is needed for bio-fuel

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This thesis follows the style of *Transactions of the ASABE*.

production. Large scale microalgae culturing is a promising field with the potential to meet these demands. Microalgae are aquatic, photosynthetic, microscopic plants that utilize sunlight and can be cultured for the production of lipids and biomass. Microalgal biomass production offers many advantages over conventional crop production technologies including higher yields per area, use of nonproductive land, reuse and recovery of waste nutrients, use of saline or brackish waters, and reuse of CO_2 from power-plant flue-gas or similar sources (Brune et al. 2009). Microalgal biomass can be utilized for many things including bio-fuels, animal feeds and pharmaceuticals.

Comprehensive microalgae culturing studies have been conducted since the early 1950's however; only recently has this technology begun to progress from the laboratory to pilot plant scale. While culturing microalgae on a large scale is not a new concept, the practice is still in its infancy. Realizing production and appropriate costs of large scale outdoor microalgae production has been speculative, relying on mathematical models and small scale outdoor experiments. The utilization of these resources to predict the economic feasibility of this technology has resulted in a wide range of values being reported in the literature. There has also been little consideration to the overall management of these large scale facilities which would affect productivity and costs. The purpose of this research is to model different culture scaling scenarios ultimately determining the most productive process while tabulating process specific capital and operational costs.

The overall goal of this research is to simulate different large scale microalgae culturing scenarios to quantify the productivity and profitability of microalgae for the utilization of bio-fuel. Specifically, the objectives of this research include:

1.) Investigate and simulate culture scaling management practices to juxtapose process time delays, photo-bioreactor utilization, resource utilization, process bottlenecks, total model throughput and total variable costs.

2.) Determine resource requirements and costs through evaluating seasonal growth rates, evaporation amounts, CO_2 consumption rates and process time delays to determine the total cost of microalgae bio-oil based on the model throughput of each scenario.

3.) Perform a what-if analysis to determine which of these areas would benefit from further research to mitigate costs.

4.) Perform an NPV analysis to evaluate microalgae production benefits and costs based on current crude oil and protein meal prices.

CHAPTER II

LITERATURE REVIEW

2.1 Process Type

Many biochemical processes consist of a sequence of processes that operate in different modes; microalgae cultivation is no different. The different modes associated with microalgae culturing consists of batch, semi-continuous and continuous modes. In batch cultivation operations, a photo-bioreactor is filled with cultivation medium and cultured for a specific duration. After a certain period, a specific cultivation volume is removed and replaced with an equal amount of media (Radmann et al., 2007). Batch cultivation presents several operational advantages, the most important of which are the maintenance of a constant inoculums and high growth rates (Fabregas et al., 1996). Repeated batch mode of operation provides an excellent means of regulating the nutrients feed rate to optimize the productivity while at the same time preventing the over and underfeeding of nutrients (Giridhar and Srivastava, 2001). As sequencing batch reactors are time oriented, the relation between filling and reaction phases time length lead to favorable productivity alterations (Lee et al. 1997). In a semi-continuous mode, systems operate by removing a fixed percentage of culture volume and replacing that volume with fresh media. However, a study conducted by Fabregas et al., (1999) concluded that in order to maximize cell productivity in semi-continuous cultures it is necessary to establish beforehand the conditions of renewal rate and light intensity that should be applied to the cultures to guarantee that the growth rate could be maintained even with the initial medium formulation. Therefore, semi-continuous cultures may be problematic to maintain outdoors. A continuous cultivation mode is in steady state so that cells are in balanced growth and the growth rate is equal to the dilution rate. Both semi-continuous and continuous modes are limited to culturing in some type of enclosed photo-bioreactor.

2.2 Photo-bioreactors

Production of biodiesel from algae involves four key steps: growth of algae, lipid induction, separation, and chemical conversions of lipid molecules to biodiesel (Leathers et al. 2007). Microalgae may be defined as aquatic, extremophilic, photosynthetic, microorganisms. These microorganisms exist in aquatic environments with extreme conditions such as high temperature, high or low pH and high salt content (Leathers et al. 2007). Through the process of photosynthesis, sunlight is converted into energy. A microalgae facility should also be located in an area that receives 5000 kcal m^{-2} d^{-1} and has more than 180 frost free d yr^{-1} (Weissman and Goebel, 1989). However, these regions are typically arid, which will result in water loss due to evaporation in outdoor raceway ponds. Currently, outdoor raceway ponds are the preferred reactor used for large scale production of microalgal biomass (Chaumont, 1993). A raceway pond is made of a closed loop recirculation channel that is typically about 0.3 m deep (Chisti, 2007). A large scale facility would operate a number of raceway ponds for the production of microalgal biomass. Outdoor raceway ponds can range from any size up to 20 ha, as larger ponds are considered unwieldy, if not impossible (Kadam, 1997). The largest raceway-based biomass production facility occupies an area of 440,000 m^2

(Spolaore et al. 2006). Despite success of open systems, future advances in microalgal mass culture will require closed systems as the algal species of interest do not grow in highly selective environments (Borowitzka, 1999). Enclosed systems include vertical tube reactors, tubular closed bioreactors, closed serpentine bioreactors and flat panel bioreactors just to name a few. Compared to open systems, greater growth densities and control of growth parameters are characteristic of enclosed bioreactors. However, this technology is more capital intensive (Chaumont, 1993).

2.3 Growth Rates

Microalgae have the ability to produce high yields compared to other types of biomass feedstocks. Early studies relating to microalgae growth consisted of laboratory controlled experiments. A previous model based on laboratory data obtained from steady state cultures calculated daily biomass production of Isochrysis galbana in a raceway algal mass culture system (Sukenik et al. 1991). This model was based on the following assumptions: the culture is nutrient saturated, productivity is only limited by light, the pond is well mixed and has no vertical gradients in biomass, nutrients or temperature and the system is a continuous culture in steady state. The model predicted a yearly average production rate of 9.7 g C (carbon) m^{-2} d^{-1} or an average yearly biomass production rate of 19.4 g m^{-2} d^{-1}.

In a study by Radmann (2007), a model was constructed based on the optimization of repeated batch cultivation of S. platensis in open raceway ponds. The six liter raceway ponds were maintained in a non-sterile chamber at 30 °C with illumination provided by daylight-type fluorescent lamps under a 12 h photoperiod. The variables in this model were blend concentration, renewal rate and medium dilutions. A productivity of 0.028 to 0.046 g L^{-1} d^{-1} or 28 to 46 g m^{-2} d^{-1}.

According to Goldman (1978), the upper limit in light conversion efficiency of large-scale outdoor culture translated to a maximum yield of 30 to 40 g m^{-2} d^{-1}. Therefore, the model predictions presented by Sukenik et al. (1991) and Radmann (2007) may be inflated and require careful consideration as these models were based on unrealistic assumptions pertaining to outdoor microalgae culturing. Becker, (1994) reported an average yield of 8 to 15 g m^{-2} d^{-1} for the *cyanobactrium* Spirulina which was consider as a realistic value in estimating the feasibility of a microalgae facility.

2.4 Media

Nutrients are needed for successful culturing of microalgae. Next to carbon, nitrogen is the most important nutrient for culturing microalgae. Generally, microalgae are able to utilize nitrate, ammonia or other organic sources of nitrogen such as urea (Becker, 1994). The utilization of urea and ammonia is the preferred form of nitrogen. Phosphorus is a major nutrient required for normal growth of all algae; it is essential for almost all cellular processes, i.e. biosynthesis of nucleic acids, energy transfer, etc. (Becker, 1994). Potassium is a requirement for all algae under potassium deficient conditions, growth and photosynthesis are reduced and respiration is high (Becker, 1994). Other nutrients include Ca, Na, Mg and Fe. Trace elements such as manganese, nickel, zinc, boron, vanadium, cobalt, copper and molybdenum are needed in minute amounts and can be toxic if excessive amounts are present in a culture.

There are several optimal media recipes reported by Becker (1994) and Anderson (2005) specific to different strains of microalgae. The existence of these recipes suggests that obtainment of nutrient requirements and appropriate costs for mass culturing should be straightforward.

2.5 Carbon Dioxide

In many green plants, carbohydrates are the most important direct organic products of photosynthesis (Stephan et al. 2002). CO_2 consumption is a lucid mass balance calculation which can be derived from the formation of glucose. The mass balance formula considered was: $6\ CO_2 + 12\ H_2O \longrightarrow C_6H_{12}O_6 + 6\ H_2O + 6\ O_2$. The different compounds and molecular weights are outlined in Table 1.

Table 1. CO_2 mass balance for microalgal biomass.

Compound	Molecular Weight ($g\ mol^{-1}$)	Mass (g biomass^1)
CO_2	44	264
H_2O	18	216
$C_6H_{12}O_6$	180	180
O_2	32	192

The CO_2 consumption ratio was determined by dividing the 264 g CO_2 by 180 g of $C_6H_{12}O_6$. This resulted in a ratio of 1.467 g CO_2 required to produce 1 g of biomass DW. In a study conducted by Kadam (1997), the utilization of CO_2 from power plant flue gas resulted in a CO_2 consumption rate of 1.49 g CO_2 for each g of biomass. In a study conducted by Watanabe and Hall, (1995), a carbon fixation rate of 14.6 g C m^{-2} d^{-1} at a growth rate of 30.2 g m^{-2} d^{-1} DW. This resulted in a ratio of 1.77 g CO_2 for each gram of biomass. Therefore, the CO_2 consumption calculated from the mass balance equation seems justifiable.

2.6 Contamination

Certain kinds of contamination in outdoor algal cultures are inevitable in view of the non-aseptic conditions, where neither the medium nor the environment are sterile (Becker, 1994). Contaminants include foreign strains of algae, cyanobacteria, protozoa, mold, yeast and fungi. Natural phenomena such as rainfall can dilute microalgae cultures and also introduce contaminates. A diluted culture is more subject to take over by these contaminants, in such an event cultures could be lost. Wind is another natural occurrence that will introduce foreign objects and contaminants into outdoor ponds. However, a common characteristic of microalgae is that because they grow in highly selective media (e.g. high pH and high salt content) they can be cultivated in open systems but remain relatively free from contamination by other microorganisms (Borowitzka, 1999).

2.7 Mixing

To prevent flocculation of microalgal cells on pond surfaces, cultures need to be agitated constantly. Raceways are generally mixed with paddle wheels, and experience has shown that paddle wheels are by far the most efficient for mixing the algal cultures and are the easiest to maintain (Anderson, 2005). Paddle wheels are widely utilized, but scaling up these mixing devices can be limited and may be cost prohibitive.

2.8 Harvesting

Microalgae biomass can be harvested by centrifugation, filtration or sedimentation. Recovery of microalgal biomass can be a significant problem because of the dilute cultures requiring large harvest volumes and small size (3-30 µm diameter) of the algal cells (Grima et al., 2003). Centrifuges can process the small cells characteristic of microalgae while handling large a volume of dilute cultures. Many harvesting processes incorporate a settling process for primary harvesting. Centrifuging is followed after the settling process which achieves a cell density of 1 to 3% solids (Benemann and Oswald 1996). A self-cleaning stack centrifuge was reported to achieve a processed cell density of 12% solids with a discharge rate of 2.99 $m^3 h^{-1}$ (Grima et al., 2003). Benemann and Oswald (1996) referenced a centrifuge that could process up to 20 $m^3 h^{-1}$.

2.9 Discrete Event Modeling

A relentless literature search yielded no results pertaining to discrete event modeling of large scale microalgae facilities. Therefore, other fields were evaluated which utilized discrete event simulation models. In a study by Sharda and Bury (2008), a discrete event simulation model (DES) of a chemical plant was constructed. This study utilized DES to identify critical subsystems and component failures, production losses, new component installation and policies for reduction in production loss. Within each subsystem, components were evaluated to exploit components causing more frequent and costly downtime. The operation of the chemical plant included: raw product loading, raw product mixing, reaction, intermediate storage, raw product washing, drying, blending, intermediate storage and final packaging (Sharda and Bury, 2008). This study utilized ExtendSim simulation to develop the DES model. The inputs required for running the simulation model were classified into simulation parameters, production information and failure information. For model verification and validation, the following parameters were checked: total production rate, reactor cycle times, total final quantity produced, mass balance of reactor and final cleaning operations, failure and repair times. To identify critical subsystems and components, the following systematic approach was used: run the simulation model without any failures and record base production/day for each product type, consider the failures for each subsystem and compute annual production loss, identify the subsystems causing highest production loss, for subsystems with highest production loss, find the critical components which contributed towards maximum downtime and evaluated the impact of changes policies for critical components (Sharda and Bury, 2008).

A study by Connelly and Bair, (2004) explored the potential of DES to advance system-level investigation of emergency department (ED) operations. The Extend Suite v.5 modeling platform was used for model development and associated data entry and data processing tools. Extend provides a DES platform with an integrated database and an object oriented programming environment that allowed a model to be built by assembling modules that represent packages of prewritten code (Connelly and Bair, 2004). The modules were connected by conduits that carry data elements representing patients, staff, orders, laboratory results and images. The accuracy of model output was tested by comparing predicted and known patient service times. EDSIM’s core engine utilized a patient-care-directed algorithm in which each patient modeled ED had a set of instructions that defined a series of individual activities that must be completed in correct order before a patient exited the ED (Connelly and Bair, 2004). Therefore, each patient had a predefined path with a defined but variable set of clinical needs. Elements of patient care included imaging studies, laboratory studies, history and physical examination, nursing activity, consultations, and intubation. Modeled patient activity was based on actual patient experience in the University of California, Davis, Medical Center (UCDMC). Using patient data from the five-day study period and comparing model output with known patient treatment and service times, the model overestimated average treatment time by 8% and underestimated average service time by 9%. For individual patient times, 28% of modeled patient treatment times had an error less than one hour, whereas 59% of known patient treatment times had an error of less than three hours. For individual patient service times, 18% of those modeled had an error of less than one hour, and 46% of the known had an error of less than three hours. The model predicted average patient times with better accuracy than individual patient times because there was no strong bias toward over- or underestimation (Connelly and Bair, 2004).

Delp, (2000) developed a full scale model and a reduced scale model of a semiconductor manufacturing plant utilizing the computer software package Extend. The main objective of this study was to minimize production costs and increase productivity. This was accomplished by analyzing input release policies, maintenance scheduling, and bottleneck queuing. There are several features that make semiconductor manufacturing difficult to schedule including random yields and rework, complex product flows, time-critical operations, batching, simultaneous resource possession, and rapidly changing products and technologies (Delp, 2000). There were five major processing areas included in this analysis: semiconductor wafer fabrication and chemical clean, photolithography, ion implant, metal deposition/oxidation, and plasma/chemical etch. Manufacturing steps were performed on single wafers, some steps were performed on an entire lot, and some steps processed several lots at the same time. Queuing regulations were used to decide what job to schedule next when a machine becomes available. These queuing regulations attempted to reduce flow times by releasing work to the plant in a controlled manner. The reduced model was setup with a deterministic input release policy release rate and first-in first-out (FIFO) at the queues. The initial deterministic input release policy for the reduced model was determined by the utilization of the bottleneck which implemented a preventative maintenance schedule (Delp, 2000). The results of the scheduling variations were measured in terms of WIP, product cycle time, bottleneck utilization, and throughput. Various simulations were devised to test the combinational effect of input release policies, bottleneck queuing, and mandating preventative maintenance. All simulations had a model duration of 17,520 factory hours on the reduced model. The WIP and cycle time had a correlation of 0.808, thus demonstrating that WIP and cycle time were highly correlated (Delp, 2000). The preventative maintenance schedule decreased the WIP and cycle time of the deterministic input release with FIFO/setup avoidance (SA) at the bottleneck, although the preventative maintenance schedule did not have a marked improvement when the earliest due date (EDD) was used at the bottleneck (Delp, 2000). Workload regulation (WR) was shown to decrease the WIP and cycle time compared to the other input release policies, with or without preventative maintenance schedule.

CHAPTER III

DEVELOPMENT OF PILOT PLANT SCALE MODELS FOR THE PRODUCTION OF GREEN MICROALGAE FOR BIO-FUEL

3.1 Introduction

Microalgae are aquatic, photosynthetic, microscopic plants that utilize sunlight and can be cultured for the production of biomass for biofuel. Microalgae biomass production offers many advantages over conventional biomass production technologies including higher yields, use of otherwise nonproductive land, reuse and recovery of waste nutrients, use of saline or brackish waters, and reuse of CO_2 from power-plant flue-gas or similar sources Brune et al. (2009). Even though there continues to be a considerable amount of interest in utilizing microalgae as a biofuel, this technology is still predominately in the research and development (R&D) phase. As this technology begins to move from the laboratory scale to the pilot plant scale, culture scaling processes become a concern in an effort to determine the actual production potential of microalgae cultivation. Currently, there is a plethora of literature pertaining to potential growth rates and production. However, many of these studies fail to consider the number of support ponds to achieve final culture volumes, an initialization period, a starvation period for lipid accumulation, specific process time delays characteristic of microalgae culturing or different scaling techniques to reduce overall culturing durations. These considerations are pivotal in determining the productivity potential of microalgae for the utilization of bio-fuel. The purpose of this analysis is to quantify different process type.

delays, resource inputs and assumptions for simulation development. These time delays and resource inputs will be utilized in discrete event models to determine the productivity of different microalgae culturing scenarios. Figure 1 provides an overview of microalgae biomass production and economic model.

3.2 Objectives

The main goal of this analysis is to identify different scaling scenarios to be modeled, analyze and quantify process time delays specific to the large scale culturing of microalgae as well as determine the resource requirements of each scaling process. Objectives to achieve this goal include:

1) Ascertain different scaling scenarios by reviewing culturing practices with-in Texas AgriLIFE Research algae facilities.

2) Evaluate current culturing practices reported in literature to ensure consilience between current technology and the scaling scenarios considered for this analysis.

3) Determine resource requirements through evaluating seasonal growth rates, evaporation amounts, CO_2 consumption rates and process time delays.

4) Define and quantify process time delays for culturing duration, culture/media transfer, contamination events and liner/mixer maintenance.

5) Identify stochastic variables and construct triangular distributions for process time delays as well as resource requirements.

6) Establish model assumptions and general inputs such as time between item arrivals (TBA), starting item volume, finishing item volume and labor resources.

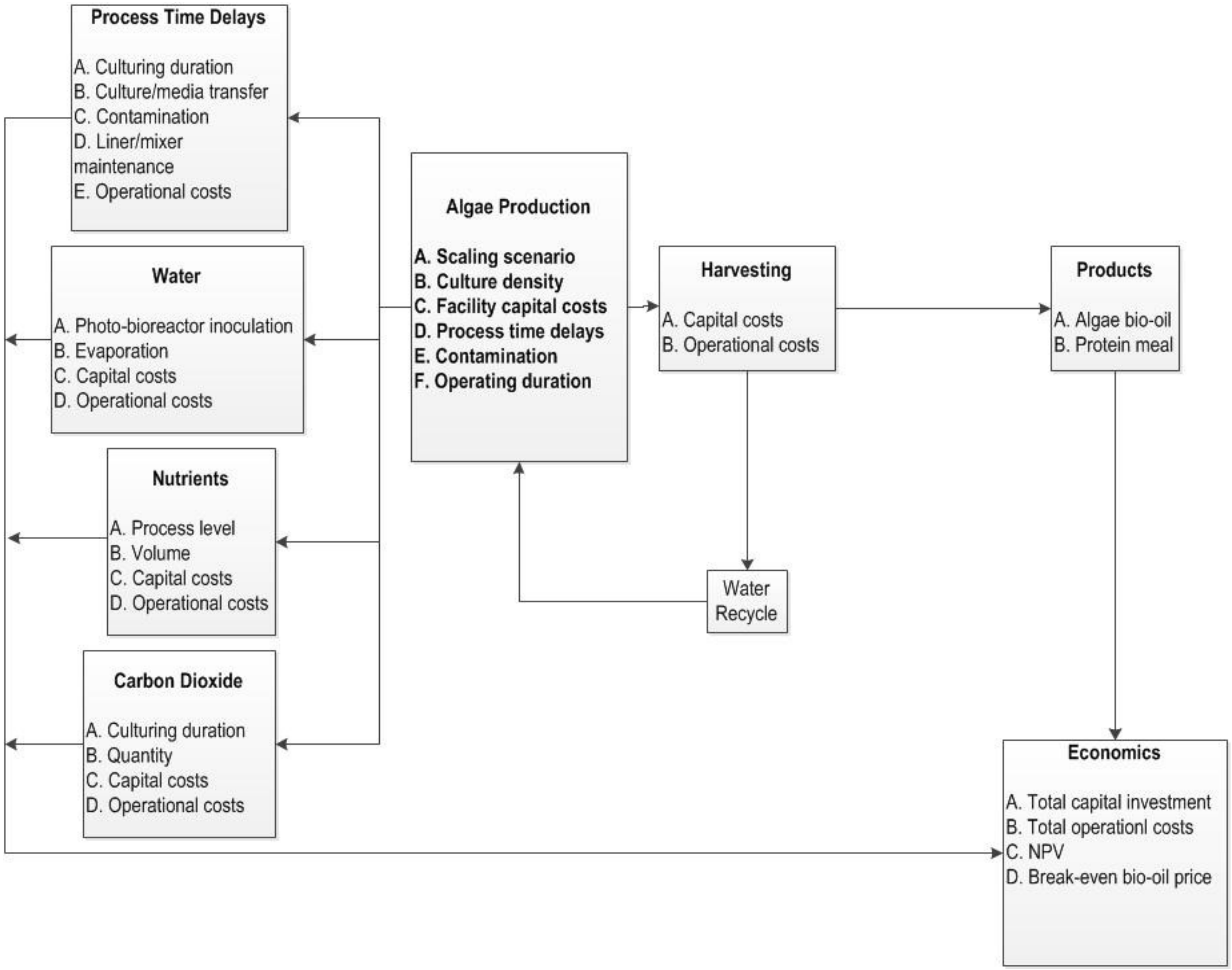

Figure 1. Overview of microalgae biomass production and economic model.

3.3 Materials and Methods

There is little in the literature pertaining to culture management for large-scale microalgae facilities. This may be a consequence of proprietary interests as this industry is still in the R&D phase. Accordingly, processes considered for this analysis were derived from culturing practices utilized at the laboratory and pilot scale within Texas AgriLIFE Research algae facilities. Three simulation models were developed which equivocated multiple scaling steps for mass culturing of microalgae using Extend-Sim 7.0, which utilizes a Discrete Event Simulation (DES) modeling methodology and models the movement and routing of items. Each scaling step in the culturing process was considered as a discrete event. The culturing of microalgae consists of a sequence of unit operations which are generally operated in a batch or semi-batch mode. The models constructed for this analysis operate in a batch mode in which cultures of microalgae flow through a network of raceways. Operating conditions for each item are determined before the culturing process of each raceway begins. Therefore, the scenarios simulated can determine process performance on the basis of the given set of operating conditions. Each of the three models was constructed to quantify the time between items (TBI), average cycle time (ACT) and resource requirements of each item. Identification of the TBI and ACT was considered advantageous in identifying downstream bottlenecks between different scaling steps. Each item had a beginning volume of 1 L and was cultured to a final volume of 9,866,752 L. It was assumed that a facility would regularly receive 1 L of microalgae seed stock which would be utilized to begin the culturing process. The total facility size considered for this analysis is 40 ha with 32 ha employed for microalgae production. Three culture management techniques were considered for this analysis and included: stepwise scaling, volume batching and intense culturing processes.

The stepwise scaling scenario is a straightforward scaling process in that each scaling step doubles the volume of the inoculating culture. An example of this process would be diluting 40 L of microalgae culture from a concentration of 1 g L^{-1} dry weight (DW) to 80 L at a concentration of 0.5 g L^{-1} DW. At the end of the culturing period, the 80 L volume would have a concentration of 1 g L^{-1} DW which would then be diluted to inoculate a volume of 160 L at a concentration of 0.5 g L^{-1} DW and so forth until the final volume of 9,866,752 L was reached. This culture scaling process is depicted in Figure 2.

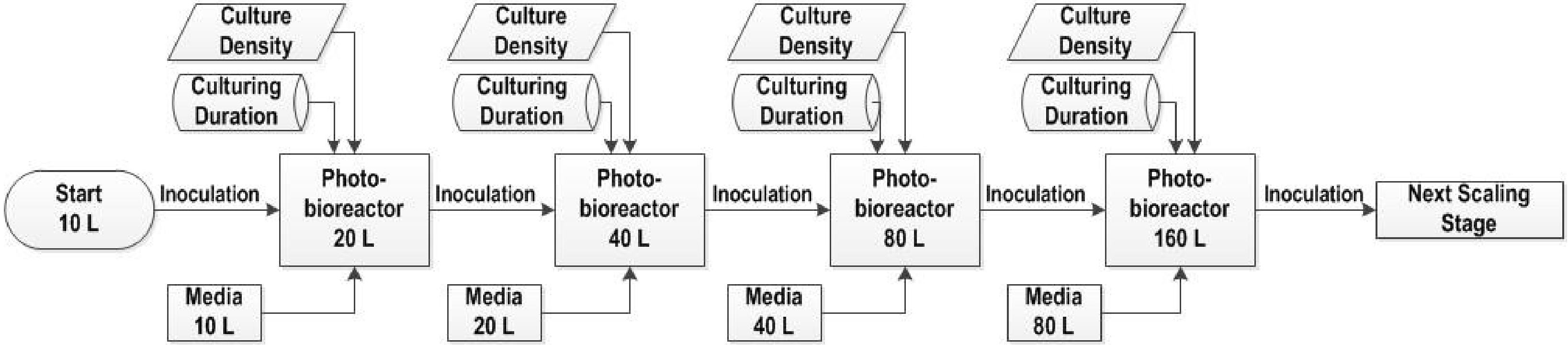

Figure 2. Flowchart of stepwise scaling process.

The volume batching scenario is similar to the stepwise scaling scenario, except that two volumes are simultaneously batched together to inoculate an appropriately larger volume. An instance of this would be culturing 40 L until achieving a concentration of 1 g L^{-1} DW which would then be diluted to inoculate a volume of 80 L at a concentration of 0.5 g L^{-1} DW. As the 80 L is cultured, the 40 L simultaneously receives an inoculating volume of 20 L at 0.5 g L^{-1} DW. At the end of the culturing period, both the 40 L and 80 L volumes are batched together. This results in a total inoculation volume of 120 L at a concentration of 1g L^{-1} DW which would be diluted to 0.5 g L^{-1} DW and utilized to inoculate a volume of 240 L. Therefore, the 40L and 80L cultures are batched together to inoculate a volume of 240L. Since the volume batching model batches two items into one item, reducing the number of items, only three scaling steps were employed to incorporate the volume batching process. The volume batching process is depicted in Figure 3.

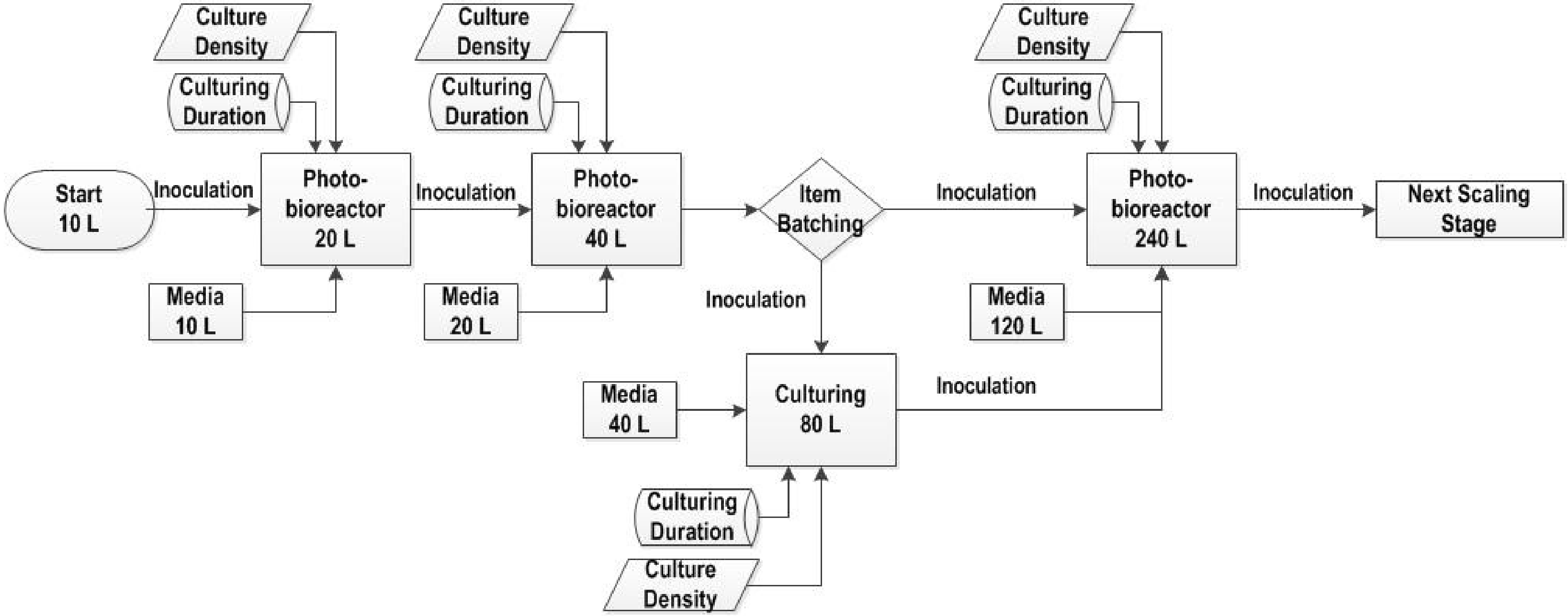

Figure 3. Flowchart of volume batching process.

The intense culturing model implements the use of flat panel bioreactors (FPR's) between the laboratory and large raceway scales. FPR's are able to grow microalgae cultures at greater densities and allow the exclusion of atmospheric contaminants (Chaumont, 1993). It was assumed that a culturing period of 4 days would yield a culture concentration beginning at 0.5 g L^{-1} DW to a final concentration of 5 g L^{-1}DW (Anderson, 2005). Therefore, the greater culture concentration yields by the FPR's allow the inoculation of a volume 10 times greater than the original volume of the FPR. An example of this process would be culturing 40L in an FPR from a concentration of 0.5 g L^{-1} DW to a concentration of 5 g L^{-1} DW. This would result in a culture of 40 L with a concentration of 5 g L^{-1} DW, which would be used to inoculate a volume of 400 L at a concentration of 0.5 g L^{-1} DW. However, FPR's are considered as capital intensive methods of cultivation. Therefore only three scaling steps utilizing FPR's were implemented into the intense culturing model. The intense culturing process is illustrated in Figure 4.

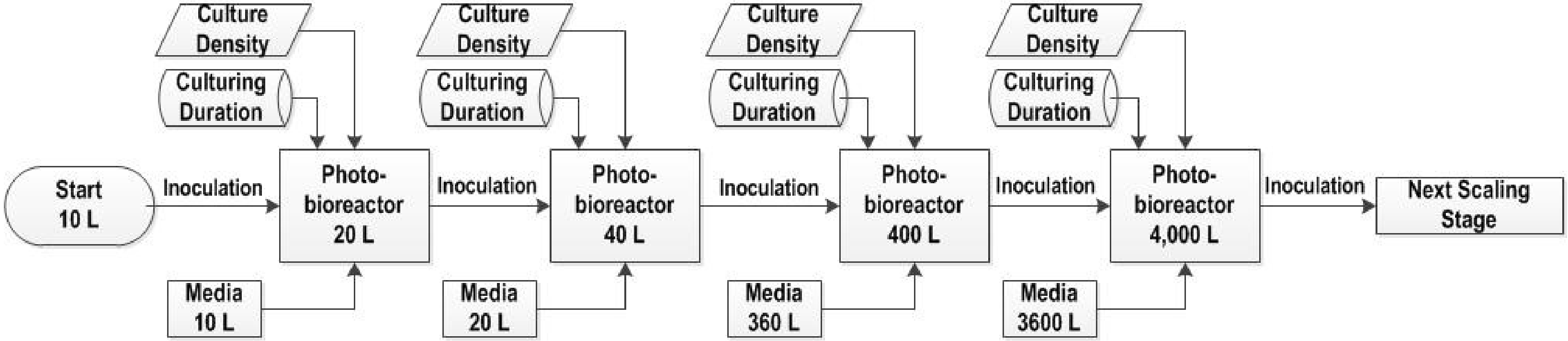

Figure 4. Flowchart of intense culturing process.

Five different process levels were developed for each model and included a laboratory, a medium raceway, large raceway, starvation pond and harvesting level. The laboratory, medium raceway and large raceway levels employ numerous scaling steps through which items progress until achieving a final volume of 9,866,752 L. As an item passes through the beginning of a new scaling step, several item specific attributes were identified which would need to be attached to each item. These attributes include: item arrival time, item volume, seasonal yield, evaporation rates and CO_2 consumption. The production of lipids from microalgae requires the culture to be stressed for a certain period of time. Therefore, a starvation period of 21 d was assumed for induction of microalgal lipid production. The starvation process was modeled with three different sets of starvation ponds encompassing a volume of 9,866,752 L. Harvesting was achieved through the utilization of disc-bowl centrifuges. The centrifuges considered for this analysis had a harvesting rate of 90,000 L hr^{-1} with a solids concentration of 10%. There is no maintenance time delay for centrifugation as this activity could be accomplished between harvesting intervals. The different process levels, scaling steps and volumes considered by this analysis are outlined in Table 2.

Table 2. Process scaling steps and volumes for the three algae pond management scenarios.

		Stepwise Model	Volume Batching Model	Intense Culturing Model
Level	Scaling Step	Microalgae Raceway Volume (L)	Microalgae Raceway Volume (L)	Microalgae Raceway Volume (L)
Laboratory	Step 1	2.00	2.00	2.00
	Step 2	4.00	4.00	4.00
	Step 3	9.00	15.0	9.00
	Step 4	19.0	30.0	19.0
	Step 5	40.0	60.0	40.0
	Step 6	80.0	140	80.0
Medium Raceway	Step 1	150	280	160
	Step 2	301	560	1600
	Step 3	602	1600	16000
	Step 4	1204	3200	•
	Step 5	2408	*	•
	Step 6	4817	*	•
Large Raceway	Step 1	9635	6400	•
	Step 2	19271	12800	•
	Step 3	38542	38542	•
	Step 4	77084	77084	•
	Step 5	154168	154168	154168
	Step 6	308336	308336	308336
	Step 7	616672	616672	616672
	Step 8	1233344	1233344	1233344
	Step 9	2466688	2466688	2466688
	Step 10	4933376	4933376	4933376
	Step 11	9866752	9866752	9866752
Starvation Ponds	Step 1	9866752	9866752	9866752
	Step2	9866752	▪	9866752
	Step 3	9866752	▪	9866752
Harvesting	Step 1	9866752	9866752	9866752

*** denotes scaling steps that were eliminated through volume batching.**

• denotes scaling steps omitted from the implementation of FPRs.

▪ denotes pond discarded from the starvation pond level.

In evaluating culture scaling scenarios, it was necessary to identify factors that encumbered process flow as these factors would influence process duration. The factors considered included: culturing duration, contamination events, culture transfer, raceway/mixer maintenance and daily culture sampling and analyzing. The culturing duration was based on assumed monthly average growth rates. Time for raceway sanitation was included in order to simulate the mitigation of contamination outbreaks. A probability of contamination was assumed to be 0.001. Culture transfer, raceway/mixer maintenance and daily culture sampling and analyzing were identified as stochastic variables in which process time delays were based on triangular distributions.

For this analysis, large-scale microalgae facilities were assumed to be similar to agricultural operations since both entities are concerned with the culturing of crops. Therefore, large-scale microalgae facilities were assumed to follow the same labor laws as agricultural operations. Accordingly, three labor resources were identified which had different educational backgrounds and subsequently different pay scales. The hourly wage rate was assumed to be \$15/hr for Lab Labor, \$12.50/hr for H.S. Labor and \$10/hr for M. Labor. For a contamination event, another labor resource pool was considered, i.e. Contract Labor. This labor resource is independent of the facility and was called upon to clean raceways in the event of a contamination. Contract Labor was assumed to encompass 12 laborers for a total cost of \$120 hr^{-1}. The availability of laborers is dictated by shift times and was assumed to have a total working period of 12 h d^{-1}, 360d yr^{-1}. Labor resource utilization was determined and allowed for an estimate of the number laborers required for each model.

3.4 Results and Discussion

3.4.1 General Inputs

It was assumed that a microalgae facility would receive 1 L of microalgae seed stock that would be utilized for culturing. Therefore, each item created was the equivalent of 1 L of microalgae seed stock with a concentration of 1 g L^{-1}. Item generation was based on a constant time between arrivals (TBA). However, determining the TBA for each model was difficult considering a model initialization period and the varying process durations for each scaling step. Therefore, the item arrival time was optimized by trial and error. The item arrival time was changed until the number of items created was equal to or less than the sum of the number of items that had already exited the model and items that were currently being processed at the conclusion of the model.

Three different types of labor groups were identified however; four different labor resource pools were created in each model. The percent utilization of these labor resources is calculated by the labor resource pool. Conversely, the utilization calculated by the resource pool is not characteristic of the processes modeled. This is due to the labor resource pool calculating the percent utilization based on the amount of time the resource is out of the resource pool regardless of the shift time. The *shift* block is communicating to the resource pool to not release any resources when it is off shift. However, resources that are in the model when the shift expires do not return to the resource pool. Therefore, the resource pool can’t control resources that are being used out in the field. Accordingly, to prevent labor resources from hindering item flow it was assumed that the percent utilization calculated by the resource pool would need to be 65% or less. The actual percent utilization of labor resources was calculated separately.

The availability of laborers to perform the tasks modeled is dependent on the *shift* block. It was assumed that a 12 hr work day would be required to operate a microalgae facility. Also, there were no time considerations for scheduled breaks or employee shift changes. This was due the assumption that a microalgae facility could be considered as an agricultural entity. Accordingly, there were also no considerations for overtime pay. The shift times incorporated into the models are outlined in Table 3. The shift schedule times are repeated every 24 hrs.

Table 3. Shift schedule for all models.

Parameters	
Time	On/Off
0	On
6	Off
7	On
13	Off

3.4.2 Model Attributes

The first item attribute is the item arrival time for each level. This attribute was implemented to quantify the overall time between items (TBI), and average cycle time (ACT). The second attribute determined for each item was the item arrival time for each scaling step. This arrival time was employed to calculate the TBI and ACT of each scaling step, which is advantageous for identifying bottlenecks. The third attribute was the item volume which was based on the inoculation volume as well as the culture concentration. This attribute was tabulated to account for the item volume which was utilized to calculate subsequent operational costs. The next attribute was the seasonal yield attribute which quantified the process time delay for the culturing duration or growing activity. This attribute is probably the most important as realistic yield predictions are necessary to accurately simulate time delays pertaining to the culturing process. According to Goldman, (1978), the upper limit in light conversion efficiency of large-scale culture translated to a maximum yield of 30-40 g m^{-2} d^{-1}. The laboratory scale in each model was assumed to have a constant culturing duration of 4 d. This constant culturing duration is based on an assumed growth rate of 20 g m^{-2} d^{-1} which is half of the upper limit determined by Goldman, (1978) and is justifiable for a laboratory setting. However, the medium and large raceways would be located outdoors in uncontrolled environments susceptible to contaminants, weather events and varying solar radiation. Therefore variable growth rates were considered on a monthly basis and incorporated into the models for a 20 yr period. The growth rates assumed by this analysis are based on assumed monthly average growth rate as actual growth rate data specific to this analysis is currently being collected within Texas AgriLIFE Research algae facilities. Table 4 summarizes the month, assumed growth rate and calculated culturing duration. The resulting average yearly growth rate for this analysis was 12.5 g m^{-2} d^{-1}or an average culturing duration of 8.43 d. Becker, (1994) reported an average yield of 8-15 g m^{-2} d^{-1} for the cyanobactrium Spirulina which is consider as a slow growing microalgae. Therefore, the seasonal growth rates assumed by this analysis should be regarded as conservative.

Table 4. Assumed seasonal area yield and culture duration by month.

Month	Seasonal Yield ($g\ m^{-2}\ d^{-1}$)	Culturing Duration (d)
Jan	5.00	15.2
Feb	5.00	15.2
Mar	10.0	7.60
Apr	15.0	5.00
May	20.0	3.80
Jun	20.0	3.80
Jul	20.0	3.80
Aug	20.0	3.80
Sep	15.0	5.00
Oct	10.0	7.60
Nov	5.00	15.2
Dec	5.00	15.2

Seasonal culturing durations were calculated by first dividing the inoculating concentration (0.5 g L^{-1} DW) by the assumed seasonal growth rate for each month. The resulting value was then divided by 0.001 m^3 as the inoculating concentration was based on 1 L. This yielded d m^{-1} which was then multiplied by an assumed raceway depth of 0.1524 m. The seasonal culturing duration equation for growth rates is depicted in equation 1.

$$CD_S = \frac{I_D D_R}{G V_{CF}} \tag{1}$$

where:

CD_S = seasonal culturing duration (d)

I_D = inoculating concentration (g L^{-1} DW)

D_R = raceway depth (m)

G = assumed growth rate (g m^{-2} d^{-1})

V_{CF} = volume conversion factor (L m^{-3})

An attribute for seasonal evaporation rates was also developed to simulate evaporation in outdoor raceways. The evaporation rates considered were indicative of actual data analyzed from arid regions located in West Texas. Seasonal weather data from a weather station located in Pecos, Texas was interpolated to determine monthly average evaporation rates which were incorporated into the models. Weather data from a time period of 8-31-2000 to 8-30-2010, in which 2003 data was not available, was analyzed utilizing Meyer’s equation. Monthly evaporation averages were calculated for each year and then averaged across the range of years. This resulted in average monthly evaporation rates over a nine year period. The average monthly evaporation rates are reported in Table 5.

Table 5. Evaporation rates utilized for all models.

Month	Evaporation Rate (m d^{-1})
Jan	0.0034
Feb	0.0043
Mar	0.0066
Apr	0.0111
May	0.013
Jun	0.0157
Jul	0.0123
Aug	0.0114
Sep	0.0092
Oct	0.0061
Nov	0.0045
Dec	0.0036

The evaporation rates were calculated on a monthly basis as implementation of daily evaporation rates seemed cumbersome and was assumed to ultimately equate monthly evaporation rates. The summer months of May, June and July yielded the highest evaporation rates compared to other months. These seasonal evaporation rates were extended for a 20 yr period.

The last attribute attached to each item is the CO_2 consumption attribute. This attribute was derived from seasonal growth rates and CO_2 mass balance calculations. The mass balance formula considered was: $6\ CO_2 + 12\ H_2O \longrightarrow C_6H_{12}O_6 + 6\ H_2O + 6\ O_2$. The different compounds and molecular weights are outlined in Table 6.

Table 6. CO_2 mass balance for algae growth.

Compound	Molecular Weight (g mol^{-1})	Mass (g biomass^{-1})
CO_2	44	264
H_2O	18	216
$C_6H_{12}O_6$	180	180
O_2	32	192

The CO_2 consumption ratio was determined by dividing the 264 g CO_2 by 180 g of $C_6H_{12}O_6$. This resulted in a ratio of 1.47 g CO_2 required to produce 1 g of biomass DW. The resulting monthly growth rates and CO_2 consumption rates are listed in Table 7. In a study conducted by Kadam, (1997), utilization of CO_2 from power plant flue gas resulted in CO_2 consumption rate of 1.49 g CO_2 for each g of biomass. Therefore, the CO_2 consumption rate determined by this analysis is justifiable. The CO_2 consumption rates vary monthly as these rates were derived from the assumed monthly growth rates.

Table 7. Seasonal CO_2 consumption for all models based on carbon mass balance.

Month	Seasonal Yield (g m^{-2} d^{-1})	CO_2 Consumption (kg m^{-2})
Jan	5.00	0.007
Feb	5.00	0.007
Mar	10.0	0.015
Apr	15.0	0.022
May	20.0	0.029
Jun	20.0	0.029
Jul	20.0	0.029
Aug	20.0	0.029
Sep	15.0	0.022
Oct	10.0	0.015
Nov	5.00	0.007
Dec	5.00	0.007

3.4.3 Model Process Time Delays and Appropriate Operational Costs

The growing activity is the first consideration for process time delays. To prevent simultaneous processing of multiple items, the maximum number of items delegated for this activity was limited to one. The growing activity time delay was derived from the culturing duration which is based on the assumed seasonal yields. Likewise, the growing activity was not directly dependent on the availability of labor resources.

Culture transfer is a process time delay consideration as microalgae cultures would be transferred from one scaling step to the next appropriately larger step. Since it was assumed that all nutrients were depleted at the end of the culturing period, microalgae cultures were assumed to be sustainable but not growing at the time of transfer. Therefore, the time required to transfer the cultures was assumed to delay culture growth and was a process time delay. The culture transfer time for the laboratory scale was determined from personal experience resulting in a triangular distribution for the laboratory level of 0.30 hrs, a minimum time of 0.15 hrs and a maximum time of 0.45 hrs. The labor considerations for the laboratory level utilized lab laborers at a labor rate of \$15 hr^{-1}. The culture transfer time triangular distribution for the medium raceway, large raceway, starvation and harvesting levels was based on an accumulated transfer volume of 24,528,708 L. It was assumed that the accumulated volume would need to be transferred in a total time period of 16 hr or less. The raceway volume at each scaling step was divided by the total facility volume of 49,057,416 L and then multiplied by the assumed total time constraint of 16 h. The resulting time requirement was the minimum value considered for the triangular distribution. The average value of the triangular distribution was determined by multiplying the minimum value by a factor of 1.25 while the maximum value was 1.5 times the value of the average time requirement. Table 8 outlines the appropriate triangular distribution for each scaling step.

Table 8. Transfer time requirements.

			Triangular Distribution		
Level	Scaling Step	Transfer Volume (L)	Minimum (hr)	Median (hr)	Maximum (hr)
Laboratory	Step 1	2.00	0.15	0.300	0.45
	Step 2	4.00	0.15	0.300	0.45
	Step 3	9.00	0.15	0.300	0.45
	Step 4	19.0	0.15	0.300	0.45
	Step 5	40.0	0.15	0.300	0.45
	Step 6	80.0	0.15	0.300	0.45
Medium Raceway	Step 1	150	0.10	0.125	0.15
	Step 2	301	0.10	0.125	0.15
	Step 3	602	0.10	0.125	0.15
	Step 4	1204	0.10	0.125	0.15
	Step 5	2408	0.10	0.125	0.15
	Step 6	4817	0.10	0.125	0.15
Large raceway	Step 1	9635	0.10	0.125	0.15
	Step 2	19271	0.10	0.125	0.15
	Step 3	38542	0.10	0.125	0.15
	Step 4	77084	0.10	0.125	0.15
	Step 5	154168	0.10	0.125	0.15
	Step 6	308336	0.10	0.125	0.15
	Step 7	616672	0.20	0.25	0.30
	Step 8	1233344	0.40	0.50	0.60
	Step 9	2466688	0.80	1.00	1.20
	Step 10	4933376	1.60	2.00	2.40
	Step 11	9866752	3.20	4.00	4.80
Starvation Ponds	Step 1	9866752	3.20	4.00	4.80
	Step2	9866752	3.20	4.00	4.80
	Step 3	9866752	3.20	4.00	4.80

In order to determine labor costs associated with transfer time, the process time (PT) from the transfer activity was quantified. The labor time associated with the transfer activity was the same as the transfer time however, the total amount of labor time associated with culture transfer may be less than the total transfer time. This is due to the fact that laborers will not have to be present for the entirety of the culture transfer process, but will be required to monitor the progression of the activity. Since the processing time was based on a daily time requirement, the PT is multiplied by a conversion factor of 24 hr d^{-1} and the appropriate labor rate. In the laboratory scale a labor rate of \$15 h^{-1} was utilized as lab personnel are responsible for all activities. The outdoor raceways utilized outdoor laborers for culture transfer therefore, the medium, large and starvation pond scales labor rate was \$12.50 h^{-1}. The labor cost formula is displayed in equation 2.

$$L_{TC} = \left(\sum PT_T \ (T_{CF}\, L_R)\right) \qquad (2)$$

where:

L_{TC} = transfer labor cost (\$)

PT_T = transfer process time of each step (d)

T_{CF} = time conversion factor (hr d^{-1})

L_R = labor rate (\$ hr^{-1})

Also, raceways would need to be cleaned periodically to mitigate biological fouling and contamination events. In the event of raceway contamination, the growing activity must remain inactive until the conclusion of the raceway cleaning activity. A contamination event is assumed to be minute therefore; a probability of 0.001 is considered for this analysis. Time considerations for raceway cleaning of a contamination event were only incorporated in the medium raceway, large raceway and starvation pond levels. The time to clean each raceway was based on current cleaning practices as well as the raceway size. The resulting time requirements were based on four laborers who were able to clean a 30,300 L raceway in approximately three hrs. However, for this analysis it is assumed that a 30,300 L raceway would need to be cleaned in a one hr time period. Accordingly, it was assumed that it would take one hr for a12 person crew to clean a raceway volume of 30,300 L or an area of 200 m^2. A constant triangular distribution for raceway cleaning time for all scaling steps in the medium raceway levels was assumed to have a minimum time of 0.25 hrs, an average time of 0.5 hrs and a maximum time of 1 hr. This triangular distribution was increased linearly in the large raceway level for each appropriately larger scaling step. The triangular distribution for the raceway cleaning time requirement was determined by dividing the raceway volume by the assumed hourly cleaning volume of 30,300 L. This resulted in the number of hours required to clean a particular raceway which was the minimum value in the triangular distribution. The median value was determined by multiplying the minimum value of the triangular distribution by a factor of 1.25 while the maximum value was determined by multiplying the minimum value by a factor of 1.5. The resulting triangular distribution for each scaling step is depicted in Table 9.

Table 9. Raceway sanitation time requirements.

Level	Scaling Step	Raceway Volume (L)	Triangular Distribution Minimum (hr)	Triangular Distribution Median (hr)	Triangular Distribution Maximum (hr)
Laboratory	Step 1	2.00	0.25	0.50	0.75
	Step 2	4.00	0.25	0.50	0.75
	Step 3	9.00	0.25	0.50	0.75
	Step 4	19.0	0.25	0.50	0.75
	Step 5	40.0	0.25	0.50	0.75
	Step 6	80.0	0.25	0.50	0.75
Medium Raceway	Step 1	150	0.25	0.50	0.75
	Step 2	301	0.25	0.50	0.75
	Step 3	602	0.25	0.50	0.75
	Step 4	1204	0.25	0.50	0.75
	Step 5	2408	0.25	0.50	0.75
	Step 6	4817	0.25	0.50	0.75
Large Raceway	Step 1	9635	1.00	1.25	1.50
	Step 2	19271	1.00	1.25	1.50
	Step 3	38542	1.00	1.25	1.50
	Step 4	77084	2.50	3.13	3.75
	Step 5	154168	5.00	6.25	7.50
	Step 6	308336	10.0	12.5	15.0
	Step 7	616672	20.0	25.0	30.0
	Step 8	1233344	40.0	50.0	60.0
	Step 9	2466688	80.0	100	120
	Step10	4933376	160	200	240
	Step11	9866752	320	400	480
Starvation Ponds	Step 1	9866752	320	400	480
	Step2	9866752	320	400	480
	Step 3	9866752	320	400	480

The labor cost associated with raceway cleaning was also calculated. The process time from the cleaning activity was multiplied by the labor cost of \$120 h^{-1} and a constant of 24 h d^{-1}. The raceway labor cost calculation is displayed in equation 3.

$$\mathrm{L_{RC}} = \left(\sum \mathrm{PT_{RC}}\ (\mathrm{T_{CF}}\ \mathrm{L_R})\right) \tag{3}$$

where:

L_{RC} = raceway cleaning labor cost ($)

PT_{RC} = raceway cleaning process time of each stage (d)

T_{CF} = time conversion factor (hr d^{-1})

L_R =labor rate ($ hr^{-1})

Another consideration for process time delay is raceway and mixer maintenance. Raceway maintenance was based on the time required for liner inspection and repair as well as mixer inspection and maintenance. A triangular distribution for raceway maintenance was incorporated into the models. The medium raceway level triangular distribution was constant for each scaling step with an average time of 2 h, a minimum time of 1 h and a maximum time of 3h. Beginning in the large raceway level, the triangular distribution was increased linearly by adding .5 hr to the previous scaling stage time delay. The maximum value was increased by adding 1 hr to the maximum time delay of the previous scaling step. The resulting triangular distribution and scaling steps are displayed in Table 10.

Table 10. Maintenance time requirements.

Level	Scaling Step	Raceway Volume (L)	Triangular Distribution Minimum (hr)	Triangular Distribution Median (hr)	Triangular Distribution Maximum (hr)
Medium Raceway	Step 1	150	1.00	2.00	3.00
	Step 2	301	1.00	2.00	3.00
	Step 3	602	1.00	2.00	3.00
	Step 4	1204	1.00	2.00	3.00
	Step 5	2408	1.00	2.00	3.00
	Step 6	4817	1.00	2.00	3.00
Large Raceway	Step 1	9635	1.00	2.50	4.00
	Step 2	19271	1.00	3.00	5.00
	Step 3	38542	1.00	3.50	6.00
	Step 4	77084	1.00	4.00	7.00
	Step 5	154168	1.00	4.50	8.00
	Step 6	308336	1.00	5.00	9.00
	Step 7	616672	1.00	5.50	10.0
	Step 8	1233344	1.00	6.00	11.0
	Step 9	2466688	1.00	6.50	12.0
	Step 10	4933376	1.00	7.00	13.0
	Step 11	9866752	1.00	7.50	14.0
Starvation Ponds	Step 1	9866752	1.00	7.50	14.0
	Step2	9866752	1.00	7.50	14.0
	Step 3	9866752	1.00	7.50	14.0

To determine the labor cost, the maintenance process time was quantified. The laboratory scale utilized the lab labor resource at a labor rate of \$15 h^{-1} while the medium raceway, large raceway and starvation pond scales utilized the manual labor resource at a rate of \$10 h^{-1}. Since the maintenance process time is determined by the number of days, a conversion factor of 24 h d^{-1} and the appropriate labor rate were multiplied together. The resulting maintenance cost formula is outlined in equation 4.

$$L_{MC} = (\sum PT_M \ (T_{CF} \ L_R)) \quad (4)$$

where:

L_{MC} = maintenance labor cost ($)

PT_M = maintenance process time of each stage (d)

T_{CF} = time conversion factor (hr d^{-1})

L_R = labor rate ($ hr^{-1})

The starvation pond level contained the same array of blocks as the final scaling step in the large raceway level. The only difference was that the growing activity was replaced with a starvation activity. The starvation activity was assumed to have a constant starvation period of 21 d. A data source table was employed, which contained a starvation period of 21 d for each month for the duration of 20 yr. Three sets of starvation ponds were assumed to maximize the number of items progressing through the models. The starvation ponds were constructed as three different series of similar processes. The composition of these blocks included *attribute set* blocks as well as *activity* blocks. The *attribute set* blocks utilized included seasonal yield, evaporation and CO_2 consumption. The *activity* blocks employed included: starvation period, culture transfer, raceway cleaning from contamination and maintenance blocks. Likewise, the maximum number of items allowed between the starvation, transfer and raceway cleaning activities was one. Items were conveyed back into a single process series to calculate operational costs associated with each item.

The harvesting time requirement was based on item volume, culture growth rates and centrifuge processing rates. Harvesting was assumed to be accomplished by employing a total of three centrifuges, each with a processing rate of 90,000 L hr^{-1}. The harvesting scale contained a centrifuge activity, which simulated the centrifugation of microalgae culture received from a single set of starvation ponds. The resulting centrifuge process time calculation is presented in equation 5.

$$H_T = \frac{V_B}{C_N \, PR_C} \qquad (5)$$

where:

H_T = harvesting time (d)

V_B = batch volume (L)

C_N = number of centrifuges

PR_C = centrifuge process rate (L hr^{-1})

It was also assumed that each centrifuge had an operating efficiency of 85.0%. Three total centrifuges in the harvesting stage, would result in an overall process efficiency of 99.6%. The high process efficiency suggests that minimal breakdowns would occur for this process. Therefore, there was no time delay consideration for centrifuge breakdowns in the harvesting process. It was assumed that if time was required for centrifuge maintenance or repair, it would occur between harvesting cycles.

3.4.4 Other Operating Costs

Operational costs play a pivotal role in the economics of microalgae cultivation. Given the nature of the models described thus far, the models quantify process durations for culturing, mixing, culture transfer, raceway/mixer maintenance and raceway cleaning. Identifying costs associated with the previously mentioned time delays would allow for quantification of operational costs. Therefore, the models developed were structured to allow precise determination of various operating costs. These operational costs included electricity for mixing, harvesting, water, media, CO_2 and labor costs.

Mixing costs were recorded by a mixing cost attribute which accrued the total mixing costs associated with each item. To determine the culture mixing costs, the culturing duration attribute was utilized to quantify the mixing time required for each item. The culturing duration is multiplied by the power requirement of the mixing devices at each scaling step and a conversion factor of 24 hr d^{-1}. This resulted in the number of kilo-watt hr which was multiplied by the 2009 Texas average electrical rate for an industrial entity. This electrical cost calculation for mixing is displayed in equation 6.

$$C_M = \left(\sum PT_M \, PC_M \, (T_{CF} \, C_E)\right) \tag{6}$$

where:

C_M = mixing cost ($)

PT_M = mixing process time (d)

PC_M = mixer power consumption (hr d^{-1})

T_{CF} = time conversion factor (hr d^{-1})

C_E = electrical rate ($ kWh^{-1})

Water costs were determined from media composition and evaporation rates. As items advance to new scaling steps, the inoculating culture was half of the raceway volume. Raceway filling was accomplished by adding water and media to the inoculating culture to achieve full raceway capacity at a culture concentration of 0.5 g L^{-1}. Therefore, the volume of water added in each scaling step was equal to the inoculating volume of microalgae culture received from the previous scaling step. The volume of water required for each scaling step is divided by a conversion factor of 3.785. This value was then divided by a factor of 1,000 as water costs were based on 3,785 L increments. The resulting value was then multiplied by a water well cost of $0.37. Equation 7 illustrates the calculation to determine water costs.

$$C_W = \frac{\sum W_B}{V_{CF}\, W_R} \tag{7}$$

where:

C_W = water costs (d)

W_B = water volume of each step (L)

V_{CF} = volume conversion factor (gal L^{-1})

W_R = water rate (\$ 3,785 L^{-1})

Water costs associated with seasonal evaporation rates were also tabulated. Seasonal evaporation rates were determined from yearly data located in the western part of Texas. Evaporation rates were duplicated for a 20 yr period and entered into a data source table. Evaporation costs were calculated by first determining the raceway surface area. Raceway surface area was determined by multiplying the raceway volume by a conversion factor of 0.001. This value was then divided by the assumed raceway depth of 0.1524 m which yielded the raceway surface area in m^2. The daily evaporation volume was then multiplied by a conversion factor of 0.001. The evaporation duration for each item would be equal to the culturing duration in each scaling step. Therefore, the culturing duration value from the seasonal yield attribute was multiplied by the daily evaporation rates pertaining to the time of year items are processed. To actuate the evaporation cost, the total volume of evaporation for each item is divided by a conversion factor of 3.785. This value was then divided by a conversion factor of 1,000 and multiplied again by a water usage cost of $0.37. Evaporation rates were not considered for the laboratory scale as these evaporation quantities would be minute compared to the overall process. The resulting calculation is represented in equation 8.

$$C_{WE} = \frac{(\Sigma V_B(V_{CF}\, E_R\, CD_S\ \ W_R))}{D_R\, V_{CF}\, V_{CF}} \tag{8}$$

where:

C_{WE} = water evaporation cost ($)

V_B = batch volume (L)

V_{CF} = volume conversion factor (m^{-3} L)

E_R = evaporation rate (d)

CD_S = seasonal culturing duration (d)

W_R = water rate ($ 3,785 L^{-1})

D_R = raceway depth (m)

V_{CF} = volume conversion factor (L m^{-3})

V_{CF} = volume conversion factor (gal L^{-1})

As items progressed through each model, media costs were calculated for each scaling step. Media costs were based on proprietary media recipes and bulk quantity costs. The laboratory media recipe and costs were different from both the medium and large raceway levels. A cost of \$0.07 L^{-1} was determined for the laboratory level while the medium and large raceway level media recipe yielded a cost of \$0.00484 L^{-1}. The starvation pond level media costs were calculated to be \$0.00410 L^{-1}. The media recipe and costs for the laboratory, medium raceways, large raceways and starvation ponds were recorded in an Excel spreadsheet. Since the inoculating culture volume was diluted from 1 g L^{-1} to 0.5 g L^{-1}, the media cost value is multiplied by the inoculating volume of the culture. The media cost formula is depicted in equation 9.

$$C_{MD} = (\sum V_B \ (M_{RC})) \tag{9}$$

where:

C_{MD} = Media cost ($)

V_B = batch volume (L)

M_{RC} = media requirement cost (L)

CO_2 was not included in the media recipes mentioned in the previous paragraph. Therefore, carbon dioxide costs are tabulated separately from the media costs. CO_2 costs were calculated by first determining the raceway surface area. The raceway volume was multiplied by a conversion factor of 0.001. This value was then divided by an assumed pond depth of 0.1524 m which yields the raceway surface area in m^2. The raceway surface area was then multiplied by seasonal CO_2 consumption rates, and the assumed CO_2 cost of $0.066/kg. The resulting CO_2 cost calculation is portrayed in equation 10.

$$C_O = \frac{(\Sigma\, V_B(\, V_{CF} C_C\, CD_S\ \ C_{R}))}{D_R} \tag{10}$$

where:

C_O = CO_2 cost (\$)

V_B = batch volume (L)

V_{CF} = volume conversion factor (m^{-3} L)

C_C = CO_2 consumption rate (d)

CD_S = seasonal culturing duration (d)

$C_{R =}$ CO_2 (\$ 1,000 gal^{-1})

D_R = raceway depth (m)

Daily monitoring of all outdoor microalgae cultures was assumed to be necessary in order to evaluate culture quality. This would be accomplished through measurement of pH, optical density of the culture, electrical conductivity, ash free dry weights, nitrate concentration, and dissolved oxygen concentration. These tests would be executed for each scaling step and would be conducted by laboratory personnel. Therefore, laboratory labor costs are calculated for daily culture testing and were implemented into the models. The time required to collect, prepare and evaluate culture samples was determined by utilizing a triangular distribution. The required time was assumed to be consistent for all scaling steps in each model. The triangular distribution time increments consisted of a minimum time of 15 min, an average time of 30 min and a maximum time of 45min. Samples would be collected on a daily basis therefore; the number of samples collected for each item was determined by culture duration through the seasonal yield *attribute get* block. This value was multiplied by the labor rate of \$15 hr^{-1} and the average collection time determined from the triangular distribution. The culture monitoring labor cost is represented in equation 11.

$$L_{CM} = (\sum PT_{CM} \ (CD_S \, L_R \, L_N)) \qquad (11)$$

where:

L_{CM} = maintenance labor cost (\$)

PT_{CM} = maintenance process time of each stage (d)

CD_S = seasonal culturing duration (d)

L_R = labor rate (\$ hr^{-1})

L_N = number of laborers

The harvesting labor cost was calculated by multiplying the processing time from the centrifuge *activity* block by the labor rate of \$12.50 hr^{-1} and a conversion factor of 24 hr d^{-1}. The resulting value was then added to the value from the H.S. labor attribute. The labor cost for centrifugation is illustrated in equation 12.

$$L_H = (\sum PT_H \ (TC_F \ L_R)) \quad (12)$$

where:

L_H = maintenance labor cost ($)

PT_H = maintenance process time of each stage (d)

T_{CF} = time conversion factor (hr d^{-1})

L_R = labor rate ($ hr^{-1})

As each item exits the model, the accumulated costs associated with that item pass through a series of *attribute get* blocks. The values derived from the cost *attribute get* blocks are conveyed to a value holding tank in which the cost specific to that *attribute* block are summed together for all the items. The resulting value was then transferred to a *throw value* block which conveys the value to a catch value block.

3.5 Conclusion

Three scaling scenarios were identified and included a stepwise scaling, volume batching and intense culturing process. Identification of process time delays and quantification of resource requirements were fundamental for model development. Process time delays included: culturing duration, culture/media transfer, contamination events and liner/mixer maintenance. The culture duration was based on assumed average monthly growth rates resulting in an average annual culturing duration of 8.43 d. The culture/media transfer time delays were implemented as triangular distributions which were based on raceway transfer volumes and an assumed facility transfer time constraint of 16 h. Contamination events were assumed to have a probability of 0.001 for each outdoor scaling step. The time to clean each raceway after a contamination event was based on current cleaning practices as well as raceway volume. Raceway cleaning time delays were employed as triangular distributions for each scaling step. Raceway/mixer maintenance was based on the time required for liner inspection and repair as well as mixer inspection and maintenance. A triangular distribution for raceway/mixer maintenance was incorporated into the models and was based on raceway volume.

Determining these process time delays was pivotal for quantifying resource demands for electricity, water, media, CO_2 and labor requirements specific to each scaling scenario. Also, implementation of process time delays allows for productivity comparisons between the scenarios. Model throughput will be determined by the attributes and time delays outlined in this article. Identification of bottlenecks will be accomplished by analyzing the TBI and ACT between different scaling steps.

Simulation of different management scenarios for large-scale microalgae facilities is imperative as this technology progresses to large-scale production. The models developed for the different management scenarios will be utilized for investigating the production potential and costs of microalgae as well as other aquatic plants. The structure of the models presented in this analysis yields a basis for initial evaluation of the process scenarios considered.

CHAPTER IV

RACEWAY MANAGEMENT AND SCALING PROCESSES FOR SMALL SCALE MICROALGAE FACILITIES

4.1 Introduction

Microalgae are aquatic, photosynthetic, microscopic plants that utilize sunlight and can be cultured for the production of biomass for bio-fuel. Microalgae biomass production offers many advantages over conventional biomass production technologies including higher yields, use of otherwise nonproductive land, reuse and recovery of waste nutrients, use of saline or brackish waters, and reuse of CO_2 from power-plant flue-gas or similar sources Brune et al. (2009). Even though there continues to be a considerable amount of interest in utilizing microalgae as a feedstock for bio-fuel production, this technology is still predominately in the research and development (R&D) phase. Currently, the literature is filled with numerous projections of the production potential of microalgae as a source of biomass. However, many of these production projections fail to consider an initialization period before a facility is fully operational, the effects of a contamination event as well as a variable growth rates. Also, as this technology begins to move from the laboratory scale to the pilot plant scale, overall raceway management becomes a concern in an effort to maximize production and minimize costs.

4.2 Objectives

The main goal of this analysis is to analyze three different scaling techniques pertaining to base case assumptions and potential best case assumptions to identify the most productive process as well as obtain a more accurate estimation of productivity. Objectives to accomplish this goal include:

1) Determine the total average process time for each scaling step to identify process bottlenecks.

2) Calculate raceway utilization to determine the percentage of time the culturing activity is engaged in relation to model duration.

3) Evaluate the effects of contamination events on the overall culturing process.

4) Determine the initialization period for each scaling technique.

5) Tabulate the mean time between items (TBI) and average cycle time (ACT) for each model level.

4.3 Materials and Methods

Scaling processes considered for this analysis were derived from culturing practices utilized at the laboratory and pilot scale within Texas AgriLIFE Research algae facilities. Three simulation models were developed which equivocated different scaling levels encompassing multiple scaling steps for large scale culturing of microalgae. The three culture management scenarios considered for this analysis included: stepwise scaling, volume batching and intense culturing processes. Models were constructed using Extend-Sim 7.0, which utilizes a Discrete Event Simulation (DES) modeling methodology and models the movement and routing of items. Pertaining to the culturing of microalgae, this software was considered suitable for model development as different batches of microalgae culture flow to and from different raceways. The total volume of microalgae cultured at a particular scaling step was utilized to inoculate the next appropriately larger scaling step. Therefore, each scaling step in the culturing process was considered as a discrete event.

A base case and potential best case were conducted to evaluate model productivity subject to variable or constant culturing durations. The culturing duration was expected to be pivotal in determining the productivity of each model. According to Goldman, (1978), the upper limit in light conversion efficiency of large-scale culture translated to a maximum yield of 30-40 g m^{-2} d^{-1}. The base case employed variable monthly growth rates which resulted in an average growth rate of 8.43 g m^{-2} d^{-1} and an average culturing duration of 9 d. The specific growth rate utilized for the potential best case was 37 g m^{-2} d^{-1} which resulted in a culturing duration of 2.1 d. Model duration for both analyses encompassed a 20 yr period 360 d yr^{-1}. The starvation period was constant with a delay of 21 d for the base case and 5 d for the potential best case. The harvesting rate was based on disc-bowl centrifuges with a process capacity of 90,000 L h^{-1}. The TBA of the stepwise, volume batching and intense culturing models was reduced to 3, 2 and 3 d for the potential best case compared to 8, 4 and 8 d for the base case.

Process bottlenecks were identified by analyzing the total average process time for each scaling step. A bottleneck occurred if a particular scaling step total average process time was twice the total average process time of the previous scaling step.

Raceway utilization was calculated by the growing *activity* block in each scaling step. Total process raceway utilization was tabulated by surmising the raceway utilization of each scaling step and then dividing by the total number of scaling steps.

4.4 Simulation Results and Discussion

4.4.1 Base Case Results

Culturing duration was defined as the amount of time required for a microalgae culture to double from a concentration of 0.5 g L^{-1} to 1 g L^{-1}. The time delay for the culturing duration was determined from assumed constant and variable growth rates. The average time delay for culturing duration activity was tabulated by the growing *activity* block for each scaling step. This average was based on a 20 yr model duration as well as predetermined growth rates for each scaling step. Raceway utilization was calculated by the growing *activity* block and was defined as the percentage of time that culturing activity was employed during the modeling period. It was useful to compare the utilization of each raceway in relation to the overall culturing process to identify trends characteristic of each scenario. The average culturing process time and raceway utilization percentage is reported in Table 11.

Table 11. Base case culturing duration and raceway utilization.

		Stepwise Model		Volume Batching Model		Intense Culturing Model	
Level	Scaling Step	Average Process Time (d)	Raceway Utilization (%)	Average Process Time (d)	Raceway Utilization (%)	Average Process Time (d)	Raceway Utilization (%)
Laboratory	Step 1	4.00	50.0	4.00	99.9	4.00	50.0
	Step 2	4.00	50.0	4.00	50.0	4.00	50.0
	Step 3	4.00	50.0	*4.00*	50.0	4.00	50.0
	Step 4	4.00	50.0	4.00	50.0	4.00	50.0
	Step 5	4.00	50.0	4.00	49.8	4.00	50.0
	Step 6	4.00	50.0	4.00	49.8	4.00	50.0
Medium raceway	Step 1	6.68	83.0	6.48	80.3	*4.00*	*49.8*
	Step 2	6.60	81.5	6.52	40.3	*4.00*	*49.8*
	Step 3	6.59	81.3	*6.44*	*39.8*	*4.00*	*49.7*
	Step 4	6.55	80.7	6.54	40.3	•	•
	Step 5	6.49	79.6	*	*	•	•
	Step 6	6.29	76.9	*	*	•	•
Large Raceway	Step 1	6.29	76.8	6.45	39.7	•	•
	Step 2	6.20	75.6	6.69	20.5	•	•
	Step 3	6.04	73.5	*6.50*	*19.9*	•	•
	Step 4	5.94	72.3	6.46	19.9	•	•
	Step 5	5.94	72.3	6.68	20.4	6.65	82.4
	Step 6	5.70	69.2	6.59	20.1	6.63	81.9
	Step 7	5.70	69.2	6.64	20.3	6.60	81.2
	Step 8	5.61	68.0	6.69	20.4	6.55	80.4
	Step 9	5.61	67.8	6.67	20.3	6.32	77.5
	Step10	5.34	64.5	6.68	20.3	6.30	77.0
	Step11	5.57	67.0	6.62	20.2	6.21	75.8
Starvation Ponds	Pond 1	21.0	83.9	21.0	64.0	21.0	85.2
	Pond 2	21.0	83.5	▪	▪	21.0	85.2
	Pond 3	21.0	83.7	▪	▪	21.0	85.0

*** denotes scaling steps that were eliminated through volume batching.**
• denotes scaling steps omitted from the implementation of FPRs.
▪ denotes pond discarded from the starvation pond level.

4.4.1.1 Stepwise Model

The average culturing process time for the laboratory level of the stepwise model was 4 d for each scaling step. This was indicative of a constant 4 d culturing duration implemented for the laboratory level. The laboratory level raceway utilization was 50% for each scaling step. Beginning in step 1 of the medium raceway level, the average culturing duration increased to 6.68 d. The increased average culturing duration was characteristic of the seasonal culturing duration incorporated in the medium and large raceway levels. However, with each subsequent scaling step beginning in step 1 of the medium raceway level, the average culturing process time decreased. This general decreasing average culturing duration can be attributed to two factors. These factors include: model initialization period and the number of items processed by each scaling step.

The model initialization period is the amount of time between the creation of the first item and the time that first item arrives at a particular scaling step. For example the model initialization period for step 1 of the medium raceway level would be approximately 20 d as an item must first progress through the laboratory level. The number of items processed by each subsequent scaling stage is reduced compared to the previous stage. This is characteristic of the scaling up process and causes a fractional reduction in the overall average culturing duration.

The raceway utilization also has an overall decreasing trend with each successive scaling step. The raceway utilization is derived from the average culturing duration activity therefore; the trends exhibited by both of these factors should be similar.

The lipid starvation duration was determined to be 21 d which is indicative of the assumed constant starvation duration. The starvation duration was significantly higher compared to the other levels which increased the starvation pond utilization.

4.4.1.2 Volume Batching Model

The average culturing process time for the laboratory level of the volume batching model was also 4 d for each scaling step. The average culturing process time for the medium and large raceway levels were increased through the incorporation of seasonal growth rates. However, the average culturing process time was variable with each scaling step resulting in no general trend. This was due to the nature of the volume batching process. After an item batching event, the first item batching scaling step receives an item while the second item batching scaling step remains inactive. Therefore, the seasonal culturing duration for the second item batching scaling step is inconsistent compared to the first item batching scaling step. This inconsistency results in a variable average culturing process time.

Raceway utilization decreased significantly between scaling steps 1 and 2 of the laboratory, medium and large raceway levels. This was attributed to the simultaneous batching of items. Starting in the laboratory level of the volume batching model, step 1 yielded a raceway utilization of 99%. However, step 1 and 2 were batched together, which decreased raceway utilization to 50% for scaling step 2 in the laboratory level. Scaling step 1 of the medium raceway level increased to 80.3% which was characteristic of a greater average culturing process time compared to the laboratory level. However, scaling steps 1 and 2 of the medium raceway level were batched together which decreased raceway utilization to 40.3%. The large raceway level displayed the same trend as scaling steps 1 and 2 were batched together. The raceway utilization for scaling step 1 of the large raceway level was 39.7% which was reduced, through volume batching, to 20.5% in scaling step 2.

Due to the nature of the volume batching model, only one starvation pond was utilized which resulted in an average culturing process time of 21 d. The starvation pond utilization was determined to be 64%.

4.4.1.3 Intense Culturing Model

The intense culturing model had an average culturing duration of 4 d at the laboratory level which was indicative of the assumed constant laboratory culturing duration. The medium raceway level implemented three scaling steps of FPRs. The culturing duration of these FPRs utilized the same 4 d constant culturing duration as the laboratory level. Therefore, the average culturing process time delay in the medium raceway level was 4 d for scaling steps 1 through 3. The implementation of FPRs resulted in the elimination of steps 4 through 6 of the medium raceway level and steps 1 through 4 of the large raceway scale.

Beginning in step 5 of the large raceway scale, the average culturing process time increased to 6.65 d. This increase was due to the implementation of a seasonal growth rate. Beginning in step 5 of the large raceway level, the average culturing process time decreased with each successive scaling stage. Therefore, a decreasing average culturing process time was also exhibited in the intense culturing model. This was attributed to the model initialization period and the number of items processed by each scaling stage.

The raceway utilization for the laboratory and medium raceway levels was 50% and was characteristic of the assumed constant culturing duration of 4 d. Scaling step 5 of the large raceway scale exhibited a greater raceway utilization of 82.4% which was reduced with each subsequent scaling stage.

The starvation pond level average culturing process time was 21 d which was the product of the assumed starvation period of 21 d. The raceway utilization of the starvation ponds was 85% respectively.

4.4.1.4 Comparison of the Three Scenarios

The laboratory level culturing duration for each model resulted in a constant average process time of 4 d, which was indicative of the assumed constant culturing duration in a controlled laboratory setting. At the laboratory level, raceway utilization in each model was 50%. The medium raceway level for both the stepwise and volume batching model raceway utilization was initially 83% then decreased through each successive scaling step. This initial increase in raceway utilization was characteristic of a greater average culturing process time compared to the laboratory scale.

Starvation pond utilization for both the stepwise and intense culturing models was greater than 80% but the volume batching model employed only one starvation pond with a utilization of 64%. The starvation pond level of each model implemented a culturing duration of 21 days which was derived from the assumed lipid formation period. Likewise, each model yielded an average starvation period of 21d.

The total average raceway utilization for the entire processes modeled by the stepwise, volume batching and intense culturing models was 69.6, 37.2 and 66.4%. Because of the constant culturing duration of 4 d as implemented by the laboratory level and FPRs in the medium raceway level, the intense culturing model overall raceway utilization was reduced compared to the stepwise model. The volume batching model produced the lowest total average raceway utilization of 37.2% which was a result of the item batching process. The general trend shown in Table 11 is a decreasing raceway utilization percentage for both the stepwise and intense culturing models. Considering the average culturing process time yielded a decreasing trend, the raceway utilization should follow a similar trend. The volume batching model did not seem to be affected by the model initialization as the average culturing process time between each scaling step was variable.

4.4.1.5 Contamination

Microalgae culturing in open outdoor raceways will have a risk of culture contamination. This can be mitigated by culture conditions and good management practices but contaminants can affect microalgae growth and are inevitable in open bioreactors. Therefore, culture disposal at each scaling step and subsequent raceway cleaning was included in each model in the event of a contamination epidemic. The time delay for a contamination event included the amount of time required to dispose of the contaminated culture as well as the time required for raceway disinfecting through cleaning. The subsequent raceway downtime was based on raceway volume and current cleaning practices. Therefore, downtime increased as raceway size increased. The probability of a contamination event was assumed to be 0.001 with the average downtime derived from a predetermined triangular distribution. The resulting contamination events and time delays are reported in Table 12.

Table 12. Base case contamination events.

			Stepwise		Volume Batching		Intense Culturing	
Level	Scaling Step	Raceway Volume (L)	# items	Time Delay (d)	# items	Time Delay (d)	# items	Time Delay (d)
Medium Raceway	Step 1	150	4.00	0.02	1.00	0.02	0.00	0.00
	Step 4	1204	3.00	0.02	1.00	0.03	0.00	0.00
	Step 5	2408	2.00	0.02	0.00	0.00	0.00	0.00
Large Raceway	Step 1	9635	1.00	0.05	0.00	0.00	0.00	0.00
	Step 6	308336	0.00	0.00	0.00	0.00	1.00	0.50
	Step 7	616672	2.00	1.11	0.00	0.00	1.00	1.14
	Step 9	2466688	2.00	3.98	0.00	0.00	2.00	4.36
	Step 10	4933376	1.00	8.48	0.00	0.00	1.00	7.41
	Step 11	9866752	2.00	14.4	0.00	0.00	2.00	17.3
Starvation Ponds	Step 2	9866752	1.00	15.5	0.00	0.00	0.00	0.00

The average growing activity process times were affected by those scaling steps that experienced a contamination event. A contamination event was structured to shutdown the growing *activity* block for raceway cleaning. This would reduce raceway operating time which would result in lower raceway utilization. However, the number of contamination events at any one scaling step was minimal compared to the total number of items processed by the culturing activity. Therefore, the raceway cleaning activity did not cause a significant reduction in the process time delay for the culturing activity. The stepwise model yielded 18 contamination events while the volume batching and intense culturing models had fewer contamination events. Contamination events occurring in larger raceways resulted in a greater time delay.

4.4.1.6 Culture Transfer and Raceway/Mixer Maintenance

Culture transfer was defined as the transfer time required for microalgae culture conveyance from one raceway to an appropriately larger raceway. Culture transfer time also included the time required for media transfer from facility storage to the raceways. The culture transfer time for the medium raceway, large raceway, starvation and harvesting levels was based on an accumulated transfer volume of 24,528,708 L. A triangular distribution was determined and implemented into each scaling step to account for culture transfer time delays. Activity utilization was also determined but was minimal since culture transfer was a minute time delay consideration compared to the overall culturing process.

Time delays were also implemented for raceway maintenance as well as mixer maintenance. It was assumed that all raceway liners would need to be inspected between culture transfers. Mixing pumps would need to be maintained and were assumed to be positioned in sumps which would also need to be cleaned of debris. Raceway/mixer maintenance average time delay was determined by a triangular distribution implemented in the maintenance *activity* block. Since raceway maintenance was based on raceway size, the time consideration for the raceway/mixer maintenance activity increased as raceway size increased. The accumulated time delays for culturing duration, contamination, culture transfer, and raceway/mixer maintenance of each scaling step are outlined in Table 13. Process bottlenecks were identified by comparing the total process time delays between the different scaling steps within each model.

Table 13. Base case total process time delays.

		Stepwise	Volume Batching	Intense Culturing
Level	Scaling Step	Total Average Process Time (d)	Total Average Process Time (d)	Total Average Process Time (d)
Laboratory	Step 1	4.03	*4.03*	4.03
	Step 2	4.01	*4.01*	4.01
	Step 3	4.01	4.01	4.01
	Step 4	4.01	4.01	4.01
	Step 5	4.01	4.01	4.01
	Step 6	23.4	47.5	4.01
Medium raceway	Step 1	7.33	*8.48*	4.10
	Step 2	6.87	*8.14*	4.12
	Step 3	6.82	8.53	24.8
	Step 4	7.05	8.70	•
	Step 5	6.84	*	•
	Step 6	6.54	*	•
Large Raceway	Step 1	6.55	8.54	•
	Step 2	6.59	9.04	•
	Step 3	6.55	8.60	•
	Step 4	6.30	8.89	•
	Step 5	6.42	9.21	8.02
	Step 6	6.28	8.67	7.32
	Step 7	6.21	8.49	7.38
	Step 8	6.42	9.57	7.39
	Step 9	6.33	8.90	7.16
	Step10	7.11	8.76	7.80
	Step11	40.2	9.35	30.6
Starvation Ponds	Pond 1	27.6	24.2	27.4
	Pond 2	27.7	▪	27.8
	Pond 3	27.9	▪	26.9

4.4.1.6.1 Stepwise Model

The total average process time for scaling step 1 of the laboratory level was 4.03 d. Scaling steps 2 through 5 yielded a total average process time of 4.01 d. However, scaling step 6 yielded a total average process time of 23.4 d which was considerably higher compared to the previous scaling steps in the laboratory scale. Scaling step 1 of the medium raceway level yielded a total average process time of 7.33 d. The perturbation between scaling stage 6 of the laboratory level and scaling step 1 of the medium raceway level signifies a bottleneck between the two levels. Other than step 6 of the laboratory level, the medium raceway level scaling steps yielded greater total average process time delays. However; the total average process time delays for both the medium and large raceway level did not exhibit a decreasing trend as portrayed by the average culturing process times in Table 12. This was due to the implementation of triangular distributions to determine time delays for contamination, culture transfer and raceway/mixer maintenance. Scaling step 11 of the large raceway level yielded a total average process time of 40.2 d while pond 1 of the starvation pond level produced a time of 27.6 d. Therefore, a bottleneck occurred between the large raceway level and the starvation pond level.

4.4.1.6.2 Volume Batching Model

The total average process time of each scaling step in the laboratory level yielded a time delay of 4.03 d for scaling step 1 and 4.01 d for scaling steps 2 through 5. Scaling step 6 of the laboratory level produced a time of 47.5 d which was significantly higher compared to the other laboratory scaling steps. In scaling step 1 of the medium raceway level, the total average process time was 7.32 d. Accordingly, a bottleneck was identified between scaling step 6 of the laboratory level and scaling step 1 of the medium raceway level in the volume batching model. The total average process time for starvation pond 1 was 24.2 d.

4.4.1.6.3 Intense Culturing Model

The total average process time delay in scaling step 1 of the laboratory scale of the intense culturing model was 4.03 d. Scaling steps 2 through 6 yielded a total average process time of 4.01 d. Scaling steps 1 and 2 in the medium raceway level produced a total average process time of 4.10 and 4.12 d. However, scaling step 3 of the medium raceway scale yielded a total average process time of 24.8 d. The implementation of FPRs in the culturing process eliminated 7 scaling steps advancing items to scaling step 5 of the large raceway level. The total average process time yielded by scaling step 5 of the large raceway scale was 8.02 d. Therefore, a bottleneck occurred between scaling step 3 of the medium raceway level and scaling step 5 of the large raceway level. Another bottleneck was identified between scaling step 11 of the large raceway level and pond 1 of the starvation pond scale. The total average process time delay for scaling step 11 of the large raceway level was 30.6 d while pond 1 of the starvation pond scale yielded a time delay of 27.4 d.

4.4.1.6.4 Comparison of the Three Scenarios

The laboratory total average process time yielded the same time delays for each scaling step between the three scenarios. Bottlenecks occurred between scaling step 6 of the laboratory level and step one of the medium raceway level for both the stepwise and volume batching models. Likewise, a bottleneck occurred between scaling step 6 of the laboratory scale and scaling step 5 of the large raceway level in the intense culturing model. Bottlenecks were also identified between scaling step 11 of the large raceway level and pond 1 of the starvation pond level for both the stepwise and intense culturing models. The volume batching model did not yield any bottlenecks between the large raceway level and pond 1 of the starvation pond level. The total time delay for the starvation pond utilized in the volume batching model was reduced compared to the other two models. Bottlenecks that were identified within the models occurred as items progressed between constant and variable culturing durations.

4.4.1.7 Base Case Model Initialization, TBI and ACT

All of the models quantified the mean time between items (TBI) average cycle time (ACT) for each level. Determining the TBI, ACT and number of items processed was advantageous in comparing the different scenarios. It was assumed that a microalgae facility would receive 1 L of microalgae seed stock which would be utilized to begin the culturing process. Through trial and error, the TBA resulted in 8, 4 and 8 d for the stepwise, volume batching and intense culturing models. Because of the nature of the volume batching model, the TBA was more frequent compared to the other two models.

Considering the implementation of three volume batching steps, the number of items created by the *start* block in the volume batching model was reduced by roughly 50% with each batching process. Thus, the volume batching scaling steps reduced the number of items generated by the *start* block by a factor of approximately 0.125. The total average TBI was the rate between items arriving at each level. The ACT for each level was an accumulation of the total average process time delay for all scaling steps within that level. The mean TBI, average ACT and total number of items processed by each level are depicted in Table 14.

Table 14. Base case process statistics.

	Stepwise Model			Volume Batching Model			Intense Culturing Moc		
Level	# items	Mean TBI	Mean ACT	# items	Mean TBI	Mean ACT	# items	Mean TBI	Mean ACT
Laboratory	894	8.02	43.5	892	8.04	67.6	897	8.00	24.1
Medium Raceway	879	8.08	41.4	443	16.1	33.9	891	8.03	33.0
Large Raceway	863	8.17	105	218	32.3	105	876	8.09	74.4
Starvation Ponds	858	8.20	27.7	218	32.3	24.2	874	8.10	27.4
Harvesting	858	8.20	3.07	218	32.3	9.15	874	8.10	3.04
Total	858	8.20	221	218	32.3	240	874	8.10	162

4.4.1.7.1 Stepwise Model

The total number of items processed from start to finish in the stepwise model was 858 items. The mean TBI increased with each level with the greatest value of 8.20 d beginning in the starvation pond level. Within the stepwise model, the greatest ACT was 105 d at the large raceway level. The large raceway level was expected to have the greatest ACT as it contained the most scaling steps. The stepwise model yielded a total ACT of 221 d.

4.4.1.7.2 Volume Batching Model

The total throughput in the volume batching model was 218 items. The implementation of a volume batching process in the laboratory, medium and large raceway levels caused the mean TBI to double between each level. For example, the mean TBI for the laboratory level was 8.03 d while the mean TBI for the medium raceway level was 16.1 d. The greatest ACT of 105 d occurred in the large raceway level. The volume batching model yielded the greatest overall ACT of 240 d.

4.4.1.7.3 Intense Culturing Model

The intense culturing model yielded a total of 874 items. The greatest mean TBI of 8.10 occurred beginning in the starvation pond level. The large raceway level incurred the greatest ACT of 74.4 compared to the other levels. The intense culturing model had a total ACT of 162 d, which was attributed to the elimination of 7 scaling steps through the implementation of FPRs.

4.4.1.7.4 Comparison of the Three Scenarios

The model initialization period, which was the amount of time required for the first item to exit each model, was 171, 169, and 129 d for the stepwise, volume batching and intense culturing models. The total number of items processed by the volume batching model was significantly less than the other models. Only 218 items were processed by the volume batching model with a total ACT of 240 d. The mean TBI of 32.2 d in the large raceway level of the volume batching model was significantly greater compared to appropriate levels within the other models. This suggests that the volume batching method is inefficient compared to the other scenarios analyzed. The stepwise and intense culturing models yielded similar productivities of 858 items and 874 items. The mean TBI for both the stepwise and intense culturing models were similar with duration of approximately 8 d.

4.4.1.8 Harvesting

Harvesting was another consideration for process time delay. This time delay was based on the utilization of disc-bowl centrifuges with a harvesting rate of 90,000 L hr^{-1}. The delay for harvesting was structured to not incur any bottlenecks in the overall process.

As depicted in Table 14, the mean TBI of the starvation pond level was 8.20, 32.2 and 8.10 d for the stepwise, volume batching and intense culturing models. Likewise, the ACT of the harvesting level would parallel the TBI of the starvation level for each model. The stepwise and intense culturing models utilized three centrifuges resulting in a total harvesting rate of 270,000 L hr^{-1}. This resulted in an ACT of 3 d in the harvesting level of both the stepwise and intense culturing models. The volume batching model utilized one centrifuge resulting in an ACT of 9 d. A harvesting ACT greater than the starvation pond level TBI would hinder the flow of items resulting in a process bottleneck. In comparing the TBI in Table 14 to the ACT in Table 15, the harvesting process did not hinder the flow of items. Therefore, there were no bottlenecks associated with the harvesting process.

The stepwise and intense culturing models yielded similar centrifuge utilization rates of 36.3 and 37% respectively. However, the volume batching model yielded fewer items and utilized only one centrifuge, resulting in a centrifuge utilization of 27.6%. The harvesting process time delay and activity utilization are depicted in Table 15.

Table 15. Base case centrifuge utilization.

		Stepwise Model		Volume Batching Model		Intense Culturing Model	
Level	Step	Average Process Time (d)	Utilization (%)	Average Process Time (d)	Utilization (%)	Average Process Time (d)	Utilization (%)
Harvesting	Step 1	3.05	36.3	9.07	27.6	3.04	37.0

4.4.1.9 Labor Requirements

Labor requirements were determined for each model and are reported in Table 16. The reported labor requirements were calculated separately from the resource utilization yielded by the *resource pool* block. The stepwise, volume batching and intense culturing model required 10, 5 and 9 total laborers. The volume batching model resulted in the lowest labor utilization which was characteristic of the batching process. The labor resource utilization for the stepwise model was less than the utilization of the intense culturing model. This was expected as the stepwise model employed 7 more scaling steps compared to the intense culturing model which required one more lab laborer.

Table 16. Base case labor resources.

	Stepwise Model		Volume Batching Model		Intense Culturing Model	
Laborers	# resources	utilization	# resources	utilization	# resources	Utilization
Lab	2	0.37	2	0.18	1	0.54
H.S.	2	0.25	1	0.31	2	0.25
Manual	5	0.15	1	0.20	5	0.11
Contract	1	0.01	1	0.00	1	0.01

4.4.2 Potential Best Case

An analysis of a potential best case was conducted to explore the prospective of utilizing strains of microalgae above current biological characteristics. The biological characteristics considered for this analysis include photosynthetic efficiencies, lipid content and lipid induction periods. A constant growth rate of 37 g m^{-2} d^{-1} was considered which resulted in a 2.1 d constant culturing duration. While a growth rate of 37 g m^{-2} d^{-1} is possible, employing a constant growth rate rather than a seasonal growth rate would require an increase in current microalgae photosynthetic efficiencies. According to Becker (1994), the average lipid content varies between 1 and 40%. This characteristic is assumed to increase above current productive limitations. Therefore a lipid content of 50% was considered for the potential best case. The average process time delay for the lipid induction period was reduced to 5 d for each model. This was assumed as the development of future strains of microalgae would need to utilize a shorter lipid induction period. The resulting average culturing process time is depicted in Table 17.

Table 17. Best case culturing duration and raceway utilization.

		Stepwise Model		Volume Batching Model		Intense Culturing Model	
Level	Scaling Step	Average Process Time (d)	Raceway Utilization (%)	Average Process Time (d)	Raceway Utilization (%)	Average Process Time (d)	Raceway Utilization (%)
Laboratory	Step 1	2.10	70.0	2.10	70.0	2.10	70.0
	Step 2	2.10	70.0	2.10	35.0	2.10	70.0
	Step 3	2.10	70.0	*2.10*	35.0	2.10	70.0
	Step 4	2.10	70.0	2.10	35.0	2.10	70.0
	Step 5	2.10	70.0	2.10	35.0	2.10	70.0
	Step 6	2.10	70.0	2.10	35.0	2.10	70.0
Medium Raceway	Step 1	2.10	69.8	2.10	34.9	*2.10*	*69.8*
	Step 2	2.10	69.7	2.10	17.4	*2.10*	*69.8*
	Step 3	2.10	69.6	*2.10*	*17.4*	*2.10*	*69.7*
	Step 4	2.10	69.6	2.10	17.4	•	•
	Step 5	2.10	69.5	*	*	•	•
	Step 6	2.10	69.4	*	*	•	•
Large Raceway	Step 1	2.10	69.3	2.10	17.4	•	•
	Step 2	2.10	69.2	2.10	8.66	•	•
	Step 3	2.10	69.2	*2.10*	*8.63*	•	•
	Step 4	2.10	69.1	2.10	8.63	•	•
	Step 5	2.10	69.0	2.10	8.63	2.10	69.7
	Step 6	2.10	68.8	2.10	8.63	2.10	69.6
	Step 7	2.10	68.7	2.10	8.63	2.10	69.5
	Step 8	2.10	68.6	2.10	8.61	2.10	69.4
	Step 9	2.10	68.5	2.10	8.58	2.10	69.3
	Step10	2.10	68.5	2.10	8.58	2.10	69.2
	Step11	2.10	68.4	2.10	8.58	2.10	69.1
Starvation Ponds	Pond 1	5.00	54.0	5.00	20.4	5.00	55.0
	Pond 2	5.00	54.0	▪	▪	5.00	55.0
	Pond 3	5.00	54.0	▪	▪	5.00	55.0

*** denotes scaling steps that were eliminated through volume batching.**

• denotes scaling steps omitted from the implementation of FPRs.

▪ denotes pond discarded from the starvation pond level.

4.4.2.1 Stepwise Model

The average culturing process time for the laboratory, medium raceway and large raceway levels was 2.10 d. Beginning in scaling step 1 of the laboratory level, the raceway utilization was 70% which started to decrease in scaling step 1 of the medium raceway level. Raceway utilization exhibited a decreasing percentage with each successive scaling step beginning in the medium raceway level. This decreasing trend was attributed to the model initialization period as well as the number of items processed by each scaling step. The average culturing process time for the starvation pond level was 5.00 d with a raceway utilization of 54%.

4.4.2.2 Volume Batching Model

The average culturing process time for the laboratory, medium raceway and large raceway levels was 2.10 d. Raceway utilization was reduced by 50% with each scaling step that implemented the volume batching process. For example, scaling step 1 of the laboratory level yielded a raceway utilization of 70%. As scaling steps 1 and 2 items are batched together, the raceway utilization for scaling step 2 was reduced to 35%. The same trend is characteristic for scaling steps 1 and 2 of both the medium and large raceway levels. The starvation pond level resulted in an average culturing process time of 5 d, while the raceway utilization was 20.4%.

4.4.2.3 Intense Culturing Model

The intense culturing model had an average culturing duration of 2.1 d for the laboratory, medium and large raceway levels. The raceway utilization decreased with each successive scaling step beginning in the medium raceway level. The average culturing duration for the starvation pond level was 5 d for each starvation pond. The raceway utilization for the starvation pond level was determined to be 55%.

4.4.2.4 Comparison of the Three Scenarios

Each scaling scenario yielded an average culturing process time of 2.10 d for the laboratory, medium and large raceway levels. The average culturing process time of 5 d for the starvation pond level was also the same across the models. The decrease in raceway utilization by the volume batching scenario was significantly greater and was attributed to the item batching process.

4.4.2.5 Comparison of the Base Case and Potential Best Case

The base case raceway utilization was higher in the medium raceway level of the stepwise model. However, the raceway utilization in the potential best case was similar to the base case beginning in step 8 of the large raceway level of the stepwise model. Therefore, while the stepwise model raceway utilization was higher in earlier scaling steps of the base case, the raceway utilization was comparable between later scaling steps. The raceway utilization of the potential best case slightly decreased with each process step which is similar to the base case. The raceway utilization of both the laboratory and medium raceway levels of the stepwise and intense culturing models increased from 50% in the base case to 70% for the potential best case.

In comparing the base case and potential best case, the stepwise and volume batching model total average raceway utilization decreased from 69.6 to 67.6% and from 37.2 to 19.9%. The intense culturing model raceway utilization increased from 66.4 to 67.4%. The minute decrease in total raceway utilization of the stepwise model is a consequence of the increase in contamination events.

In the volume batching model, the mean TBA was reduced which increased the number of items. The time delay attributed to item batching resulted in a greater frequency as more items were processed. This greater frequency coupled with a shorter culturing duration increased the growing activity downtime. Therefore, the overall raceway utilization of the volume batching model was decreased compared to the base case. Also, the reduced starvation pond utilization of the potential best case was the product of a truncated starvation period of 5 d compared to a duration of 21 d for the base case scenario.

4.4.2.6 Contamination

The probability of a contamination event remained at 0.001 for the potential best case. Because of the implementation of a shorter culturing duration, model throughput increased which increased the number of contamination events. The total number of contaminated items for the stepwise, volume batching, and intense culturing models increased to 41, 9, and 21 items, respectively. The intense culturing model produced the greatest increase of contaminated items while the volume batching model yielded the lowest increase.

Raceway utilization for the intense culturing model increased while a decrease was observed in the other models. This demonstrates that the intense culturing model may better buffer contamination events. The number of contaminations and average time delays are reported in Table 18. The greatest time delay for contamination events occurred in step 11 of the large raceway level for both the stepwise and intense culturing models.

Table 18. Best case contamination events.

			Stepwise		Volume Batching		Intense Culturing	
Level	Scaling Step	Raceway Volume (L)	# items	Time Delay (d)	# items	Time Delay (d)	# items	Time Delay (d)
Medium raceway	Step 1	150	3.00	0.03	2.00	0.02	1.00	0.02
	Step 2	301	3.00	0.02	0.00	0.00	2.00	0.02
	Step 3	602	0.00	0.00	1.00	0.02	1.00	0.02
	Step 4	1204	4.00	0.02	0.00	0.00	N/A	N/A
	Step 5	2408	2.00	0.03	N/A	N/A	N/A	N/A
	Step 6	4817	2.00	0.02	N/A	N/A	N/A	N/A
Large Raceway	Step 1	9635	3.00	0.05	2.00	0.06	N/A	N/A
	Step 2	19271	1.00	0.05	0.00	0.00	N/A	N/A
	Step 3	38542	1.00	0.06	0.00	0.00	N/A	N/A
	Step 4	77084	4.00	0.12	0.00	0.00	N/A	N/A
	Step 5	154168	5.00	0.25	0.00	0.00	1.00	0.25
	Step 6	308336	1.00	0.5	0.00	0.00	5.00	0.55
	Step 7	616672	3.00	0.96	0.00	0.00	3.00	1.08
	Step 8	1233344	2.00	1.76	1.00	2.24	1.00	2.21
	Step 9	2466688	2.00	4.62	0.00	0.00	4.00	4.13
	Step 10	4933376	1.00	8.00	0.00	0.00	0.00	0.00
	Step 11	9866752	3.00	16.1	0.00	0.00	3.00	16.4
Starvation Ponds	Pond 1	9866752	1.00	15.7	1.00	19.3	0.00	0.00

4.4.2.7 Culture Transfer and Raceway/Mixer Maintenance

The same considerations for culture transfer and raceway/mixer maintenance time delays in the base case were implemented in the potential best case. The resulting average process time delays are reported in Table 19.

Table 19. Best case total time delay.

		Stepwise	Volume Batching	Intense Culturing
Level	Scaling Step	Total Average Process Time (d)	Total Average Process Time (d)	Total Average Process Time (d)
Laboratory	Step 1	2.13	*4.01*	2.13
	Step 2	2.11	*2.62*	2.11
	Step 3	2.11	2.33	2.11
	Step 4	2.11	2.73	2.11
	Step 5	2.55	2.56	2.55
	Step 6	2.11	3.70	2.11
Medium Raceway	Step 1	2.23	*4.13*	2.23
	Step 2	2.45	*3.52*	2.46
	Step 3	2.36	3.51	2.40
	Step 4	2.21	3.43	•
	Step 5	2.47	*	•
	Step 6	2.34	*	•
Large Raceway	Step 1	2.27	3.14	•
	Step 2	2.60	3.08	•
	Step 3	2.34	5.08	•
	Step 4	2.63	3.86	•
	Step 5	2.46	3.42	2.50
	Step 6	2.67	3.33	2.60
	Step 7	2.65	2.39	2.68
	Step 8	2.73	5.38	2.71
	Step 9	2.85	4.74	2.83
	Step10	3.31	3.83	3.30
	Step11	3.13	3.33	3.14
Starvation Ponds	Pond 1	5.95	6.68	5.96
	Pond 2	5.98	▪	5.95
	Pond 3	5.97	▪	5.97

4.4.2.7.1 Stepwise Model

The total average process times for the different levels in the stepwise model were variable between the different scaling steps. Scaling step 11 of the large raceway scale exhibited 3 contamination events resulting in an average time delay of 16.1 d. Scaling step 11 of the large raceway scale and starvation ponds 1 through 3 of the starvation pond level incorporated the largest pond area and subsequently the greatest time delays for contamination events. Therefore, contamination events occurring in these scaling steps resulted in temporary bottlenecks. The starvation pond level resulted in a total average process time of roughly 6 d.

4.4.2.7.2 Volume Batching Model

The total average process time between the different scaling steps of the volume batching model did not exhibit a general trend. Given that the volume batching model throughput was relatively lower, contamination events had a greater effect on the variability between the different scaling steps. For example, step 8 of the large raceway scale yielded one contamination event resulting in the greatest total average process time of 5.38 d in the large raceway level. The total average process time for starvation pond 1 of the large raceway scale was 6.80 d.

4.4.2.7.3 Intense Culturing Model

The total average process time between the different scaling steps of the intense culturing scenario were variable resulting in no trend. Contamination events that occurred resulted in temporary bottlenecks. The total average process time for starvation ponds 1 through 3 of the starvation pond level was approximately 6 d.

4.4.2.7.4 Comparison of the Three Scenarios

The total average process time between the three models were variable and did not exhibit a general trend. Scaling steps 10 and 11 of the large raceway level in the stepwise and intense culturing scenarios did yield greater time delays however; these delays were attributed to raceway cleaning as a consequence of contamination events. Therefore, temporary bottlenecks occurred between scaling steps 10 and 11 of the large raceway level for both the stepwise and intense culturing models.

4.4.2.7.5 Contrast of the Base and Potential Best Cases

The total average process time for the base case resulted in process bottlenecks while the potential best case yielded temporary bottlenecks caused by contamination events. Compared to the base case, the implementation of a reduced constant culturing time by the potential best case resulted in greater variation of the total average process time between each scaling step. The total average process time of the potential best case models were reduced significantly compared to the base case.

4.4.3 Potential Best Case Model Initialization, TBI and ACT

The TBA of items for the potential best case was determined by utilizing the same process implemented for the base case. Therefore, the item arrival time was optimized by trial and error. The TBA for the stepwise, volume batching and intense culturing models resulted in 3, 3, and 3 d respectively. Because of the nature of the volume batching model, the TBA was decreased compared to the other two models. The TBI, ACT and total number of items processed by each level are depicted in Table 20.

Table 20. Best case process statistics.

	Stepwise Model			Volume Batching Model			Intense Culturing Model		
Level	# items	TBI	ACT	# items	TBI	ACT	# items	TBI	ACT
Laboratory	2396	3.00	13.1	1198	6.00	18.6	2396	3.00	13.1
Medium Raceway	2377	3.02	14.1	596	12.1	17.4	2390	3.00	7.09
Large Raceway	2342	3.05	29.6	294	24.3	51.5	2367	3.03	19.8
Starvation Ponds	2339	3.05	5.96	292	24.4	6.68	2365	3.03	5.96
Harvesting	2338	3.05	1.82	292	24.4	9.14	2365	3.03	1.83
Total	2338	3.05	64.6	292	24.4	75.1	2365	3.03	47.8

4.4.3.1 Stepwise Model

The stepwise model of the potential best case yielded a total throughput of 2338 items. The mean TBI for each level was roughly 3 d with a total average TBI of 3.05 d. The ACT was the greatest in the large raceway level which is expected as this level incorporated the most scaling steps. The harvesting level yielded an ACT of 1.82 d which was the least ACT reported. The total ACT for items exiting the model was determined to be 64.6 d.

4.4.3.2 Volume Batching Model

The volume batching scenario resulted in a total model output of 292 items. The mean TBI of the volume batching model was doubled with each set of scaling steps batching two items together. For example the laboratory average TBI was 6.00 d and increased to 12.1 d in the medium raceway level. Beginning in the large raceway level the mean TBI was 24.4 d which resulted for the remaining levels. The greatest ACT occurred in the large raceway level as this level encompassed the most scaling steps. The total ACT was 75.1 d.

4.4.3.3 Intense Culturing Model

The intense culturing model total throughput was 2365 items. The mean TBI was approximately 3 d between the different levels. The greatest ACT was 19.8 and was produced by the large raceway level. The harvesting ACT was 1.83 d which was the least ACT. The total ACT of each item was determined to be 47 d.

4.4.3.4 Comparison of the Three Scenarios

The ACT for the stepwise, volume batching and intense culturing model was 64.6, 75.1, and 47.8 d respectively. The intense culturing model yielded the shortest total ACT of 47.8 d. A total of 2338, 292, and 2365 items were processed by the stepwise, volume batching, and intense culturing models, respectively. Even though the intense culturing model implemented 3 steps of FPRs in the overall process, this resulted in a throughput of only 27 more items compared to the stepwise model.

The TBI in the harvesting level of the volume batching model resulted in a time of 24.4 d compared to a time of approximately 3 d for the other two models. This variation in TBI was a product of the volume batching process and increased with each set of scaling steps that were batched together.

4.4.3.5 Contrast of the Base and Potential Best Cases

Compared to the base case, the potential best case yielded 1480, 74 and 1491 more items for the stepwise, volume batching and intense culturing models. The ACT yielded by the potential best case was significantly reduced compared to the base case. Like the base case, the potential best case yielded the greatest ACT in the volume batching model. The mean TBI in the volume batching scenario of the potential best case was reduced compared to the base case but was still significantly higher compared to the stepwise and intense culturing models.

4.4.4 Harvesting

Given that the TBA of items was decreased compared to the base case, the harvesting rate was increased accordingly. A harvesting process rate of 450,000 L $h^{-1}$was implemented for the stepwise and intense culturing models. The volume batching model utilized a harvesting process rate of 90,000 L h^{-1} as fewer items were processed. For both the stepwise volume batching and intense culturing models, the centrifuge utilization increased to 59.3, 37.2 and 60%, respectively. The average process time of the harvesting activity did not cause any bottlenecks in the overall process. The average harvesting process time and utilization percentages are listed in Table 21.

Table 21. Best case centrifuge utilization.

		Stepwise Model		Volume Batching Model		Intense Culturing Model	
Level	Scaling Step	Average Process Time (d)	Utilization (%)	Average Process Time (d)	Utilization (%)	Average Process Time (d)	Utilization (%)
Harvesting	Step 1	1.82	59.3	9.14	37.2	1.82	60

4.4.5 Labor Requirements

Labor requirements for the potential best case resulted in 10, 4, and 10 laborers for the stepwise, volume batching and intense culturing models, respectively. In comparison to the base case, the stepwise model lab labor resource was reduced by one while the H.S. labor resource was increased by one. The volume batching model lab labor resource was also reduced by one. The intense culturing model H.S. labor resource was increased by one. Considering the potential best case increased model throughput, it was expected that labor resources would increase rather than decrease. However, the only activity time delay calculated for the lab labor was for the laboratory level transfer activity. Since the transfer activity time delay was based on a triangular distribution, the utilization between the base case and best case may yield results not indicative of expectations. The labor resource requirements and utilization are reported in Table 22.

Table 22. Best case labor utilization.

	Stepwise Model		Volume Batching Model		Intense Culturing Model	
Laborers	# resources	utilization	# resources	utilization	# resources	utilization
Lab	1	0.78	1	0.09	1	0.59
H.S.	3	0.32	1	0..41	3	0.23
Manual	5	0.40	1	0.27	5	0.31
Contract	1	0.01	1	0.00	1	0.01

4.5 Conclusions

The total average raceway utilization for both the stepwise and intense culturing models indicated relatively efficient processes for both the base case and best case. The volume batching scenario was an inefficient process compared to the other scenarios. The implementation of FPRs in the intense culturing model did improve overall productivity compared to the other two models. However, the elimination of 7 scaling steps in the intense culturing models did not significantly increase model output compared to the stepwise model for either the base case of sensitivity analysis.

Bottlenecks were identified in all models of the base case; however, the volume batching model yielded the fewest bottlenecks. This was because the simultaneous batching of items reduced the total number of items exiting the model. Bottlenecks that occurred within the base case emerged as items progressed between constant and variable culturing durations.

Contamination events decreased raceway utilization and increased overall process time delays. Also contamination events yielded the progression of items in the potential best case resulting in temporary bottlenecks in the stepwise and intense culturing model.

The harvesting process modeled did not cause any bottlenecks in the overall process for both the base case and potential best case. The growth rates modeled by the potential best case would require the development of an efficient strain of microalgae in which growth rates would not be seasonal. Therefore, the utilization of microalgae for bio-fuel may require the development of genetically modified organisms.

CHAPTER V

ECONOMICS OF A SMALL SCALE MICROALGAE FACILITY

5.1 Introduction

America's energy demand is heavily dependent upon foreign oil, accounting for roughly 59% of America's oil consumption. The economic and national security issues attributed to the dependence on foreign oil, as well as the recent price escalation of non-renewable fossil fuels, has raised awareness for the utilization of alternative renewable fuel sources.

In the field of renewable bio-fuel resources, microalgae may be able to meet the demands of a renewable bio-fuel feedstock. Microalgae are aquatic, photosynthetic, microscopic plants that utilize sunlight and can be cultured for the production of biomass for bio-fuel. Microalgae biomass production offers many advantages over conventional biomass production technologies including higher yields, use of otherwise nonproductive land, reuse and recovery of waste nutrients, use of saline or brackish waters, and reuse of CO_2 from power-plant flue-gas or similar sources Brune et al. (2009).

Even though there continues to be a considerable amount of interest in utilizing microalgae as a bio-fuel, this technology is still predominately in the research and development (R & D) phase. Economic feasibility is a major consideration for the development of this technology. As this technology begins to move from the laboratory scale to the pilot plant scale, the cost of scaling up becomes a concern. Also, microalgae cultivated for bio-fuel must be price competitive with crude oil to be considered a viable fuel alternative. Fossil based fuels are relatively inexpensive, but the inevitable depletion of this nonrenewable resource will continue to diminish supplies thereby increase prices.

Microalgae facilities in existence today, such as the Hutt Lagoon in Western Australia, are economically sustainable due to the production of high-end products such as beta-carotenes. The production of low-end products such as biofuel may prove to be uneconomical given the current technology. However, bio-fuel derived from renewable sources, such as microalgae, may become a more economically sustainable endeavor in the future.

5.2 Objectives

The purpose of this analysis was to accurately determine and analyze the total capital and operational costs, based on current practices and technology, of producing microalgal biomass for the utilization of bio-fuel. Objectives to achieve this purpose include:

1) Identify and analyze capital costs associated with pilot plant scale microalgae production.

2) Quantify variable costs associated with different scaling scenarios.

3) Determine total costs for both the base case and potential best case assumptions.

4) Recognize capital and operational cost items contributing greatly to overall variable costs and performing a what-if analysis to explore the effects of reducing these costs.

5) Perform an NPV analysis to evaluate microalgae production benefits and costs based

on current crude oil and protein meal prices.

6) Determine the break-even price of microalgae bio-oil produced by the different scenarios.

5.3 Materials and Methods

Capital and operational costs were determined from discrete event models simulating different large scale microalgae culturing scenarios. These cost estimates represent present values over the assumed 20 yr facility operation period for 2011. Total costs were determined for a stepwise, volume batching and intense culturing scenario and were indicative of a base case and potential best case assumptions. The base case and potential best case assumptions for each scaling scenario are outlined in Tables 23 and 24.

Table 23. Base case assumptions.

	Base case			
Scenario	Average culturing duration (d)	Time between arrivals (d)	% lipids	% biomass
Stepwise	8.43	8.00	30.0	70.0
Volume batching	8.43	4.00	30.0	70.0
Intense culturing	8.43	8.00	30.0	70.0

Table 24. Best case assumptions.

	Best case			
Scenario	Constant culturing duration (d)	Time between arrivals (d)	% lipids	% biomass
Stepwise	2.1	3.00	50.0	50.0
Volume batching	2.1	3.00	50.0	50.0
Intense culturing	2.1	3.00	50.0	50.0

The potential best case assumptions utilized a 2.1 d constant culturing duration compared to an average base case variable culturing duration of 8.43 d. Therefore, the potential best case assumptions yielded a significantly greater volume of microalgae culture compared to the base case assumptions. The base case time between item arrivals (TBA) was 8 d, 4 d and 8 d for the stepwise, volume batching and intense culturing scenarios. The best case TBA was 3 d for each scaling scenario. The oil yield for the base case was 30% while the lipid extracted algae (LEA) was 50% for the best case assumptions. The biomass yield for the base case was 70% and the LEA was 70%. Model duration was 20 yr, operating 360 d yr^{-1} and employed 32 ha in microalgae production.

A what-if analysis was performed which employed the results obtained from each scaling scenario in the best case to identify costs that may be reduced or eliminated through future technological advances. The what-if analysis was utilized to exhibit the effects on the cost of production by reducing identified capital and operational costs. Capital costs considered for reduction included electric mixers and sumps, piping infrastructure for nutrient and culture conveyance between ponds and pond liners. The electric mixer cost item was reduced to a value of zero while the sump cost item was reduced by a cost of $11,495. The nutrient and culture conveyance capital cost item was reduced by a value of $9,670. The capital cost for pond liner was eliminated resulting in a cost of $0.00. Operational costs that were reduced include power for electric mixers, nutrients, CO_2 and contamination costs. Power costs for electric mixers were eliminated as these devices were discarded from the capital cost section. Nutrient requirements were also eliminated as these resources may be able to be satisfied by utilizing waste streams from sewage treatment or agricultural operations. CO_2 costs were reduced to a value of $0.00. Contamination costs were also reduced to a value of $0.00 as contamination events may be insignificant for cultivation of future strains of microalgae. The what-if analysis was conducted by utilizing the best case assumptions production results coupled with the previously stated cost reductions to determine total production costs.

A net present value (NPV) analysis was conducted for the stepwise, volume batching and intense culturing scenarios in the base case and best case assumptions as well as the what-if analysis. The NPV analysis was performed to account for the time value of money for the benefits and costs related to each scaling scenario in an effort to recognize the risk associated with future cash flows. The discount rate utilized for the NPV analysis was 10% over a 20 year horizon. Capital cost items were depreciated by utilizing the straight line depreciation method in which the salvage value of the facility was assumed to be 1% of the capital costs. The NPV of each scaling scenario was determined by implementing a microalgae bio-oil sale price of $0.71 L^{-1} and was based on current crude oil prices. Protein meal was a by-product derived from the lipid extraction process and was determined to have sale price of $381 t^{-1}. The microalgae protein meal sale price was assumed to be similar to the price of soybean protein meal and was indicative of the May, 2011 average price. The NPV analysis was constructed utilizing Microsoft Excel in which capital cost items were depreciated utilizing the straight line depreciation method over the 20 yr operating duration.

A broad literature review was conducted to identify capital costs associated with the pilot plant scale production of microalgae. A comprehensive microalgae economics report by Benemann and Oswald (1996) was attained which compiled four other similar studies including: Benemann et al. (1987); Benemann et al. (1982) and Wiesmann et al. (1989). Benemann and Oswald (1996) updated the costs derived from the previously mentioned reports to 1994 cost values. For this analysis, capital cost items from the report by Benemann and Oswald (1996) were re-evaluated based on current technology and subsequent costs. The capital and operational costs reported by Benemann and Oswald (1996) were updated to 2009 cost values by utilizing the Consumer Price Index (CPI) between the years of 1994 and 2009. These costs were updated to compare the costs reported by Benemann and Oswald (1996) to the re-evaluated capital costs determined by this report.

Capital and operating costs of the 32 ha facility were evaluated utilizing a number of sources. The RS Means catalog, RSM (2009), was used to determine most construction costs. The Texas Custom Rate Statistics, USDA (2008), was utilized to produce costing values pertaining to site preparation and raceway construction. Where the Texas Custom Rate Statistics were unable to provide cost information, the Iowa Custom Rate Survey (Edwards 2009) was used to provide cost figures. Construction costs that were unable to be determined from the previously mentioned methods were derived from a literature review pertaining to the item in question. Operating inputs such as electricity and natural gas were updated based on 2009 cost averages for the state of Texas. The capital costs determined by this analysis were incorporated into an Excel spreadsheet which also contained operational costs derived from the different discrete event models constructed with Extend Sim 7.0.

Operational costs were based on the three different scaling scenarios and accumulated as items progressed through the models. Major operational costs items included: electrical, nutrient, CO_2 and labor costs. Electrical costs were derived from power for mixing, harvesting, water supply and other electrical costs. Mixing power costs were based on electrical mixer power requirements, culturing duration for each batch of microalgae and industrial entity electrical rates. Power for harvesting was subject to power requirements for centrifugation, harvesting process time and industrial electric rates. Water supply electrical costs were based on-site water well costs as well as the volume of water required for facility operation. For this analysis, water discharged from the harvesting process was recycled. The water discharge was stored in a holding pond and would be utilized for reuse in the culturing process. It was assumed that nutrients would be depleted at the end of the starvation period resulting in no nutritional cost benefit from recycling water. Nutrient costs were based on proprietary media recipes utilized within Texas AgriLIFE microalgae research facilities. With-in each scaling step, media volume was equal to the inoculation volume. CO_2 costs were based on culture growth rates and a CO_2 consumption rate derived from a mass balance equation. Labor costs were based on time delay triangular distributions for contamination events, culture transfer, raceway/mixer maintenance and culture sampling.

5.4 Results and Discussion

5.4.1 Capital Costs

<u>5.4.1.1 Land</u>

One of the major advantages of microalgae is the use of nonproductive land. Exploitation of this advantage implies that microalgae facilities would be located in regions that are unable to be utilized for conventional farming practices. Also, a facility must be located in an area that receives 5000 kcal m^{-2} d^{-1} and has more than 180 frost free d yr^{-1} (Johnson et al., 1988). Therefore, locations suitable for microalgae cultivation were identified by reviewing an average annual solar radiation map (Figure. 5) and an average annual temperature map (Figure. 6).

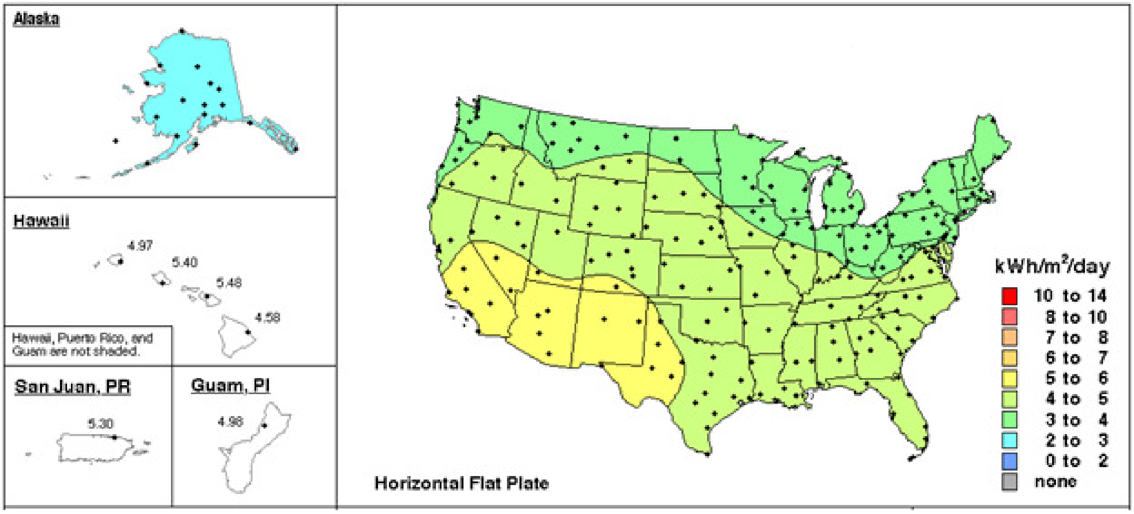

Figure 5. General trends in the amount of solar radiation received in the United States from the time period of 1961-1990. The dots on the map represent 239 sites of the National Solar Radiation Data Base (NSRDB) sites. Source: National Renewable Energy Laboratory (NREL, 2011).

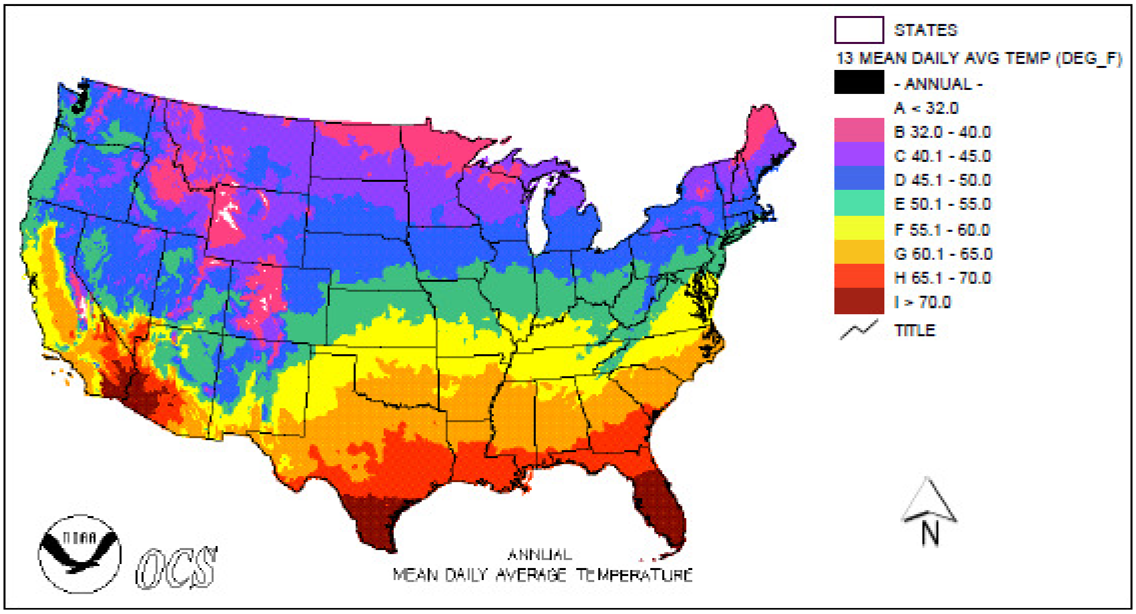

Figure 6. U.S. annual mean daily average temperatures (°F) from 1961-1990. Source: National Climatic Data Center (NCDC, 2011).

Locations ideal for outdoor production of microalgae are confined to the southern region of the United States. States considered for outdoor production of microalgae include: Texas, New Mexico, Arizona, Nevada and California. For the purpose of this analysis, only the state of Texas is considered for the location of a microalgae facility. The average price for pasture land in Texas was \$1360 ac^{-1} (USDA, 2009). A 10% adjustment was considered by this analysis to account for brokerage fees, perimeter surveying fees and legal fees. This resulted in a total price of \$3700 ha^{-1} and is the land cost determined for this analysis. By comparison, the land price reported by Benemann and Oswald (1996) was \$3300 ha^{-1}, which was determined by applying the appropriate CPI. This value and all other values in this report are updated to 2009 values. It was assumed that brokerage fees, perimeter surveying fees and legal fees were included in the price reported by Benemann and Oswald (1996). However, the price of \$3700 ha^{-1}

identified for this analysis and the updated land price of \$3300 ha^{-1} reported by Benemann and Oswald (1996) are comparable.

It should also be noted that 15 to 20% of the land area in microalgae production is needed for site non-productive uses as suggested by Neenan et al. (1986). Benemann et al. (1982) used a non-productive land area of 25%. Non-productive uses include access roads, buildings, raceway levees and storage for nutrients and other inputs. For this analysis, a factor of 25% was considered to account for the amount of non-productive land. Therefore, a 32 ha area dedicated to microalgae production would require a total land area of 40 ha.

5.4.1.2 Site Preparation

The first step in facility construction is site preparation; these costs are site dependent and will vary between different locations. Site preparation can include: removal of vegetation (trees, shrubs), large (and small) rocks, and other impediments, and rough cut and fill to level the land (Benemann and Oswald, 1996). Therefore, it was assumed that a location, which is relatively flat with few impediments, would be chosen to locate a microalgae facility. There are five major considerations for site preparation including: primary clearing, plowing, site leveling, compaction and surveying.

Primary clearing is the leading consideration for site preparation; this includes removal of vegetation, large rocks, other impediments and rough cut and fill to level the site. The average cost of site clearing was reported to be \$470 ha^{-1}, which was the Texas state average (USDA, 2008). The rate at which a parcel of land can be cleared depends mainly on existing vegetation and topographical characteristics. However, it is assumed that a parcel of land with as few impediments as possible would be sited for a microalgae facility. Thus, the average land clearing cost of \$470 ha^{-1} is the primary clearing cost considered for this analysis. The report by Benemann and Oswald (1996) assumed a cost of \$1000 ha^{-1} which included surveying.

The second consideration for site preparation is plowing the topsoil in preparation for site leveling. The custom plowing rate for Texas was reported to be \$20 ac^{-1} (USDA, 2008). Therefore, a total cost of \$50 ha^{-1} for site plowing was determined for this analysis.

The third consideration in site preparation is site leveling. This can be accomplished with large tractors and pull type earth movers equipped with laser levels. The entire site should be leveled to simplify site surveying and construction. According to Salassi (2001) the cost of laser leveling with a 300 hp tractor and a 17 yd^3 scraper was about \$240 ha^{-1}. To effectively level the entire site, two passes would be required with the tractor and scraper. The total cost to level the site should be twice the reported rate, which results in a total cost of \$480 ha^{-1}. Benemann and Oswald (1996) provided an estimate of \$1650 ha^{-1}, which is considerably greater.

The fourth consideration in site preparation is compaction of the entire site. It was assumed two passes would be needed to sufficiently compact the entire site. The custom rate for compaction had a reported range of \$4 - \$12 ac^{-1} (Edward, 2009). A cost of \$20 ha^{-1} was utilized for this analysis resulting in a total compaction cost of \$50 ha^{-1}.

The report by Benemann and Oswald (1996) listed compaction costs with percolation control and estimated a cost of \$165 ha^{-1}.

The fifth step in site preparation is surveying. To begin facility construction requires the layout of buildings and microalgae raceways through surveying. Surveying costs were determined to be \$2134 d^{-1} (RSM, 2009). This analysis assumed that five hectares could be surveyed in an eight h d, resulting in a cost of \$425 ha^{-1}. Therefore, the surveying cost considered for this analysis is \$425 ha^{-1}.

Total site preparation costs including primary clearing, leveling, surveying and percolation control was reported by Benemann and Oswald (1996) to be \$3300 ha^{-1}. The total cost for site preparation determined by this analysis was \$1475 ha^{-1}, which is less than half the cost reported by Benemann and Oswald (1996).

5.4.1.3 Raceway Levees and Dividers

Currently, outdoor raceways are widely utilized as photo-bioreactors for the cultivation of microalgae. Raceways are constructed by levees, which form the raceway perimeter, and a divider located in the middle of the raceway. Raceways considered for this analysis range from an operating depth of 0.152 m to a maximum depth of 0.305 m. A raceway pond is illustrated in Figure 7.

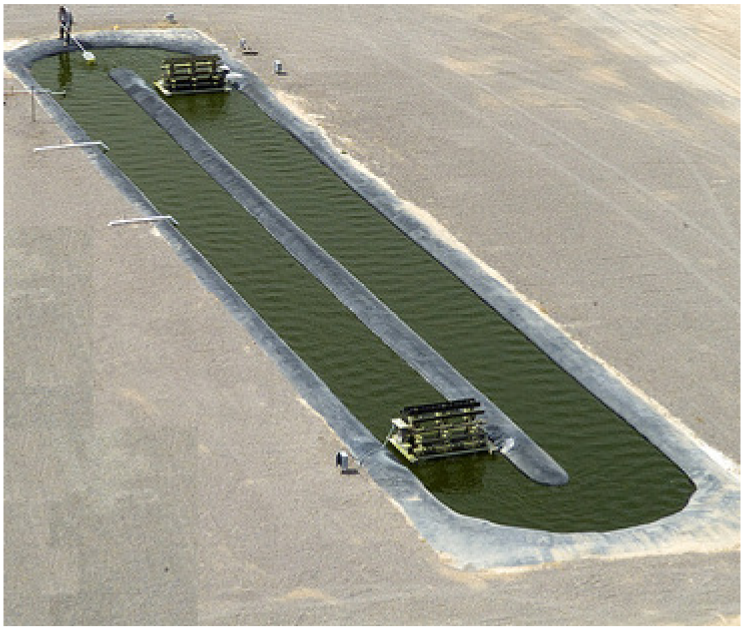

Figure 7. Depiction of a raceway photo-bioreactor.
Source: AGLR, 2011

The raceway dimensions that are considered for this analysis are listed in Table 25.

Table 25. Raceway dimensions and area.

	Raceway production area (ha)								
Parameter	0.0032	0.0063	0.0126	0.0253	0.0506	0.1012	0.2023	0.4047	Units
Width of raceway	7.62	12.19	12.19	13.72	9.14	15.24	21.34	30.5	m
Width of center berm	1.22	1.22	1.22	1.22	1.22	1.22	3.05	3.05	m
Length of raceway	6.92	6.92	13.83	27.66	82.98	82.98	110.6	147.5	m
Length of center berm	3.05	6.10	9.15	15.47	64.69	64.69	92.35	120.1	m
Total raceway area	0.005	0.008	0.017	0.038	0.076	0.126	0.236	0.450	ha
Number of raceways	1.00	1.00	1.00	1.00	1.00	1.00	1.00	78.0	n/a
Total area	0.005	0.008	0.017	0.038	0.076	0.126	0.236	35.1	ha

Earthen levees are sufficient to construct the raceways described above. Therefore, it was assumed that conventional farm equipment would suffice for levee construction. Levees constructed with conventional farm equipment are referred to as temporary levees in rice cultivation. Temporary levees are built by pulling a levee plow across a prepared field, gathering soil from a width of 2.72 to 4.20 m (AMCO, 2005). The construction of levees for raceway photo-bioreactors can be accomplished with a levee plow working width of 2.72 m. Since the entire site of the 40 ha facility has already been compacted, levee construction will require 3 different steps.

The first step will require the plowing of the area where the levees will be constructed. This step is necessary to loosen the soil before levee construction.

The second step will be the use of a levee plow which constructs the levees. According to Smith and Dilday (1997), four to five passes with a levee plow are required to achieve a height of 51 to 61 cm. Levee construction with a levee plow is depicted in Figure 8.

Figure 8. Rice levee construction with a levee plow.
Source: Smith, C.W. and R.H. Dilday

The third step is levee compaction which will result in a compacted levee height of approximately 40 cm. Levee compaction can be completed by a commercially available levee packer or by a tractor driving on top of the levees. It is estimated that each levee construction step will require about 1 h to sufficiently construct a 0.4 ha raceway. To determine the cost of temporary levee construction, the 2008 Texas Custom Rates Statistics were analyzed. The highest state average custom rate for moldboard plowing was considered, resulting in a cost of \$45 ha^{-1} (USDA, 2008). This is the cost determined for each step outlined above, which results in a total cost of \$135 ha^{-1}. This is considerably less than the cost reported by Benemann and Oswald (1996). With the consideration of levee compaction, the cost of levee construction reported by Benemann and Oswald (1996) was \$500 ha^{-1}.

5.4.1.4 Raceway Leveling

Raceway leveling is the next consideration in raceway construction. Raceway leveling can be accomplished with a 13.6 t motor-grader equipped with a laser level. After raceway leveling, the raceway will need to be sloped 0.051 m for every 91.5 m in the direction of channel flow to promote channel velocity. A cross section of a completed raceway is depicted in Figure 9.

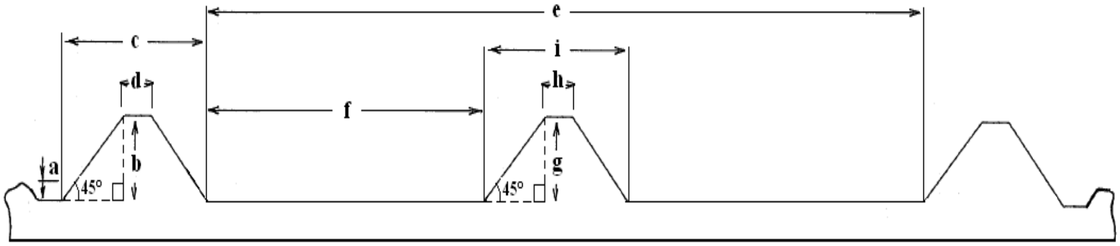

Figure 9. Cross section diagram of a completed raceway. a. plow lip height, b. perimeter berm height, c. perimeter berm bottom width, d. perimeter berm top width, e. total raceway width, f. raceway channel width, g. center berm height, h. center berm top with, i. center berm width.

Raceway center berms, dividers in the raceways, may be constructed by the soil displaced from raceway leveling, sloping, and sump construction. The amount of soil required for center berm construction was determined by considering a trapezoid shape as depicted by the center trapezoid in the Figure 9. The center berm width in Table 25 was utilized as the bottom width of the trapezoid. The berm height was assumed to be 0.40 m after compaction. The top width of the berm was calculated by considering a 45-45-90° triangle. The amount of soil required for center berm construction was calculated by utilizing equation 13.

$$\mathrm{CB_{TW}} = \mathrm{CB_{BW}} - 2(\mathrm{CB_H}) \tag{13}$$

where:

$\mathrm{CB_{TW}}$ = trapezoid top width (m)

$\mathrm{CB_{BW}}$ = trapezoid bottom width (m)

$\mathrm{CB_H}$ = center berm height (m)

The total amount of soil required for center berm construction was determined by equation 14. The center berm length can be found in Table 25.

$$CB_{SR} = CB_H(CB_{BW} + CB_{TW})/2\ (CB_L) \tag{14}$$

where:

CB_{SR} = center berm soil requirement ($m^{3)}$

CB_H = center berm height (m)

CB_{BW} = center berm bottom width (m)

CB_{TW} = center berm top width (m)

CB_L = center berm length (m)

The total amount of soil displaced from raceway leveling and sloping was determined by equation 15.

$$R_{SD} = R_L(R_L \times 2\ /\ 91.5)\ (.051)\ (R_{CW}) \tag{15}$$

where:

R_{SD} = raceway soil displaced ($m^{3)}$

R_L = raceway length (m)

R_{CW} = raceway channel width (m)

It was determined that raceway dividers could be constructed from the soil displaced by raceway leveling as well as sump construction. The daily cost for fine grading of a lagoon bottom is \$1,495 d^{-1} (RSM, 2009). Assuming a motor-grader could level and slope 0.4 ha h^{-1} this results in a cost of \$470 ha^{-1}. There is no cost consideration for raceway dividers as they will be constructed with excess material from raceway leveling and sump construction. However a cost for raceway construction soil removal was considered resulting in a cost of \$1910 d^{-1} or \$590 ha^{-1} (RSM, 2009). The total cost for raceway leveling and sloping which included soil removal was \$1060 ha^{-1}.

5.4.1.5 Sump Construction

There are two different types of sumps required for each outdoor raceway. The first is a sump used for drainage, conveyance of water, media and CO_2. Sumps constructed for these uses were natural earthen sumps determined to have a cost of \$380 ha^{-1} (RSM, 2009). This cost included soil excavation and assumed that a sump for a 0.4 ha raceway could be constructed in one h. Each sump would be the same width as the bottom of the raceway with a depth of approximately 0.40 m. Sumps would be covered with a synthetic pond liner, which would be sufficient for preventing erosion and maintaining sump shape.

A second sump is required to house the electric mixers that will be used to circulate the microalgae culture in the raceways. The construction of these sumps includes the excavation of soil, construction of forms and concrete. It was assumed that the soil could be excavated in one hour. The forms could be constructed and filled in the same day. The concrete would cure overnight, resulted in eight labor hours for each sump constructed. A side profile of the sump shape with dimensions for the 0.4 ha raceway is depicted in Figure 10.

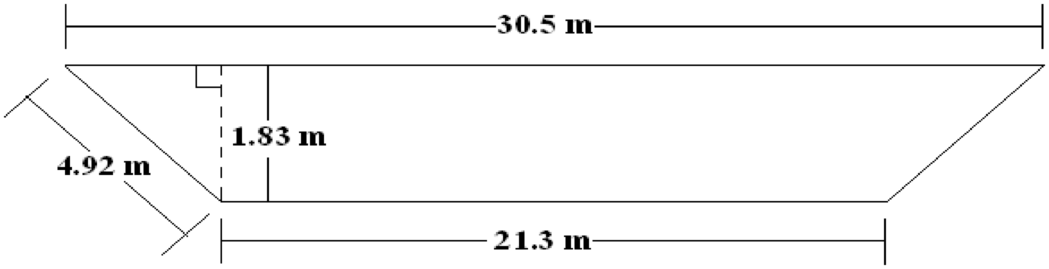

Figure 10. Dimensions of a 0.4 ha raceway electric mixer sump.

The total cost for excavation was determined to be \$395 ha^{-1}(RSM, 2009). The cost for form construction was calculated to be \$7410 ha^{-1} (RSM, 2009). Each sump would require approximately 15.3 m^{3} of concrete. According to CNW (2011), the 2008 national average price of concrete was \$98 m^{-3} resulting in a total concrete cost of \$3690 ha^{-1}. The total construction cost for electric mixer sumps was determined to be \$11,495 ha^{-1}. These sumps would be required for each raceway utilizing electric mixers as a source of culture agitation. The total cost of sump construction considered for this analysis was \$11,875 ha^{-1}. Sump construction was coupled with the overall CO_2 carbonation system and was reported to be \$2,775 for each 8 ha pond (Benemann and Oswald, 1996). However, the report by Benemann and Oswald (1996) used paddle wheels as raceway mixing devices. The sumps constructed for these mixing devices were natural earthen sumps with a granular liner. The concrete sumps considered for this analysis have a significantly higher capital costs compared to the sumps considered by Benemann and Oswald (1996).

5.4.1.6 Pond Liner

There are many different types of pond liners to consider for use in outdoor microalgae cultivation. Liners requirements include: the ability to create an impermeable surface, that they generate the least amount of resistance to flow, are relatively easy to install, have a long useful life, and are inexpensive. Certainly in some areas of the raceway bottom, such as near the paddle wheels and carbonation sumps, or possibly at the bends, some provision of erosion control must be provided (Benemann and Oswald, 1996). The use of synthetic pond liners may be advantageous in extending the life of raceway dividers and levees. Without the protection of a synthetic pond liner, raceway dividers and levees are susceptible to deterioration from natural elements.

Currently, the use of synthetic pond liners such as plastic or rubber is highly practiced. These synthetic pond liners are expensive at a cost of about \$10.76 m^{-2} (Lou Brown, AgriLIFE Research, personal communication, 12 August 2009). However, a 30 mm thick high density polyethylene (HDPE) pond liner has a bare cost of \$4.74 m^{-2} (RSM, 2009). Rowe and Sangman (2001) determined that HDPE liners have a service life of 45 yr. Therefore, the 20 yr facility operation time considered by this analysis is within the liner service life. The total cost for material and installation was \$14 m^{-2} which included overhead and profit (RSM, 2009).

The cost of installation seemed high, so this cost was reevaluated pertaining to the RS Means Crews cost sheets. It was assumed that a crew consisting of 1 foreman, 5 laborers, and 2 equipment operators (1 forklift and 1 grader) would be needed to install the liner. It was also assumed that this crew could install a liner surface area of about 0.4

ha in an eight h day. The liner would be held in place by extending the liner over the raceway perimeter berms and into the plow lip, (a) in Figure 5, and then covering and packing soil on top of the liner. This evaluation resulted in an installation cost of \$.965 m^{-2} or \$9650 ha^{-1}. Therefore, the total cost considered for pond liner and installation is \$5.70 m^{-2} or \$57,000 ha^{-1}.

Benemann and Oswald (1996) determined a total cost of \$4950 ha^{-1}, which included geotextile material and installation for pond bottom erosion and percolation control. The geotextile material was placed on all pond perimeters, dividers, and interior levees, as well as along the bottom near the paddle wheels, to prevent erosion. (Neenan et al., 1986) reported a pond liner of a granular cover over clay with a cost of \$10,460 ha^{-1}. The synthetic liner may prove to be the least expensive option given the benefits of berm protection, raceway management and erosion mitigation of raceway bottoms and sumps. Plastic pond liners allow the raceways to be cleaned permitting better control of the biotic environment and preventing percolation of culture from the pond (Benemann et al., 1987).

5.4.1.7 Mixing

Raceways are generally mixed with paddle wheels, and experience has shown that paddle wheels are by far the most efficient for mixing the algal cultures and are the easiest to maintain (Anderson, 2005). Paddle wheels are widely utilized, but scaling up these mixing devices can be limited and may be cost prohibitive. Therefore, electric mixers were considered for this analysis. Electric mixer requirements were based on a raceway channel flow rate of 0.46 m s^{-1} which was utilized to calculate the cross sectional flow rate for each raceway scale. The mixers determined for each raceway size is listed in Table 26. An electric mixer is depicted in Figure 11.

Figure 11. Electric mixer employed for raceway circulation of microalgae culture. Source: Flygt pumps.

Table 26. Electric mixers.

	Raceway size (ha)								
Parameter	0.0032	0.0063	0.0126	0.0253	0.0506	0.1012	0.2023	0.4047	Units
Rated power	2.5	2.5	2.5	4	8.3	15	20	40	hp
Power Input	1.65	1.65	1.65	1.70	6.00	6.40	10.75	11.65	kW
Cost	17582	17582	17582	18190	26847	31749	43092	52373	\$ $pump^{-1}$
Total cost	17582	17582	17582	18190	26847	31749	43092	4085094	\$

The total cost derived from the electric mixers outlined in Table 26 was \$4,257,718 or \$133,055 ha^{-1}. This cost is the largest capital cost considered for this analysis. A six bladed paddle wheel was specified by Benemann and Oswald (1996) with a cost of \$8,250 ha^{-1}. The cost of a paddle wheel specified by Neenan et al. (1986) was reported to be \$5,230 ha^{-1} with an efficiency of 59%. The cost of the paddle wheels specified by Oswald et al. (1988) used to mix an eight ha pond was \$5,150 ha^{-1}. While paddle wheel costs considered by Benemann and Oswald (1996) and Neenan et al. (1986) are considerably less, the utilization of electric mixers is justifiable. The continued utilization of paddle wheels by this analysis would require 22 units to maintain a channel flow of 0.46 m s^{-1} for each 0.4 ha raceway (Lou Brown, AgriLIFE Research, personal communication, 12 August 2009). The cost for each unit is \$6,000 therefore; the utilization of paddle wheels would result in a total cost of \$330,000 ha^{-1}. This cost is considerably greater, justifying the use of electric mixers instead of paddle wheels.

5.4.1.8 Nutrients

Capital costs pertaining to nutrients include water well installation and piping infrastructure for both water and nutrients. Capital costs for nutrient storage were also analyzed in this section. To determine the capital costs of well installation, an economic study of irrigation systems conducted by Amosson et al. (2001) was reviewed. Water well capital costs were based on well depth and included drilling, pump and engine costs. Table 27 lists different well depths with updated costs. The deepest well depth of 168 m was considered by this analysis since aquifer depth is variable between different site locations. There may also be the need to utilize deeper wells due to facility water requirements and consideration for the potential of facility expansion. The capital cost for water well installation for this analysis was \$3,555 ha^{-1}.

Table 27. Capital costs of water well installation.

Lift (m)	Well (\$)	Pump (\$)	Engine (\$)	Total (\$)	\$ ha^{-1}
76	25432	19094	4760	49300	1540
107	32130	26670	6800	65620	2050
137	38080	32130	7480	77570	2425
168	46664	46664	27200	113770	3555

The capital costs for water piping infrastructure was based on one main line running the length of the facility with a network of smaller pipes used to convey water from the main line to the raceways. A conservative average distance of the water pipe network required was 140 m ha^{-1} with a mainline 1050 m in length. Figure 8 depicts the facility layout and the length considered for piping infrastructure. The diameter of the water mainline was determined by analyzing evaporation rates in desert regions of Texas. An evaporation rate of 1.57 cm d^{-1} was the highest average monthly evaporation rate. Water replenishment of a 1.57 cm d^{-1} evaporation rate would result in a flow rate of 7,080 L min^{-1}. According to Fipps (1995) a 40.64 cm pipe size would be sufficient for a flow rate of 11,855 L min^{-1}. The diameter of network pipes for water conveyance to the raceways was determined to be 15.24cm with a flow rate of 1,665 L min^{-1} (Fipps, 1995). Therefore, one main 40.64 cm water line would be used to convey water to a network of 15.24 cm pipes connected directly to the raceways.

Material and installation costs for 40.64 cm schedule (SCH) 40 pipe was determined to be \$3830 ha^{-1} and \$2740 h^{-1} for the 15.24 cm pipe RSM (2009). These cost included material and installation of pipe, tee's, 90° elbows, butterfly valves and flanges. This resulted in a total water pipe infrastructure capital cost of \$6570 ha^{-1}. Water supply/distribution costs were increased by \$1650 ha^{-1} as this was the cost for water treatment reported by Benemann & Oswald (1996). The total water supply/distribution costs were determined to be \$11,775 ha^{-1}. A diagram of the facility layout considered for this analysis is illustrated in Figure 12.

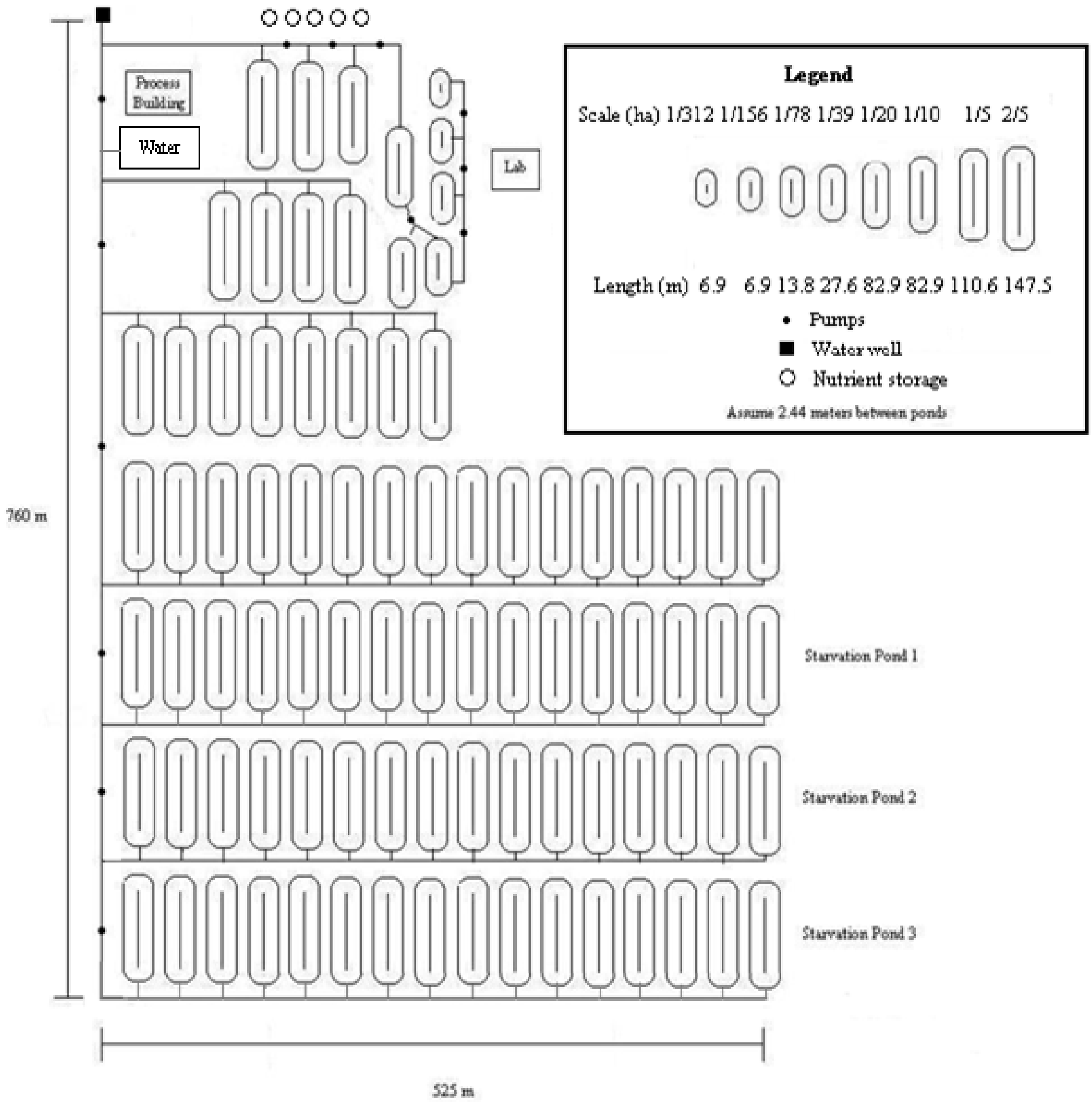

Figure 12. Facility layout considered to determine pipe infrastructure costs.

This section also considers infrastructure costs for microalgae culture conveyance between raceways. It was determined that a total of 13 electric pumps of various sizes would be required for this system to transfer the microalgae culture to and from different raceways. The different pump sizes and costs are outlined in Table 28.

Table 28. Culture conveyance pump costs.

Pump Rate (LPM)	Cost ($)	# of Pumps	Total Cost ($)
380	3720	3	11160
950	4665	1	4665
1136	5325	1	5325
1893	6000	1	6000
3975	8250	1	8250
7570	13,325	2	26,650
11355	19,125	4	76,500

Culture conveyance electric pumps resulted in a total cost of $138,550 or $4330 ha^{-1} which included installation (RSM, 2009). The different pumping rates resulted in the utilization of three different pipe diameters consisting of 3.81 cm, 15.24 cm, and 20.32 cm. The material and installation costs of the previously stated pipe diameters were $32 ha^{-1}, $1200 ha^{-1}, and $4110 ha^{-1}. The total cost considered for piping infrastructure and pumps for microalgae culture conveyance between raceways was $9670 ha^{-1}.

Capital costs for nutrient storage were based on the total media requirement when the facility operates at full capacity. The total media requirement for the 32 ha facility at full capacity was determined to be 24,528,708 L for each transfer event. The fertilizer was assumed to be in a concentrated liquid form; therefore, the media volumes are based on the liquid concentration pertaining to each fertilizer. Nutrient costs were based on proprietary media recipes utilized within Texas AgriLIFE microalgae research facilities; therefore, different fertilizers will be referred to as compounds. The different compounds and appropriate volumes are depicted in Table 29.

Table 29. Facility fertilizer storage requirements.

Compound	Total Weight (kg)	Total Volume (kl)	On-hand Storage (kl)
A	367930	171	684
B	2349	1.78	7.12
C	614	0.63	2.52
D	1840	1.90	7.60
E	107	0.11	0.44
F	3165	3.27	13.1
G	322	0.33	1.32
H	N/A	0.21	0.85
I	N/A	0.02	0.06

It was assumed that the facility would need on-site fertilizer storage with capacity for at least one week. This resulted in a fertilizer storage volume four times the volume required for media transfer for the entire facility. Fertilizer was assumed to be delivered in a concentrated liquid form and stored in upright, bottom funnel plastic tanks. The different tanks sizes and costs considered for fertilizer storage are listed in Table 30 (USP, 2009).

Table 30. Fertilizer storage tank and pump costs.

Compound	Tank size (kl)	# of tanks	Tank cost	Pump cost	Total cost
A	31.23	22	7555	4230	259270
B	10.15	1.00	2060	1190	3250
C	3.78	1.00	1280	1190	2470
D	10.15	1.00	2060	1190	3250
E	0.75	1.00	530	1190	1720
F	17.41	1.00	4545	2155	6700
G	1.89	1.00	860	1190	2050
H	1.32	1.00	655	1190	1845
I	0.75	1.00	530	1190	1720

The tanks and pumps outlined in the table above resulted in a total cost of \$282,275 or \$8820 ha^{-1}. It was assumed that the culture conveyance infrastructure could be utilized for the media transfer events. Therefore, there is no additional cost for the infrastructure pertaining to culture conveyance.

The costs reported by Neenan et al. (1986) were based on the costs described by Benemann et al. (1982). In this report, the water and nutrient distribution system for an 800 ha facility comprised of 40 ha modules required \$910,740 of fixed costs and incremental module costs of \$45,540. This resulted in a water and nutrient distribution total capital cost of \$2275 ha^{-1}. The capital costs pertaining to water and nutrient supply reported by Benemann and Oswald (1996) was \$8580 ha^{-1}. This cost included \$6930 ha^{-1} for water supply and distribution, and 1650 ha^{-1} for nutrient supply. However, it was not specified if the costs provided by these reports considered fertilizer storage costs. The cost of \$6570 for water supply and distribution determined by this analysis is comparable to the costs reported by Benemann and Oswald (1996). The cost of \$18,490 for nutrient storage and culture distribution determined by this analysis is considerably higher than the costs reported by Benemann and Oswald (1996).

5.4.1.9 CO_2

There have been a number of different CO_2 carbonation systems suggested in the literature, most of which have CO_2 transfer efficiencies of 70% or higher (Oswald et al., 1988). The basic system for both flue gas and pure CO_2 transfer reported by Benemann and Oswald (1996) is the use of a 1.5 m deep sump, with the CO_2 sparger at the downflowing side, for counter-current contacting. This analysis only considers the costs associated with the use of pure CO_2. CO_2 would be stored on site in a large tank. The average length of pipe required to convey CO_2 to each raceway was determined to be 170 m ha^{-1}. It was assumed that SCH 40 pipe with a diameter of 5.08 cm would be sufficient for CO_2 distribution. Material and installation costs for the 5.08 cm SCH 40 pipe was determined to be \$1215 ha^{-1} (RSM, 2009). Benemann and Oswald (1996) reported a CO_2 supply and distribution infrastructure cost of \$495 ha^{-1}.

Storage for CO_2 was also considered in this section. The amount of CO_2 required each day was determined to be 394,756 moles of CO_2 for a productivity of 37 g m^{-2} d^{-1}. The tank pressure was determined to be 1,723,500 Pa which resulted in a total volume of 519 m^3 d^{-1}. The largest industrial steel tank size considered by this analysis is 35.2 m^3. A 2 day culturing duration resulted in a total of 30 metal tanks to supply CO_2. The cost of these tanks was reported to be \$75,000 for each tank (UIG, 2011). Assuming a discount of 15% for a bulk tank purchase, the total cost was determined to be \$50,800 ha^{-1}. Considering the high storage cost for CO_2, it may be advantageous for the facility to have CO_2 delivered via pipeline. However, the feasibility of a pipeline would be dependent on the location of the CO_2 source in approximation to the microalgae facility.

5.4.1.10 Harvesting

For this analysis it was assumed that centrifugation will be utilized to concentrate the microalgae culture. Many harvesting processes incorporate a flocculation process for primary harvesting. However, because of the uncertainty of the effect that flocculants may have on secondary microalgae products this process was not considered. As stated before, this analysis is mainly concerned with growing microalgae biomass. It was assumed that the microalgae biomass will be purchased by another entity that specializes in lipid extraction and bio-fuel conversion. Once fully operational, the stepwise, volume batching, and intense culturing scenarios would harvest a microalgae culture volume of 9,866,752 L. The time delay for harvesting was structured to not create a bottleneck in the overall process. Therefore, the number of centrifuges required for harvesting was based on the time between items (TBI) arriving at the harvesting process. Likewise, the base case scenario would need to harvest 6.4 ha in a 3.8 d period and the best case scenario would need to harvest 6.4 ha in a 2 day period. It was assumed that as the frequency of harvesting events increased, the number of centrifuges could also be increased without incurring major alterations to the existing facility. The resulting harvest volume of 9,866,752 L or 3600 LPM was based on a 12 h day.

The disc bowl centrifuge specified for this analysis has a capacity of approximately 1500 LPM with a solids concentration of 10%. This centrifuge has a cost of $229,270 which includes installation (MGH, 2011). The report by Benemann and Oswald (1996) used a centrifuge that could process up to 20 m^3 h^{-1}. According to Benemann and Oswald (1996) the number of centrifuges was based on an operating time of 22 h d^{-1} resulting in a total of 6 centrifuges for a total cost of $4,140,000. This cost in significantly higher as the facility size of the Benemann and Oswald (1996) study was 400 ha.

Storage of the concentrated microalgae slurry was also considered in this section. Since the biomass must be stored for no longer than 48 h to prevent spoiling, it was assumed that the microalgae slurry would be conveyed to an independent processing facility through a pipeline. The centrifuge considered for this analysis can produce a concentration of 10% solids; this resulted in a microalgae slurry total volume of 986,675 L harvest^{-1} at 10% solids. If the 986,675 L of microalgae slurry were transported utilizing 34,100 L tanker trucks, this would result in a total of 30 loads at 340 kg of biomass per load.

5.4.1.11 Buildings, Roads, Drainage and Other Capital Costs

Capital costs allocated for this section include buildings for a laboratory facility, a processing building for centrifugation and water storage. Roads will need to be constructed for building access and raceway access. These roads are assumed to be constructed with an inexpensive material such as rock. Drainage should also be constructed to divert water away from the facility during rainfall events.

The surface area of the water storage pond was based on the centrifuge water discharge volume of 888,000 L for each harvesting event. The resulting water storage pond surface area was determined to be 0.2 ha with a depth of 1.22 m. This water storage pond total capital cost was calculated to be $5330 (USDA, 2008).

The capital cost for building, roads and drainage was based on the cost reported by (Benemann and Oswald, 1996). The cost reported by Benemann and Oswald (1996) was $3300 ha^{-1} or roughly 3% of total direct capital. The total direct capital cost projected for this analysis is considerably higher than the cost of Benemann and Oswald (1996). Therefore, 1% of total direct capital cost is a conservative estimate and was considered in this analysis for buildings, roads, drainage and other capital costs.

5.4.1.12 Electrical Supply and Distribution

It was assumed that a microalgae facility would be located by a major highway for logistical reasons such as fertilizer deliveries and biomass shipments. Therefore, there is no capital cost consideration for electrical supply as this would already be onsite. Capital costs were considered for electrical infrastructure required to power pumps, buildings, and centrifuges. These costs were based on the analysis by Benemann and Oswald (1996) resulting in a total of \$3300 ha^{-1} which is a conservative estimate given the assumption that electricity supply is already on site.

5.4.1.13 Instrumentation and Machinery

Capital costs in this section pertain to costs associated with instrumentation and machinery. This cost was included as the onsite laboratory will need the proper instrumentation to monitor outdoor raceways and maintain indoor stock cultures. Also, facility machinery will be needed for maintenance and monitoring of the raceways. The cost consideration for this value was \$1500 ha^{-1}. Benemann and Oswald (1996) considered a cost of \$825 ha^{-1}.

5.4.1.14 Engineering and Contingency

Engineering and other fees were considered by this analysis to be 5% of the capital cost subtotal. The engineering and other fees costs considered by Benemann and Oswald (1996) was 15% of capital costs. However, given the higher capital costs determined in this analysis, 5% is justifiable.

5.4.1.15 Summary of Capital Costs

Table 31 lists a summary of the capital costs determined by this analysis based on 2011 values. These costs were utilized for the base case scenario and potential best case scenario.

Table 31. Summary of capital costs (2011$).

Capital Cost Items	Stepwise Scaling ($/ha)	Volume Batching ($/ha)	Intense Culturing ($/ha)
Land costs	$4,625	$4,625	$4,625
Site preparation	$1,475	$1,475	$1,475
Raceway levees and dividers	$135	$135	$135
Raceway leveling	$1060	$1060	$1060
Sump construction	$11,875	$11,220	$10,776
Pond liner (HDPE)	$57,000	$57,000	$57,000
Mixing (Electric Mixers)	$133,055	$127,508	$125,585
Water supply, distribution	$11,775	$11,775	$11,775
Nutrient storage / distribution (culture)	$18,490	$18,490	$18,490
CO2 storage / distribution	$59,800	$59,800	$59,800
Harvesting	$21,495	$21,495	$21,495
Building, roads, drainage	$3,295	$3,295	$3,295
Electrical supply	$3,300	$3,300	$3,300
Machinery	$1,500	$1,500	$1,500
FPR	$0	$0	$5,873
Sub Total / ha	$328,880	$322,680	$326,185
Eng. And Conting.	$16,445	$16,135	$16,310
Total Direct Capital	$345,325	$338,815	$342,495
Working Capital 25% Op.Cost	$27,363,015	$7,543,780	$27,651,222
Total Capital Investment	$38,413,385	$13,981,205	$38,525,395

5.4.1.15.1 Comparison of the Three Scenarios

In comparing the capital costs between the three scenarios, the volume batching total capital investment was significantly reduced compared to the stepwise scaling and intense culturing scenarios. However, the volume batching process batched items together thereby reducing model throughput. Therefore, two starvation ponds were eliminated reducing the volume batching scenario facility size by 13 ha. Capital costs were not incurred for this 13 ha, compared to the other scenarios, which reduced the total capital costs of the volume batching scenario.

5.4.2 Base Case Operational Costs

The base case assumption operational costs were derived from each scaling scenario in which costs were tabulated as items progressed through each model. The stepwise scaling, volume batching, and intense culturing scenarios yielded a total of 858, 218 and 874 items, respectively. Operational costs for each scaling scenario are listed below in Table 32.

Table 32. Summary of base case operational costs (2011$).

Operating Cost Items	Stepwise	Volume Batching	Intense Culturing
Power, Mixing	$10,100,000	$2,740,000	$11,100,000
Power, Harvesting	$794,000	$202,000	$809,000
Power, Water Supply	$1,675,145	$450,220	$1,729,300
Power, Other	$230,400	$136,800	$228,600
Nutrients	$88,700,000	$22,500,000	$90,100,000
CO2	$2,300,000	$623,000	$2,360,000
Labor	$5,100,000	$2,981,000	$3,730,000
Maint. Tax, Ins (5% of Capital)	$552,520	$542,100	$547,990
Total Net Operating Costs	$110,206,920	$30,366,900	$111,375,590
Capital Charge (5%)	$1,920,670	$699,060	$1,926,270
Total Operating Costs	$111,372,730	$30,874,180	$112,531,160

5.4.2.1 Power, Mixing

The operational cost of mixing power was derived from the electric mixers used to circulate the raceways. Power costs were calculated by first determining the culturing duration which was multiplied by the mixer kW demand. This was also multiplied by the unit conversion of 24 h d^{-1} and the electrical cost of $.0804 kWh^{-1}(EIA, 2009). The resulting calculation yielded the total operational cost for electric mixers for each item upon exiting the models. The different mixer sizes, electrical requirements and costs kW h^{-1}are outlined in Table 33.

Table 33. Electric mixer requirements.

Parameter								
Rated power (hp)	2.5	2.5	2.5	4	8.3	15	20	40
Rated power (kW)	1.65	1.65	1.65	1.7	6	6.4	10.75	11.65
Number of mixers	1	1	1	1	1	1	1	78
$\$\ \mathrm{kW}^{-1}\mathrm{hr}^{-1}$	.13	.13	.13	.14	.48	.51	.86	.94

5.4.2.1.1 Stepwise Model

The stepwise scenario employed 26 scaling steps and subsequently the greatest number of mixing devices which was also 26. At full capacity, the electric mixer power requirement for the stepwise scenario was determined to be 940 kW. Culture agitation requires the electric mixers to operate 24 hr d^{-1} resulting in a total of 22,560 kWh d^{-1}. The total electric mixer power cost was \$10,100,000 which resulted in an average daily power requirement of 17,450 kWh d^{-1}. The average daily power requirement is less than the power requirement when the facility is at full capacity. This is due to the time delay between items as well as the model initialization period.

5.4.2.1.2 Volume Batching Model

The volume batching scenario utilized 22 scaling steps resulting in an electric mixer power requirement of 13,920 kWh d^{-1} at full capacity. The volume batching scenario total power cost for electrical mixers was $2,740,000, which resulted in an average daily power requirement of 4733 kWh d^{-1}. The average daily mixer power requirement is significantly less than the mixer power requirement when the facility is at full capacity. This was characteristic of a greater TBI yielded by the volume batching process as well as the model initialization period.

5.4.2.1.3 Intense Culturing Model

The intense culturing scenario employed 19 scaling steps, thus requiring only 19 mixing devices. At full capacity, the electric mixer power requirement was calculated to be 22,560 kWh d^{-1}. The total cost for electric mixer power consumption was $11,100,000, which resulted in an average daily power requirement of 19,175 kWh d^{-1}. The average daily power requirement was less than the mixer power requirement at full capacity. This was a product of the TBI and the model initialization period.

5.4.2.1.4 Comparison of the Three Scenarios

The volume batching scenario yielded the least power requirement for electric mixers compared to the other scenarios. This was because of the elimination of 2 starvation ponds that reduced the number of 40 hp electric mixers from 78 to 46 mixers. Even though the intense culturing scenario yielded the least number of scaling stages, the highest daily average power requirement was observed. FPR's were incorporated into the medium raceway scale which required more electrical power for culture agitation compared to open raceways. Also, the 7 scaling stages that were eliminated in the intense culturing scenario employed smaller mixers which had lower power requirements.

The intense culturing scenario and stepwise scenario required 78 electric mixers. These electric mixers contributed significantly to the amount of power required for culture agitation. Therefore, the intense culturing scenario yielded the greatest power requirement for electric mixers. Considering that the microalgae culture must be circulated 24 h d^{-1} to prevent settling, one way to reduce mixing costs is to employ more efficient mixers. Also, mixing costs may be reduced by developing more efficient strains of microalgae that require less agitation.

5.4.2.2 Power, Harvesting

Harvesting was achieved through the utilization of disc-bowl centrifuges which yielded a solids concentration of 10%. The centrifuges considered for this analysis have a throughput capacity of 900 hl h^{-1} (ALFA, 2010). The power requirement for the specified throughput is 100 kW (ALFA, 2010). Each harvesting event resulted in a total processing volume of 9,866,752 L of microalgae culture at a concentration of 1 g L^{-1}. The total electrical cost for harvesting was calculated by multiplying the number of centrifuges by the electrical demand of 100 kW. This resulted in the total hourly kW demand for the centrifuges. This figure was then multiplied by the conversion factor of 24 h d^{-1} and the electrical cost of $.0804 kWh^{-1}.

5.4.2.2.1 Stepwise Model

The stepwise scenario required three centrifuges for a total of processing rate of 270,000 L hr^{-1}. Each item that was harvested had a total volume of 9,866,752 L, which resulted in a power requirement of 10,965 kWh.

5.4.2.2.2. Volume Batching Model

The volume batching scenario employed one centrifuge for a total processing rate of 90,000 L hr^{-1}. The utilization of one centrifuge was sufficient for harvesting as the volume batching scenario yielded fewer items and a greater TBI. The total power requirement for harvesting was determined to be 10,965 kWh for each item.

5.4.2.2.3 Intense Culturing Model

The intense culturing scenario utilized three centrifuges for a total processing rate of 270,000 L hr^{-1}. This resulted in a power requirement of 10,965 kWh for each item.

5.4.2.2.4 Comparison of the Three Scenarios

The stepwise and intense culturing scenarios utilized three centrifuges for the harvesting activity while the volume batching scenario required only one centrifuge. Even though the number of centrifuges for each model was variable, the total power requirement was the same for each scenario resulting in a total harvesting power cost of

\$880 for each item. Evaporation may be able to reduce the operational costs of the centrifuges. Considering an average evaporation rate of 0.84 cm d^{-1}, if water is not added for two days leading up to harvesting, the harvesting volume could be reduced by an average of 1,644,460 L. Reducing the amount of water through evaporation would increase the microalgae solids concentration through centrifugation. Considering an average harvesting volume reduction of 1,644,460 L, the solids concentration after centrifugation could be increased by 20% or 12 g L^{-1}. However, the harvesting cost would only be decreased by \$150 $item^{-1}$.

5.4.2.3 Power, Water Supply

Power for the water supply was based on the volume of water required for raceway inoculation as well as evaporation rates. As batches of microalgae progress through the models, each raceway is filled with a volume of water equal to the inoculation transfer volume. For this analysis, water discharged from the harvesting process was recycled. The water discharge would be conveyed to a holding pond and would be utilized for reuse in the culturing process. It was assumed that nutrients would be depleted at the end of the starvation period resulting in no nutritional cost benefit from recycling water. However, this is an area that requires more research because of the uncertainty of regulations and implications that may arise from continuously recycling water.

Evaporation is a major concern for any microalgae facility, considering that facilities would be located in arid regions. Evaporation rates in these regions can cause excessive water losses, which would need to be replenished daily. The model parameter for evaporation selected by Neenan et al. (1986) was 0.0022-0.01 m d^{-1} to determine the net evaporation in microalgae culture systems located in the Southwest. This was a conservative estimate of net evaporation in mass culture facilities. As stated previously, microalgae raceways located in Texas can sometimes exceed evaporation rates of 1.57 cm d^{-1}. Monthly average evaporation rates for Pecos, Texas were analyzed to acquire evaporation data indicative of arid regions located in Texas. These monthly evaporation rates were incorporated into the model to determine seasonal evaporation costs.

Water supply power costs were determined by analyzing water conveyance costs associated with irrigation of conventional crops. According to Amosson et al. (2001), variable pumping costs were based on a natural gas price of \$75.88 m^{-3}; lubrication, maintenance and repairs were 65% of the fuel cost; and labor cost to operate a system was assessed at \$8.00 h^{-1}. Amosson et al. (2001) determined total variable costs for a subsurface irrigation system (SDI) with a well depth of 168 m to be \$6.13. In 2009, the Texas average cost of natural gas for industrial users was \$114.24 m^{-3} (EIA, 2010). The updated variable cost for water supply, based on the report by Amosson et al. (2001) was determined to be \$1030 ha m^{-1}. This results in a total operational water supply cost of \$0.37 for each 3785 L.

According to the study by Benemann and Oswald (1996), the electrical demand for mixing, harvesting, water supply and other was \$1870 ha^{-1} yr^{-1}. The cost of electricity in 1994 was \$0.065 kWh^{-1}, from which it was estimated that represented an electricity requirement of 28,770 kWh ha^{-1} yr^{-1}. According to EIA (2009), the average retail price of electricity for industrial customers in the state of Texas was \$0.0804 kWh^{-1}. This rate was used to update Benemann and Oswald (1996) cost to \$2315 ha^{-1} yr^{-1}.

5.4.2.3.1 Stepwise Model

The stepwise scenario power cost for water supply was determined to be \$1,675,145. The total amount of water required for culturing was calculated to be approximately 1690 ha-m. Evaporation accounted for 65% of the total amount of water required for the stepwise scenario. The total power cost for each item exiting the stepwise culturing scenario was calculated to be \$1950 or \$2620 ha^{-1} yr^{-1}.

5.4.2.3.2 Volume Batching Model

The volume batching scenario power cost for water supply was tabulated to be \$450,220, resulting in a total volume of 455 ha-m. The volume batching process yielded fewer items compared to the other scenarios resulting in a reduced total volume of water required for microalgae culturing. For each item exiting the volume batching scenario, the power cost for water supply was tabulated to be \$2065 for each item or \$1185 ha^{-1} yr^{-1}.

5.4.2.3.3 Intense Culturing Model

The intense culturing scenario power cost for water supply was calculated to be \$1,729,300 which resulted in a total volume of 1750 ha-m. The intense culturing scenario yielded the greatest water requirement which was characteristic of a greater model throughput. The total power cost for water supply for each item exiting the intense culturing scenario was determined to be \$1980 item^{-1} or \$2700 ha^{-1} yr^{-1}.

5.4.2.3.4 Comparison of the Three Scenarios

The volume batching scenario yielded the lowest water requirement which was characteristic of a reduced item throughput compared to the other scenarios. The intense culturing scenario yielded the greatest water requirement; however, the volume batching scenario produced the greatest power cost for each item. This was because of reduced model throughput coupled with seasonal evaporation rates. The volume batching scenario water requirements attributed to evaporation increased to 67% which suggests that items were processed when evaporation rates were greater. Also, the reduced model throughput exhibited by the volume batching scenario would affect the overall average evaporation rate compare to the other scenarios. Even though the total water requirement for each facility was different, the power cost of water supply for each item was similar.

5.4.2.4 Power Supply, Other

According to Benemann and Oswald (1996), the cost of other power supply requirements, updated to 2009 costs, was \$360 ha^{-1} yr^{-1}. Other power supply requirements include buildings and laboratories as well as other unanticipated sources. The cost of \$360 ha^{-1} yr^{-1} is the other power supply operational cost considered for this analysis for both the base case and potential best case assumptions.

5.4.2.5 Nutrients

Nutrients play an essential role in the culturing of microalgae. Like many other agricultural commodity crops, nutrients derived from fertilizers are required for proper plant growth. The total cost of a liter of laboratory media was \$0.07 L^{-1}, while outdoor raceway media costs were \$0.0043 L^{-1}. Media for starvation ponds was calculated to be \$0.0041 L^{-1}. Nutrient costs were tracked through the model by multiplying the culture transfer volume for each scaling step by the cost L^{-1} of media. The nutrient costs of nitrogen (N), phosphorus (P), and iron (Fe) reported by Benemann and Oswald (1996) was \$1485 ha^{-1} for a productivity of 30 g m^{-2} d^{-1}. However, this system was developed to reuse the nutrient solution after centrifugation, reducing the fertilizer cost. This analysis does not consider nutrient reuse. It was assumed that if nutrients were added in optimal quantities during cultivation, water recycling would include negligible amounts of nutrients.

5.4.2.5.1 Stepwise Model

The stepwise scenario nutrient cost was determined to be \$88,700,000 which resulted in a total cost of \$103, 380 for each item exiting the model.

5.4.2.5.2 Volume Batching Model

The volume batching scenario nutrient cost was calculated to be \$22,500,000 yielding a total cost of \$103,210 for each item.

5.4.2.5.3 Intense Culturing Model

The intense culturing scenario nutrient cost was tabulated to be \$90,100,000 which resulted in a total cost of \$102,855 for each item exiting the model.

5.4.2.5.4 Comparison of the Three Scenarios

The intense culturing scenario yielded the greatest total nutrient cost which was indicative of a greater model throughput. However, the stepwise model produced the greatest nutrient cost for each item exiting the model. This was because of the employment of all 26 scaling steps in the stepwise scenario. The model structure of the nutrient cost calculation was based on transfer volume and was not subject to any stochastic variables such as seasonal growth rates. Therefore as scaling steps were eliminated in the volume batching and intense culturing scenarios, the nutrient cost was reduced for each item. The nutrient cost on a L^{-1} basis of microalgae solution exiting the large raceway scale of each scenario was \$0.0043. However, as items exited the starvation scale, the nutrient cost increased to \$0.01 L^{-1}. Thus the base case starvation period of 21 d increased the nutrient cost.

5.4.2.6 CO_2

The daily amount of CO_2 determined through mass balance resulted in a ratio of 1.467 g CO_2 to produce 1 g of biomass dry weight (DW). Since this ratio doesn't include atmospheric CO_2, it was assumed that the CO_2 transfer efficiency would be 100%, resulting in no extra costs above the required amount. The commercial cost of CO_2

reported by Benemann et al. (1982) was \$100 t^{-1} and the report by Benemann and Oswald (1996) utilized a cost of \$66 t^{-1}(both costs updated to \$ 2009). A cost of \$66 t^{-1} of carbon dioxide was considered for this analysis and was used to calculate the total cost of CO_2 for both the base case and potential best case assumptions. The Benemann and Oswald (1996) analysis concluded that CO_2 costs were \$12,210 ha^{-1} for a productivity of 30 g m^{-2} d^{-1}. The costs reported by Benemann and Oswald (1996) are comparable to this analysis. If each scaling scenario were to operate 360 d^{-1} yr^{-1} with a productivity of 37 g m^{-2} d^{-1}this would result in a cost of \$12,880 ha^{-1} yr^{-1}. This would be comparable to the Benemann and Oswald (1996) CO_2 requirement of 185 t yr^{-1}.

5.4.2.6.1 Stepwise Model

The stepwise scenario total CO_2 costs were calculated to be \$2,300,000 or \$2680 for each item exiting the model.

5.4.2.6.2 Volume Batching Model

The volume batching scenario total CO_2 costs were determined to be \$623,000 which resulted in a cost of \$2860 for each item.

5.4.2.6.3 Intense Culturing Model

The intense culturing scenario total CO_2 costs were tabulated to be \$2,360,000 which yielded a cost of \$2700 for each item exiting the model.

5.4.2.6.4 Comparison of the Three Scenarios

The intense culturing scenario yielded the greatest total CO_2 cost. The volume batching scenario yielded the greatest CO_2 cost of \$2700 item^{-1}. The increased cost on a per item basis was attributed to variable CO_2 consumption rates which were derived from seasonal growth rates. However, this cost increase was minute compared to the CO_2 costs determined for the stepwise and intense culturing scenarios.

5.4.2.7 Labor

Large scale microalgae facilities were assumed to follow the same labor laws as agricultural operations. Labor demands for the stepwise, volume batching, and intense culturing scenarios were based on time delays for contamination events, culture transfer, raceway/mixer maintenance, and culture sampling. Employees that would receive salaries included 1 plant engineer and 1 administrator for a total cost of \$100,000 yr^{-1}. Three labor resources were identified which had different educational backgrounds and subsequently different pay scales. The hourly wage rate was assumed to be \$15 hr^{-1} for Laboratory Labor, \$12.50 hr^{-1} for H.S. Labor and \$10 hr^{-1} for M. Labor. For a contamination event, another labor resource was considered dubbed Contract Labor. This labor resource was independent of the facility and was called upon to clean raceways for a contamination event. This labor resource was assumed to encompass 12 laborers for a total cost of \$120 hr^{-1}. Also, an overhead cost of 50% of direct labor is considered for this analysis.

The reported labor and overhead by Benemann and Oswald (1996) was \$4950 ha^{-1}, which included a 50% overhead expense of direct labor. The production labor cost reported by Benemann (1982) was \$6505 ha^{-1} of total facility size. These labor costs included annual salary requirements for 1 plant engineer, 4 shift supervisors, 20 pond operators, 8 secondary harvesting operators, 8 processing operators and 2 laboratory operators for a 1000 ha facility. Additional overhead expenses of 75% of direct labor were included in the final production labor costs for the facility. These labor requirements were consistent with a highly automated facility. The labor costs determined by this analysis are significantly higher than the reported values. The labor required by the stepwise, volume batching, and intense culturing scenarios were attributed to the lack of facility automation. Therefore, facility automation is an important consideration for reducing labor costs.

5.4.2.7.1 Stepwise Model

The stepwise scenario total labor cost was calculated to be \$5,100,000 or \$5945 for each item exiting the model. The total cost for laboratory labor, H.S. labor and manual labor was \$1,930,000, \$534,000 and \$639,000, respectively. Labor costs for a facility manager and administrative assistant was constant for each model with a total cost of \$2,000,000.

5.4.2.7.2 Volume Batching Model

The volume batching scenario yielded a total labor cost of \$2,981,000 or \$13,674 for each item exiting the model. The total cost for laboratory labor, H.S. labor and manual labor was \$474,000, \$334,000 and \$173,000. Facility managerial and administrative costs were \$2,000,000.

5.4.2.7.3 Intense Culturing Model

The intense culturing scenario total labor cost was determined to be \$3,730,000 or \$4260 for each item exiting the model. The total cost for laboratory labor, H.S. labor and manual labor was \$698,000, \$534,000 and \$494,000. \$2,000,000 was also included in the total labor costs.

5.4.2.7.4 Comparison of the Three Scenarios

The intense culturing scenario yielded the least total laboratory labor cost of \$800 item^{-1}. The stepwise scenario produced the greatest total laboratory labor cost of \$2250 item^{-1}. The stepwise scenario laboratory labor was increased from 1 to 2 laborers as the utilization of one laborer was calculated to be 69%. The only consideration for laboratory labor in the medium scale, large scale, and starvation ponds was culture sampling and testing. The stepwise scenario employed 26 scaling steps, increasing the labor costs associated with culture sampling and testing. Therefore, the increased number of laboratory laborers coupled with 26 scaling steps resulted in a greater laboratory labor cost for the stepwise scenario.

The stepwise and intense culturing scenarios yielded similar total H.S. labor costs of \$625 and \$610 item^{-1}. The volume batching scenario produced the greatest total H.S. labor cost of \$1530 item^{-1}. The increased total H.S. labor cost determined by the volume batching scenario was indicative of a longer harvesting period compared to the other models. The volume batching scenario TBI was greater compared to the other two models requiring the utilization of one centrifuge. This increased the harvesting duration by 3 times resulting in a greater total H.S. labor cost. The stepwise and volume batching scenarios produced similar total manual labor costs of \$730 and \$790 item^{-1}. The intense culturing scenario yielded the least total manual labor cost of \$575 item^{-1}. This cost reduction was attributed to the elimination of 7 scaling steps compared to the stepwise scenario.

5.4.2.8 Maintenance, Tax, Insurance

Maintenance, Tax, and Insurance were reported to have a total cost of 5% of the capital costs (Benemann and Oswald, 1996). Likewise; maintenance, tax and insurance costs for this analysis were calculated utilizing a 5% capital cost factor. This capital cost factor was utilized for each model.

5.4.2.9 Contamination

Contamination costs were calculated separately as contaminated items were structured to exit the models separately from non-contaminated items. Similar to the non-contaminated items, operational costs for each contaminated item exiting the models were summed together. The total operational costs derived from contamination are depicted in Table 34. Contaminated items exited the models before harvesting therefore; the operational cost item for harvesting power yielded a cost of \$0.00. The operational cost item for other power also produced a value of \$0.00 as this cost was based on a \$ ha^{-1} basis. The total volume of contaminated algae was 40,719,015 L, 3,480 L and 30,525,564 L for the stepwise, volume batching and intense culturing scenarios.

Table 34. Base case total operational costs of contamination (2011\$).

Operating Cost Items	Stepwise Scaling	Volume Batching	Intense Culturing
Power, Mixing	\$10,710	\$0.43	\$9,175
Power, Harvesting	\$0	\$0	\$0
Power, Water Supply	\$4,295	\$0.55	\$2,450
Power, Other	\$0	\$0	\$0
Nutrients	\$109,800	\$21.6	\$64,265
CO2	\$2,415	\$0.04	\$1,415
Labor	\$208,165	\$1,100	\$156,215
Total Net Operating Costs	\$335,385	\$1,123	\$233,520

5.4.2.9.1 Stepwise Model

The stepwise scenario yielded a total of 18 contaminated items, 9 of which occurred in the large raceway and starvation pond levels. The overall contamination cost was \$18,630 $item^{-1}$.

5.4.2.9.2 Volume Batching Model

The volume batching scenario yielded a total of 2 contaminated items occurring in the medium raceway level. Therefore, the reduced raceway volume in the medium level resulted in a lower contamination cost of \$560 item^{-1}.

5.4.2.9.3 Intense Culturing Model

The intense culturing scenario produced a total of 7 contaminated items which transpired in the large raceway and starvation pond levels. The resulting overall contamination cost was determined to be \$33,360 item^{-1}.

5.4.2.9.4 Comparison of the Three Scenarios

The intense culturing scenario yielded the greatest overall contamination cost and was attributed to the larger volume of each contaminated item compared to the other models. The volume batching scenario exhibited the least cost derived from contamination however; the contamination events occurred in early scaling steps resulting in a lower contaminated volume. The stepwise scaling scenario generated the greatest contamination volume between the three models and subsequently the greatest total contamination costs. The largest contamination cost item for each model was labor while nutrients were the second greatest cost. The overall cost of contamination was dependent upon the volume of each contaminated item as greater contaminated volumes incurred greater costs. The present value (2011\$) of the total capital and operational costs for each scenario are displayed in Table 35.

Table 35. Summary of total costs (2011$).

	Stepwise	Volume Batching	Intense Culturing
Capital Costs	$38,413,385	$13,981,205	$38,525,395
Operating Costs	$111,708,115	$30,875,303	$112,764,680
Total Costs	$150,121,500	$44,856,510	$151,290,075

Total microalgae oil and LEA production yielded by each scenario is listed in Table 36. Items exiting each model had a final volume of 9,866,752 L at a concentration of 1 g L^{-1}. The intense culturing scenario productivity was the greatest, but was not significantly higher compared to the stepwise scenario. The volume batching scenario yielded the lowest raceway production compared to the other scaling scenarios. The microalgae bio-oil yield was tabulated based on model throughput and an assumed lipid production of 30%. Microalgal biomass derived from lipid extraction was also considered and was assumed to be 70% of model throughput.

Table 36. Total production.

Model	Duration (d)	Raceway Production (L)	Oil yield (L)	LEA yield (t)
Stepwise	7200	8,465,673,216	2,821,891	5926
Volume Batching	7200	2,121,351,680	707,117	1485
Intense Culturing	7200	8,623,541,248	2,874,514	6036

Model output and total facility costs were utilized to calculate the unit costs ($ g^{-1} DW $ L^{-1}) of bio-fuel and unit costs per metric tonne of LEA derived from bio-fuel conversion. The cost for one kg of LEA produced from the stepwise, volume batching and intense culturing scenarios were \$14.4, \$17.4, and \$14.3, respectively. The resulting costs are reported in Table 37.

Table 37. Cost of production (2011$).

Model	(\$ / kg DW of algae)	(\$ bbl^{-1} of bio-oil)	(\$ / t DW of LEA)
Stepwise	\$14.4	\$6,760	\$20,290
Volume batching	\$17.4	\$8,195	\$24,580
Intense culturing	\$14.3	\$6,685	\$20,060

The cost L $^{-1}$ of microalgae oil was based on the amount of oil contained in the microalgae feedstock. Therefore, the cost of converting this oil into a bio-fuel is not included. The cost L^{-1} of microalgae oil was similar for both the stepwise and intense culturing scenarios, suggesting that the implementation of the FPR level in the intense culturing model is not advantageous from a cost perspective. However, the cost of microalgae bio-oil for each model is very high compared to current crude oil prices. Therefore, the base case scenario production of microalgae for bio-fuel is currently not cost competitive with crude oil prices.

5.4.3 Potential Best Case Capital and Operational Costs

A potential best case scenario was conducted which reduced the culturing duration from an average of 8.43 d in the base case scenario to a constant culturing duration of 2 d. The potential best case assumptions yielded 2338, 291, and 2365 items for the stepwise, volume batching and intense culturing scenarios, respectively. Capital and operational costs for each scaling scenario of the potential best case assumptions are reported in Tables 38 and 39.

Table 38. Best case capital costs (2011$).

Capital Cost Items	Stepwise Scaling ($/ha)	Volume Batching ($/ha)	Intense Culturing ($/ha)
Land costs	$4,625	$4,625	$4,625
Site preparation	$1,475	$1,475	$1,475
Raceway levees and dividers	$135	$135	$135
Raceway leveling	$1,060	$1,060	$1,060
Sump construction	$11,875	$11,220	$10,776
Pond liner (HDPE)	$57,000	$57,000	$57,000
Mixing (Electric Mixers)	$133,055	$127,508	$125,585
Water supply, distribution	$11,775	$11,775	$11,775
Nutrient storage / distribution (culture)	$18,490	$18,490	$18,490
CO2 storage / distribution	$59,800	$59,800	$59,800
Harvesting	$21,495	$21,495	$21,495
Building, roads, drainage and other	$3,295	$3,295	$3,295
Electrical supply	$3,300	$3,300	$3,300
Machinery	$1,500	$1,500	$1,500
FPR	$0	$0	$5,873
Sub Total / ha	$328,880	$322,680	$326,185
Eng. And Conting.	$16,445	$16,135	$16,310
Total Direct Capital	$345,325	$338,810	$342,495
Working Capital 25% Op.Cost	$65,426,505	$8,772,995	$66,905,430
Total Capital Investment	$76,476,875	$15,210,420	$76,780,600

5.4.3.1 Comparison of the Three Scenarios

In comparing the capital costs between the three scenarios, the volume batching total capital investment was significantly reduced compared to the stepwise scaling and intense culturing scenarios. The volume batching process batched items together thereby reducing model throughput. Capital costs were not incurred for 13 ha of starvation ponds, compared to the other scenarios, which reduced the total capital costs of the volume batching scenario. The stepwise culturing yielded the greatest capital cost ha^{-1}. However, the intense culturing scenario produced the highest total capital cost which was attributed to a greater model throughput, increasing the working capital cost item.

Table 39. Best case total operational costs (2011$).

Operating Cost Items	Stepwise	Volume Batching	Intense Culturing
Power, Mixing	$7,900,000	$988,000	$8,540,000
Power, Harvesting	$2,160,000	$270,000	$2,190,000
Power, Water Supply	$1,403,100	$173,300	$1,399,400
Power, Other	$230,400	$136,800	$228,600
Nutrients	$242,000,000	$30,200,000	$244,000,000
CO2	$1,680,000	$208,000	$1,700,000
Labor	$5,780,000	$2,794,000	$5,110,000
Maint. Tax, Ins (5% of Capital)	$552,518	$321,871	$543,710
Total Net Operating Costs	$261,706,020	$35,091,970	$263,711,710
Capital Charge (5%)	$3,823,845	$760,520	$3,840,105
Total Operating Costs	$265,963,670	$35,852,490	$267,551,815

5.4.3.2 Total Cost Comparison of the Three Scenarios

The stepwise scenario yielded a total operating cost of $265,963,670 or $113,755 $item^{-1}$. The volume batching scenario total operating costs were $35,852,490 or $123,205 $item^{-1}$. The intense culturing model produced a total operating cost of $267,460,690 or $113,090 $item^{-1}$. The total operational costs for each item were similar for both the stepwise and intense culturing scenarios. Therefore, each operational cost was comparable for both models. The volume batching scenario yielded the greatest total operational cost of $123,205 $item^{-1}$. The increased total operational cost was attributed to labor costs. As stated in the base case section of this paper, there was a $2,000,000 labor cost consideration for facility management and administration over the life of the facility. This resulted in a labor cost of \$9500 item $^{-1}$ compared to a cost of approximately \$2500 item $^{-1}$ for both the stepwise and intense culturing scenarios.

5.4.3.2.1 Comparison of the Base and Best Cases for the Stepwise and Intense Culturing Models

In comparing operational costs between the base case and potential best case scenarios, some operational cost items increased while others decreased. The operational costs for harvesting power, H_2O power, nutrients and labor increased in the best case for both the stepwise and intense culturing scenarios. However operational costs for mixing power and CO_2 decreased.

The increase for harvesting power was characteristic of a greater model throughput for the best case assumptions of both the stepwise and intense culturing models. Even though the starvation period was reduced, H_2O power costs increased which was also attributed to a significant model throughput compared to the base case assumptions. Nutrient costs increased which was also characteristic of a greater model output. Labor costs increased which was a product of a greater model throughput, an increased number of contamination events, greater labor resource requirements for culture sampling and analyzing, culture transfer, and harvesting.

Operational costs for mixing power in the best case assumptions were reduced as the electric mixers incurred greater downtime. The base case stepwise scenario average culturing duration for the medium and large raceway levels was 8.43 d while the potential best case was 2.1 d. Therefore, mixer downtime for any scaling step could be calculated. The resulting base case mixer downtime for the medium and large raceway levels was calculated to be approximately 45 d while the potential best case was determined to be 2295 d. Therefore, the electric mixers in the potential best case assumptions incurred more total down time which reduced mixer operating costs.

5.4.3.2.2 Contrast of the Base and Best Case Volume Batching Model Assumptions

The volume batching scenario operational costs items that increased included: power for harvesting and nutrients. Operational costs items that decreased were power for mixing, power for H_2O, CO_2 and labor costs.

The operational cost increase for harvesting and nutrients was attributed to the increased model throughput compared to the base case assumptions.

The reduced operational cost for mixing power was characteristic of a greater mixer downtime compared to the base case assumptions. The reduced CO_2 and H_2O cost were mainly credited to a reduced starvation period coupled with a greater time between items (TBI). The H_2O volume required for culture dilution increased from the base case assumptions volume of 215 ha m to 288 ha m for the potential best case assumptions. This was representative of a greater model throughput exhibited by the potential best case assumptions. However, the amount of H_2O required to compensate for evaporation decreased from a volume of 433 ha m in the base case assumptions to a volume of 146 ha m for the potential best case assumptions. This decreased evaporation volume was characteristic of a shorter starvation period compared to the base case assumptions. The reduced operating cost for labor was derived from a reduced laboratory labor requirement compared to the base case assumptions. Reducing the starvation period reduced the laboratory labor requirement for culture sampling and analyzing. This coupled with a marginal model throughput compared to the other potential best case scenarios resulted in a reduced labor cost.

5.4.3.3 Contamination

Culture contamination was considered in the potential best case assumptions utilizing a probability of 0.001. Model throughput was increased compared to the base case assumptions, which resulted in a greater number of contamination events. The total volume of contaminated microalgae culture was 55,145,315 L, 11,115,056 L and 44,343,016 L for the stepwise, volume batching and intense culturing scenarios. The total operational costs are listed in Table 40.

Table 40. Best case total contamination operational costs (2011$).

Operating Cost Items	Stepwise Scaling	Volume Batching	Intense Culturing
Power, Mixing	$6,135	$1,754	$8,450
Power, Harvesting	$0	$0	$0
Power, Water Supply	$3,920	$1,225	$2,330
Power, Other	$0	$0	$0
Nutrients	$141,200	$45,495	$91,265
CO2	$955	$302	$350
Labor	$281,595	$65,575	$227,800
Total Net Operating Costs	$433,805	$114,351	$330,195

5.4.3.3.1 Stepwise Model

The stepwise scenario yielded a total of 41 contaminated items, 26 of which occurred in the large raceway and starvation pond levels. The resulting overall contamination cost was calculated to be \$10,330 item^{-1}.

5.4.3.3.2 Volume Batching Model

The volume batching scenario yielded a total of 7 contaminated items resulting in a contamination cost of \$16,335 item^{-1}. The increased contamination cost was representative of a greater number of contamination events occurring in the large raceway and starvation pond levels.

5.4.3.3.3 Intense Culturing Model

The intense culturing scenario produced a total of 21 contaminated items which emerged in the large raceway and starvation pond levels. The resulting overall contamination cost was determined to be \$15,723 item^{-1}.

5.4.3.3.4 Comparison of the Three Scenarios

The volume batching scenario yielded the greatest total average contamination cost and was attributed to a greater number of contamination events occurring in the large raceway and starvation pond scale. The stepwise scaling scenario exhibited the least cost for contamination. The stepwise scaling scenario yielded the greatest contamination volume between the three models. The largest contamination cost item for each model was labor while nutrients were the second greatest cost. The overall cost of contamination was dependent upon the volume of each contaminated item as greater contaminated volumes incurred greater costs. The stepwise scaling scenario yielded the greatest contamination volume of 55,145,313 L and subsequently the greatest total contamination operational cost of $433,805.

5.4.3.3.5 Comparison of the Base Case and Potential Best Case

The base case intense culturing scenario yielded the greatest overall contamination cost while the potential best case volume batching model produced the greatest overall contamination cost. The base case volume batching scenario generated the least contamination cost and the potential best case assumptions stepwise scaling scenario yielded the least contamination cost. The largest contamination cost item for both the base case and potential best case assumptions was labor while nutrients were the second greatest cost. Again, the overall cost of contamination was dependent upon the volume of each contaminated item as greater contaminated volumes incurred greater costs. Total capital and operational costs for each scenario are displayed in Table 41.

Table 41. Summary of best case total costs (2011$).

	Stepwise	Volume Batching	Intense Culturing
Capital Costs	$76,476,875	$15,210,420	$76,802,100
Operating Costs	$265,963,670	$35,966,845	$267,882,010
Total Costs	$342,874,350	$50,177,260	$344,570,485

Decreasing the culturing duration and increasing the time between item arrivals (TBA) increased model throughput for each potential best case scaling scenario. The intense culturing scenario yielded the greatest volume of microalgae culture compared to the other scenarios. However; this increase was not significant compared to the stepwise scenario output. The resulting model throughput volumes are displayed in Table 42. The oil yield was tabulated based on an assumed lipid production of 50%. Likewise, the LEA yield was assumed to be 50% and was a secondary product derived from lipid extraction.

Table 42. Best case total production.

Model	Duration (d)	Raceway Production (L)	Oil yield (L)	LEA yield (t)
Stepwise	7200	23068466176	12815815	11534
Volume Batching	7200	2871224832	1595124	1436
Intense Culturing	7200	23334868480	12963816	11668

The overall cost of production derived from the best case was determined to be \$12 kg^{-1} DW, \$14.7 kg^{-1} DW, and \$11.9 kg^{-1} DW for the stepwise, volume batching and intense culturing scenarios, respectively. These costs are reduced compared to the results obtained from the base case. The resulting costs are depicted in Table 43.

Table 43. Best case total production costs (2011$).

Model	(\$ kg^{-1} DW)	(\$ bbl^{-1} of bio-oil)	(\$ t^{-1} DW of LEA)
Stepwise	\$12.0	\$3,375	\$23,185
Volume batching	\$14.7	\$4,140	\$28,530
Intense culturing	\$11.9	\$3,360	\$23,060

5.4.4 What If Analysis

In evaluating the capital and operational costs produced by the base case and potential best case assumptions, several costs were identified that would need to be decreased in order for microalgal biomass to be a feasible feedstock for bio-fuel production. Capital costs considered for reduction included electric mixers and sumps, piping infrastructure for nutrient and culture conveyance between ponds and pond liners. Culture agitation may require the implementation of a natural energy source such as wind power in order to maintain production and reduce costs. Likewise, the removal of electric mixers would result in the elimination of the sump costs. Another consideration for reducing capital costs included the utilization gravity flow for nutrients and culture conveyance between the raceways. This would reduce the pumps and piping infrastructure costs dedicated for culture conveyance between raceways. Pond liners may also be eliminated, as it is possible to successfully culture microalgae in natural earthen raceways. Table 44 summarizes the total capital costs determined for the what-if analysis.

Operational costs that could be reduced include power for electric mixers, nutrients, CO_2, and contamination costs. Power costs for electric mixers were eliminated as the mixers were discarded from the capital cost section. In order to achieve economic feasibility, nutrients and CO_2 would both need to be obtained at no cost. Nutrient requirements may be able to be satisfied by utilizing some type of animal waste stream characteristic of an agricultural operation. CO_2 may be able to be attained from power plant flue gas. Typical power plant flue gases have carbon dioxide levels ranging from

10%-15%. These cost considerations outlined above were reduced to a value of $0.00 and are reported in Tables 44 and 45. Likewise, the power for other operational cost item was increased by 10%. Culture contamination was considered to be non-existent resulting in no operational costs dedicated to contamination events. Total operational costs are reported in Table 45.

Table 44. What if analysis capital costs (2011$).

Capital Cost Items	Stepwise ($ ha^{-1})	Volume Batching ($ ha^{-1})	Intense Culturing ($ ha^{-1})
Land costs	$4,625	$4,625	$4,625
Site preparation	$1,475	$1,475	$1,475
Raceway levees and dividers	$135	$135	$135
Raceway leveling	$1,060	$1,060	$1,060
Sump construction	$380	$380	$380
Pond liner (HDPE)	$0	$0	$0
Mixing (Electric Mixers)	$0	$0	$0
Water supply, distribution	$11,775	$11,775	$11,775
Nutrient storage / distribution (culture)	$8,820	$8,820	$8,820
CO2 storage / distribution	$59,800	$59,800	$59,800
Harvesting	$21,495	$21,495	$21,495
Building, roads, drainage	$3,295	$3,295	$3,295
Electrical supply	$3,300	$3,300	$3,300
Machinery	$1,500	$1,500	$1,500
FPR	$0	$0	$5,873
Sub Total / ha	$117,660	$117,660	$123,535
Eng. And Conting.	$5,885	$5,883	$6,180
Total Direct Capital	$123,545	$123,545	$129,710
Working Capital 25% Op.Cost	$2,442,790	$872,870	$2,450,585
Total Capital Investment	$6,396,170	$3,220,185	$6,568,880

Table 45. What if analysis operational costs (2011$).

Operating Cost Items	Stepwise Scaling	Volume Batching	Intense Culturing
Power, Mixing	$0	$0	$668,416
Power, Harvesting	$2,160,000	$270,000	$2,190,000
Power, Water Supply	$1,403,100	$173,300	$1,399,400
Power, Other	$230,400	$136,800	$228,600
Nutrients	$0	$0	$0
CO2	$0	$0	$0
Labor	$5,780,000	$2,794,000	$5,110,000
Maint. Tax, Ins (5% of Capital)	$197,670	$117,370	$205,915
Total Net Operating Costs	$9,771,170	$3,491,470	$9,802,330
Capital Charge (5%)	$319,810	$161,010	$328,445
Total Operating Costs	$10,090,980	$3,652,475	$10,130,775

The resulting total costs and total annual costs for each model are displayed in Table 46. Compared to the best case assumptions, total costs were reduced by 95%, 86%, and 95% for the stepwise, volume batching and intense culturing scenarios, respectively. Reducing the previously stated capital and operational cost items significantly reduces the total costs determined through the best case assumption.

Table 46. What if analysis summary of total costs (2011$).

	Stepwise	Volume Batching	Intense Culturing
Capital Costs	$6,396,170	$3,220,185	$6,568,880
Operating Costs	$10,090,980	$3,652,475	$10,130,775
Total Costs	$16,487,145	$6,872,658	$16,699,650

The cost of bio-oil produced by the what-if analysis for stepwise scaling, volume batching, and intense culturing was reduced to $0.94, $3.97, and $0.95 L^{-1}, respectively. The current price of crude oil is $112.52 $barrel^{-1}$ or $0.71 L^{-1}. The least expensive cost of

$0.74 L^{-1} for microalgae bio-oil determined by the what-if analysis is 105% greater than the current price of crude oil. Crude oil would have to reach a price of over $120 barrel^{-1} in order for microalgal bio-oil to be competitive with crude oil. The resulting what-if analysis production costs are depicted in Table 47.

Table 47. What if analysis cost of production (2011$).

Model	($ kg^{-1} DW)	($ bbl^{-1} of bio-oil)	($ t^{-1} DW of LEA)
Stepwise	$0.60	$117	$412
Volume batching	$2.05	$532	$3,312
Intense culturing	$0.60	$118	$416

5.4.5 Project NPV

To provide future cash risk analysis of the base case assumptions, best case assumptions, and what-if analysis, a Net Present Value (NPV) was calculated. The NPV for each scaling scenario was determined by utilizing equation 16.

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+i)^t} \tag{16}$$

NPV = net present value ($)

n= planning horizon (yr)

t = time period index (yr)

CF_t = cash flow in period t ($)

i = discount rate (%)

The NPV for the base case, best case, and what-if analysis was calculated using a discount rate of 10%. The payback period for the total capital investment was equal to the model duration of 20 years. The subtotal capital costs ha^{-1} were multiplied by the total number of ha for each scaling scenario to determine total capital costs that would be depreciated. These capital costs were depreciated using straight line depreciation method and were assumed to have a salvage value of 1% at the end of the 20 yr period. The working capital, which was included in the capital costs, was subtracted for the first time period and then discounted over the 20 yr period. Appropriately, the discounted working capital cost item was added back in for the last time period.

Even though this analysis was based on the production of microalgae biomass which would be sold to an intermediate biofuel processor, the price at which the biomass would be sold is uncertain. Therefore, to determine the revenue of this facility, two products are considered that would be derived from the microalgae biomass. The first product is microalgae bio-oil. The amount of bio-oil produced from the microalgae biomass was assumed to be 30% DW for the base case and 50% DW for the best case with a density of 0.9 kg L^{-1}. The bio-oil sale price was assumed to be \$0.71 L^{-1}which is based on current crude oil prices (OPN, 2011). The second product that would be produced from the microalgae biomass is protein meal for livestock consumption. It was assumed that 70% and 50% of the microalgae biomass would be LEA and could be utilized as protein meal. According to USDA (2011), the March 2011 average U.S. price of protein meal was \$381 t^{-1}. The resulting NPV values are reported in Table 48.

Table 48. Summary of NPV values.

Scenario	Base Case	Potential Best Case	What-If Analysis
Stepwise	($50,083,950)	($109,939,500)	$7,429,272
Volume batching	($14,310,890)	($16,943,205)	($873,430)
Intense culturing	($50,346,740)	($110,577,085)	$7,503,145

The base case stepwise, volume batching and intense culturing scenarios yielded greatly negative NPV's. The best case produced an even more negative NPV compared to the base case models. The what-if analysis volume batching scenario produced a negative NPV while the stepwise and intense culturing scenarios generated a positive NPV. The positive NPV displayed by the stepwise and intense culturing scenarios suggests that if the cultivation of microalgae were achievable by meeting the outlined capital and operational cost considerations, the utilization of microalgae bio-oil would be competitive with current crude oil prices.

A break-even microalgae bio-oil price was also determined for the base case , best case, and what-if analysis. The break-even microalgae bio-oil price was calculated to display the cost magnitude compared to current crude oil prices. The resulting break-even microalgae bio-oil prices are reported in Table 49.

Table 49. Summary of break-even price of bio-oil L^{-1}.

Scenario	Base Case	Potential Best Case	What-If Analysis
Stepwise	$18.5	$9.30	$0.13
Volume batching	$21.0	$11.3	$1.30
Intense culturing	$18.2	$9.20	$0.13

The base case volume batching scenario generated the greatest break-even microalgae bio-oil price of \$21.0 L^{-1} which is significantly higher than the current crude oil price of 0.71 L^{-1}. The what-if analysis stepwise and intense culturing scenarios displayed the least break-event price of \$0.13 L^{-1} which is lower than the current crude oil price of \$0.71 L^{-1}. This reinforces that the capital and operational cost considerations in the what-if analysis would need to be realized in order for microalgae bio-oil to be competitive with current crude oil prices.

5.5 Conclusion

Through this analysis, those capital costs based on current technological advances and microalgae culturing practices were evaluated and implemented into discrete event microalgae culture scaling models. Operational costs for power requirements, nutrients, CO_2 and labor were tabulated for each model and utilized with the capital costs to determine the total operational cost of each model. The total costs were tabulated for three scaling scenarios and encompassed base case and best case assumptions.

The total costs calculated for the base case and best case assumptions resulted in a negative NPV. The benefits derived for the NPV analysis were based on current crude oil and protein meal prices and suggest that the utilization of microalgae bio-oil is not currently economical. Also, the utilization of LEA for power generation may become more attractive in the future as utility prices will increase. The LEA value for power generation was calculated to be \$0.19 kg^{-1}, assuming that the LEA was 70% of the microalgae biomass, an energy content of 22,000 BTU kg^{-1}, the price of electricity was \$0.15 kWh^{-1} and was combusted in a fluidized bed gasifer with an efficiency of 20% (Appendix C).

A what-if analysis was performed which eliminated or reduced capital and operating costs that contributed greatly to the overall costs under the best case assumptions. Under the What If conditions the stepwise and intense culturing model yielded a positive NPV suggesting that if the reduced capital and operational costs were achievable, the utilization of microalgae bio-oil would currently be economically feasible.

The depletion of non-renewable resources will inevitably cause fossil fuel prices to increase. Thus, the utilization of microalgae for biofuel may become a more feasible option in the future. The continuation of research and advances in technology will reduce the cost of biofuel produced from microalgae. Raceway design, more efficient electric mixers, inexpensive pond liners and higher yielding strains of microalgae with less nutrient requirements are important consideration which could significantly reduce costs. There are also many different considerations in the design of microalgae facilities. Optimizing these designs as well as cultivation techniques require further research for the development of microalgae as a renewable resource for biofuel. Currently, it may be more practical for microalgae facilities interested in generating biomass for bio-fuel production to produce high value products until the cost of crude oil becomes appealing enough to utilize microalgae as a feedstock for bio-fuel.

CHAPTER VI

CONCLUSIONS

Three scaling scenarios were identified and included a stepwise scaling, volume batching and intense culturing process. The total average raceway utilization for both the stepwise and intense culturing models indicated relatively efficient processes for both the base case and sensitivity analysis. The volume batching scenario was an inefficient process compared to the other scenarios. The implementation of FPRs in the intense culturing model did improve overall productivity compared to the other two models. However, the elimination of 7 scaling steps in the intense culturing models did not significantly increase model output compared to the stepwise model for either the base case of sensitivity analysis. Bottlenecks were identified in all models of the base case; however, the volume batching model yielded the fewest bottlenecks. This was because the simultaneous batching of items reduced the total number of items exiting the model. Bottlenecks that occurred within the base case emerged as items progressed between constant and variable culturing durations. Contamination events decreased raceway utilization and increased overall process time delays. Also contamination events yielded the progression of items in the potential best case resulting in temporary bottlenecks in the stepwise and intense culturing models. The harvesting process modeled did not cause any bottlenecks in the overall process for both the base case and potential best case. The total costs were tabulated for three scaling scenarios encompassing a base case and potential best case. The total costs calculated for the base case and potential best case resulted in a negative NPV. A what-if analysis was performed which eliminated or reduced those capital and operating costs contributing greatly to the overall costs determined by the potential best case. Through this analysis the stepwise and intense culturing model yielded a positive NPV suggesting that if the reduced capital and operational costs were achievable, the utilization of microalgae bio-oil would currently be feasible. Nonetheless, the depletion of non-renewable resources will inevitably cause fossil fuel prices to increase. This suggests that the utilization of microalgae for biofuel may become a more feasible option in the future. Currently, it may be more practical for microalgae facilities interested in generating biomass for bio-fuel production to produce high value products until the cost of crude oil becomes appealing enough to utilize microalgae for bio-fuel.

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APPENDIX A

DEVELOPMENT OF DISCRETE EVENT SIMULATION MODELS FOR THE PRODUCTION OF MICROALGAE FOR BIO-FUEL

Model Parameters

There is little in the literature pertaining to culture management for large-scale microalgae facilities. This may be a consequence of proprietary interests as this industry is still in the R&D phase. Accordingly, processes considered for this analysis were derived from culturing practices utilized at the laboratory and pilot scale within Texas AgriLIFE Research algae facilities. Three simulation models were developed which equivocated multiple scaling steps for mass culturing of microalgae. These models were constructed using Extend-Sim 7.0, which utilizes a Discrete Event Simulation (DES) modeling methodology and models the movement and routing of items. This software was considered suitable for model development as culture volumes flow to and from raceways or scaling steps. Therefore, each scaling step in the culturing process is considered as a discrete event. Each of the three models was constructed to quantify the time between items (TBI), average cycle time (ACT) and operating costs of each item. Identification of the TBI and ACT is considered advantageous in identifying bottlenecks between different scaling steps. Each item had a beginning volume 1 L and was cultured to a final volume of 9,866,752 L. It was assumed that a facility would regularly receive 1 L of microalgae seed stock, which would be utilized to begin the culturing process. This seed stock would be cultured through a network of raceways until completing the harvesting step. Additional downstream processes (e.g. extraction and fuel conversion) were not included in these models. The total facility size considered for this analysis was 40 ha with 32 ha employed for microalgae production.

Three culture management techniques were considered for this analysis: stepwise scaling, volume batching, and intense culturing scenarios. The stepwise scaling model is a straightforward scaling process in that each scaling step doubles the volume of the inoculating culture. An example of this process would be diluting 40 L of microalgae culture from a concentration of 1 g L^{-1} dry weight (DW) to 80 L at a concentration of 0.5 g L^{-1} DW. At the end of the culturing period, the 80 L volume would have a concentration of 1 g L^{-1} DW which would then be diluted to inoculate a volume of 160 L at a concentration of 0.5 g L^{-1} DW and so forth until the final volume of 9,866,752 L was reached.

The volume batching model is similar to the stepwise model, except that two volumes are simultaneously batched together to inoculate an appropriately larger volume. An instance of this would be culturing 40 L until achieving a concentration of 1 g L^{-1} DW which would then be diluted to inoculate a volume of 80 L at a concentration of 0.5 g L^{-1} DW. As the 80 L is cultured, the 40 L simultaneously receives an inoculating volume of 20 L at 0.5 g L^{-1} DW. At the end of the culturing period, both the 40 L and 80 L volumes are batched together. This results in a total inoculation volume of 120 L at a concentration of 1g L^{-1} DW which would be diluted to 0.5 g L^{-1} DW and utilized to inoculate a volume of 240 L. Therefore, the 40L and 80L cultures are batched together to inoculate a volume of 240L. Since the volume batching model batches two items into one item, reducing the number of items, only three scaling steps were employed to incorporate the volume batching process.

The intense culturing model implements the use of flat panel bioreactors (FPR's) between the laboratory and large raceway scales. FPR's are able to grow microalgae cultures at greater densities and allow the exclusion of atmospheric contaminants (Chaumont, 1993). It was assumed that a culturing period of 4 days would yield a culture concentration beginning at 0.5 g L^{-1} DW to a final concentration of 5 g L^{-1}DW (Anderson, 2005). Therefore, the greater culture concentration yields by the FPR's allow the inoculation of a volume 10 times greater than the original volume of the FPR. An example of this process would be culturing 40L in an FPR from a concentration of 0.5 g L^{-1} DW to a concentration of 5 g L^{-1} DW. This would result in a culture of 40 L with a concentration of 5 g L^{-1} DW, which would be used to inoculate a volume of 400 L at a concentration of 0.5 g L^{-1} DW. However, FPR's are considered as capital intensive methods of cultivation. Therefore only three scaling steps utilizing FPR's were implemented into the intense culturing model.

Five different levels were developed for each model and included a laboratory scale, a medium raceway scale, large raceway scale, starvation pond scale and harvesting process. The laboratory scale, medium raceway scale and large raceway scales employ numerous scaling steps through which items progress until achieving a final volume of 9,866,752 L. The different processes were self-contained in `hierarchal` blocks (H-blocks), which encompass several scaling steps for each scale (Figure A-12). The basic processes in each of the scaling steps within the laboratory, medium raceway and large raceway scales consisted of similar process blocks. As an item passes through the beginning of a new scaling step, several attributes are determined and applied to each item. These attributes include: item arrival time, item volume, seasonal yield, evaporation rates and CO_2 consumption. These attributes were attached to each item to analyze various activity time delays as well as operational costs.

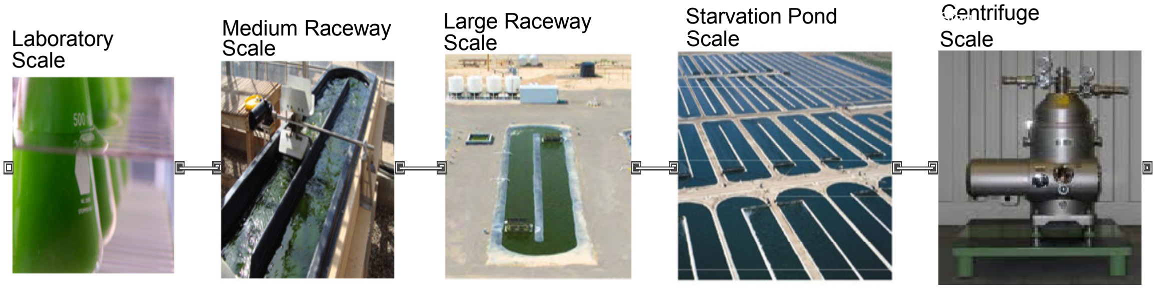


Figure A-12. Hierarchical Blocks of different scales in the culturing process

These scales are then followed by a starvation period, which is the amount of time required for nutrient depletion to trigger the accumulation of lipids in the algae. The production of lipids from microalgae requires the culture to be stressed for a certain period of time. Therefore, a starvation period of 21 d was the time delay consideration for induction of microalgal lipid production. The starvation process was modeled with three different sets of starvation ponds encompassing a volume of 9,866,752L. Harvesting was achieved through the utilization of disc-bowl centrifuges. The centrifuges considered for this analysis have a total harvesting rate of 90,000 L hr^{-1} with a solids concentration of 10%. There is no maintenance time delay for centrifugation as this activity could be accomplished between harvesting intervals. The different process scales, scaling stages and volumes are outlined in Table A-50.

Table A-50. Process stages and volumes for the three algae pond management scenarios.

		Stepwise Model	Volume Batching Model	Intense Culturing Model
Scale	Scaling Stage	Microalgae Raceway Volume (L)	Microalgae Raceway Volume (L)	Microalgae Raceway Volume (L)
Laboratory	Step 1	2.00	2.00	2.00
	Step 2	4.00	4.00	4.00
	Step 3	9.00	15.0	9.00
	Step 4	19.0	30.0	19.0
	Step 5	40.0	60.0	40.0
	Step 6	80.0	140	80.0
Medium Raceway	Step 1	150	280	160
	Step 2	301	560	1600
	Step 3	602	1600	16000
	Step 4	1204	3200	•
	Step 5	2408	*	•
	Step 6	4817	*	•
Large Raceway	Step 1	9635	6400	•
	Step 2	19271	12800	•
	Step 3	38542	38542	•
	Step 4	77084	77084	•
	Step 5	154168	154168	154168
	Step 6	308336	308336	308336
	Step 7	616672	616672	616672
	Step 8	1233344	1233344	1233344
	Step 9	2466688	2466688	2466688
	Step 10	4933376	4933376	4933376
	Step 11	9866752	9866752	9866752
Starvation Ponds	Step 1	9866752	9866752	9866752
	Step2	9866752	▪	9866752
	Step 3	9866752	▪	9866752
Harvesting	Step 1	9866752	9866752	9866752

*** denotes scaling steps that were eliminated through volume batching.**
• denotes scaling steps omitted from the implementation of FPRs.
▪ denotes pond discarded from the starvation pond level.

In evaluating the scaling scenarios, it was necessary to identify the factors that encumbered process flow as these factors would influence process duration. The factors considered included: culturing duration, contamination events, culture transfer, raceway/mixer maintenance and daily culture sampling and analyzing. These factors were included in the model as stochastic variables in which process time delays were based on triangular distributions.

Culture duration is the amount of time required for the culture concentration to increase from an inoculating concentration of 0.5 g L^{-1} DW to a final concentration of 1 g L^{-1} DW. The culturing duration was assumed to be seasonal as temperature and photoperiod affect microalgal growth. The seasonal growth rates determined by this analysis were assumed on a monthly basis and are within the realm of growth rates that are currently achievable in outdoor raceways. The culture durations were calculated from the assumed growth rates and are depicted in Table A-51.

Table A-51. Assumed seasonal area yield and culture duration by month.

Month	Seasonal Yield ($g\ m^{-2}\ d^{-1}$)	Culturing Duration (d)
Jan	5.00	15.2
Feb	5.00	15.2
Mar	10.0	7.60
Apr	15.0	5.00
May	20.0	3.80
Jun	20.0	3.80
Jul	20.0	3.80
Aug	20.0	3.80
Sep	15.0	5.00
Oct	10.0	7.60
Nov	5.00	15.2
Dec	5.00	15.2

Contamination and culture failure events are another time constraint for item flow. It was assumed that outdoor raceways would periodically be contaminated with undesirable organisms or fail for some other reason, resulting in disposal of the original culture. Time for raceway sanitation was included in the process model in order to mitigate contamination outbreaks. Raceway cleaning time requirements were also considered as stochastic variables therefore; a triangular distribution was determined for raceway cleaning time requirements. However, contamination events may still occur so a probability of contamination was assumed to be 0.001. Thus, at each step in the cultivation stages there was one chance in a thousand that the culture would fail. Transfer time is the time required to pump the entire contents of one raceway into another larger raceway. The transfer time consideration also incorporated the time requirement for media transfer to the raceways after inoculation. The time delay for transfer time was determined by dividing the transfer volume of each scaling step by the total facility volume. This figure was then multiplied by a 16 h transfer time constraint, which yielded the minimum value for the triangular distribution. The median and maximum values were determined by multiplying the minimum value by a factor of 1.25 and 1.5.

General raceway/mixer maintenance was also considered as an activity that would delay the progression of items. Raceway maintenance includes liner inspection for liner shifting, holes, or separation from the ground. Mixer maintenance encompasses mixer inspection and removal of debris from the mixer as well as the sump. The time consideration for raceway/mixer maintenance was considered to be a stochastic variable as the time to complete these tasks would vary. The time requirement for raceway/mixer maintenance employed a constant triangular distribution for all scaling steps in the medium raceway scales of each model. The triangular distribution was increased linearly, due to increased liner surface area, for all scaling steps in the large raceway scale. The minimum time remained at 1 hr for all scaling steps in the large raceway scale.

Daily culture sampling and analyzing include taking daily culture samples and conducting tests to monitor the microalgae culture. However, taking daily samples is not an activity that hinders the growth of the microalgae culture. Therefore, sampling and analyzing was a time consideration that would not affect the overall process flow of items. The activity of sampling and analyzing culture was only a time consideration in evaluating labor requirements and costs.

For this analysis, large-scale microalgae facilities were assumed to be similar to agricultural operations since both entities are concerned with the culturing of crops. Therefore, large-scale microalgae facilities were assumed to follow the same labor laws as agricultural operations. Different tasks associated with the operation of a microalgae facility require different skill levels. Accordingly, three labor resources were identified which had different educational backgrounds and subsequently different pay scales. Laboratory personnel are responsible for all activities inside the laboratory as well as culture monitoring of all outdoor raceways. Therefore, laboratory personnel were assumed to require a college education, as they would be responsible for operating lab equipment and monitoring microalgae cultures. The laboratory labor resource is referred to as Lab Labor in the models. Outdoor laborers responsible for day to day facility operations, such as outdoor culture transfer and media mixing, were assumed to need a high school education. The outdoor labor resource is denoted as H.S. Labor in the models. General laborers responsible for raceway maintenance such as cleaning, mixer maintenance and raceway inspection were assumed not to require a formal education. The general labor resource is referred to as M. Labor in the models. The hourly wage rate is assumed to be \$15/hr for Lab Labor, \$12.50/hr for H.S. Labor and \$10/hr for M. Labor.

For a contamination event, another labor resource pool was considered dubbed Contract Labor. This labor resource is independent of the facility and was called upon to clean raceways in the event of a contamination. This labor resource was assumed to encompass 12 laborers for a total cost of \$120 hr^{-1}. Since some factors such as culture transfer are dependent upon the availability of labor, work shift constraints and labor resource pools are incorporated into the models. The availability of laborers is dictated by shift times and was assumed to have a total working period of 12 h d^{-1}, 360d yr^{-1}. The addition of a `shift` block simulates the availability of the labor resources for activities such as culture transfer, raceway/mixer maintenance and raceway inoculation at all scaling steps. Labor resource utilization was determined and allowed for an estimate of the number laborers required for each model.

Model Development

General Inputs

The first block implemented in each model was the `executive` block, which is pictured in Figure A-13. This block must be placed to the upper most left of all other blocks in discrete event models. The `executive` block provides event scheduling, simulation control, item allocation, attribute management and other model settings. This block utilizes all the general settings for the stop simulation option and item allocation under the control tab. The attributes, discrete rate and LP solver tabs in the `executive` block maintained the general settings.

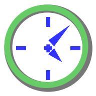


Figure A-13. Executive block located at the top left of each model.

Items were randomly created by the `start` block depicted in Figure A-14. It was assumed that a microalgae facility would receive 1 L of microalgae seed stock which would be utilized for culturing. Therefore, each item created by the model is the equivalent of 1 L of microalgae seed stock with a concentration of 1 g L^{-1}. However, determining the time between arrivals (TBA) for each model was difficult considering the model initialization period and the varying process durations for each scaling step. Therefore, the item arrival time was optimized by trial and error. The item arrival time was changed until the number of items created was equal to or less than the sum of the number of items that had already exited the model and items that were currently being processed at the conclusion of the model. Since some process time delays were based on the availability of labor, limited labor resources could reduce the output of the models. Therefore, as the TBA was increased, the utilization percentage of the labor resources was monitored to ensure that the number of items exiting the models was not hindered by the availability of labor. The labor requirement utilization percentage was required to be no greater than 60% and could be determined by the utilization connector on each labor `resource pool`.

Seed stock arrival was assumed to be constant for the stepwise, volume batching and intense culturing models. Through trial and error, the TBA resulted in 8 days, 4 days and 8 days respectively. Because of the nature of the volume batching model, the TBA was lower compared to the other two models because of the combination of two items into one. Considering that there were three batching steps implemented, the number of items created in the `start` block was reduced by 50% with each batching step. Thus, the three volume batching steps resulted in an item reducing factor of 0.125. Therefore, if 800 items were created by the `start` block, the greatest number of items that could exit the model was 100.

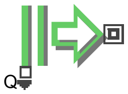


Figure A-14. Create block that manages the creation and arrival of items.

Three different types of labor groups were identified; however, four different labor resource pools were created in each model. The laboratory labor resource pool is depicted in Figure A-15 along with the percent utilization determined by the resource pool and the set of `value` block incorporated to calculate the actual resource utilization.

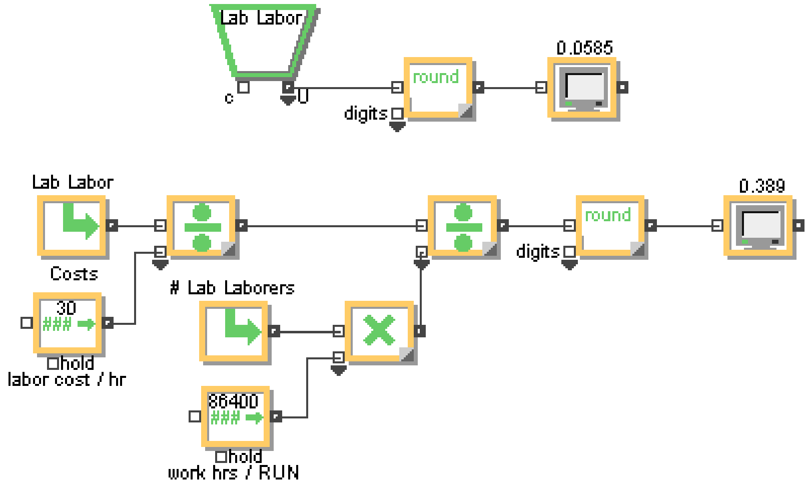


Figure A-15. Laboratory labor resource pool and laboratory labor resource utilization value blocks.

The `resource pool` blocks contain the number of laborers employed for each labor division. The percent utilization of these labor resources is calculated by the labor `resource pool` block. However, the utilization calculated by the `resource pool` blocks is not characteristic of the processes modeled. This is because of the labor resource pool calculating the percent utilization based on the amount of time the resource is out of the resource pool regardless of the shift time. The `shift` block is communicating to the resource pool to not release any resources when it is off shift. However, resources that are in the model when the shift goes off do not return to the resource pool. Therefore, the resource pool can't control resources that are being used out in the field. Accordingly, to prevent labor resources from hindering item flow it was assumed that the percent utilization calculated by the resource pool would need to be 60% or less. In a real world situation, the laborers from each division would be employed with both the tasks modeled as well as other tasks. Therefore, it seems valid to assume that the tasks considered in the models would utilize 60% of the labor time. The number of employees for each labor resource was increased until the assumed 60% utilization was achieved. The actual percent utilization of labor resources was calculated from a series of `value` blocks. The labor cost for each labor resource was conveyed through a `catch` block and divided by the labor rate. This value was then divided by the product of the number of laborers and the number of work hours for the duration of 20 yr. The resulting value is the actual labor utilization percentage.

The availability of laborers to perform the tasks modeled is dependent on the `shift` block. It was assumed that a 12 hr workday would be required to operate a microalgae facility. There were no time considerations for scheduled breaks or employee shift changes. It was assumed that a microalgae facility would be considered as an agricultural entity. Accordingly, there were also no considerations for overtime pay. The `shift` block is depicted in Figure A-16.

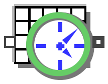


Figure A-16. Shift block responsible for dictating time constraints for labor pools and activity blocks.

The shift times incorporated in the `shift` block are outlined in Table A-52. The shift schedule times were repeated every 24 hrs. The shift start time and simulation start time must be equal therefore; the shift time starts at time zero.

Table A-52. Shift schedule for all models.

Parameters	
Time	On/Off
0	On
6	Off
7	On
13	Off

The only break time implemented in the `shift` block was a 1 hr break for lunch. Periodic breaks were assumed to be taken by employees between tasks or when convenient. Therefore, these break considerations were not utilized in the shift schedule of the `shift` block.

Each item exited the model through an item `exit` block, which recorded the number of items as they progressed through the block. The `exit` block is illustrated below in Figure A-17.

Figure A-17. Exit block

The items exiting the block encompassed a volume of 9,866,752 L with a concentration of 1 g L^{-1} DW. Therefore, the dry weight produced in each batch of algae exiting the model was 9867 kg.

Model Attributes

At the beginning of each step, the first item attribute is the item arrival time for that step. This attribute was used to evaluate the overall time between items (TBI), and average cycle time (ACT) for each scale. This was accomplished by connecting a simulation `variable value` block to the value connector on the arrival time `attribute set` block. The simulation `variable value` block labeled Time, determines the current model time upon item arrival and attaches that time to an item. The next attribute determined for each item was the item arrival time for each scaling step. This arrival time was employed to calculate the TBI and ACT of each scaling step, which is advantageous for identifying bottlenecks between different scaling steps. Figure A-18 depicts the `time` block attached to the arrival time `attribute set` block for the beginning of the medium raceway scale (MR AT) as well as the arrival time `attribute set` block for the scaling step (Arrival Time).

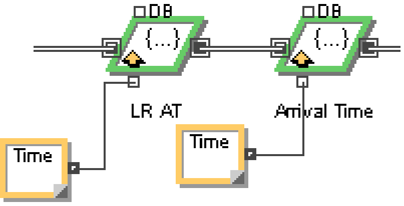


Figure A-18. Item arrival time attribute blocks connected to simulation variable value block.

Following the item arrival `time set` block, is a pair of item `volume attribute` blocks. The first of these two blocks is an `attribute get` block, which acquires the volume attribute value associated with the current item. A series of `value` blocks were implemented to determine the new volume attribute for an item at each scaling stage. These `value` blocks divide the scaling step ending volume by the inoculating volume of the current scaling stage, which yields a raceway volume ratio. This ratio was then multiplied by the ending concentration of the microalgae culture and then multiplied again by the volume of the previous scaling stage through the volume attribute `get` block. With the assumed ending concentration of 1 g L^{-1}, the volume calculation basically doubles the inoculation volume for each scaling step. Figure A-19 below portrays the volume `attribute get` and `set` blocks as well as the `value` blocks utilized to calculate the new volume for each item.

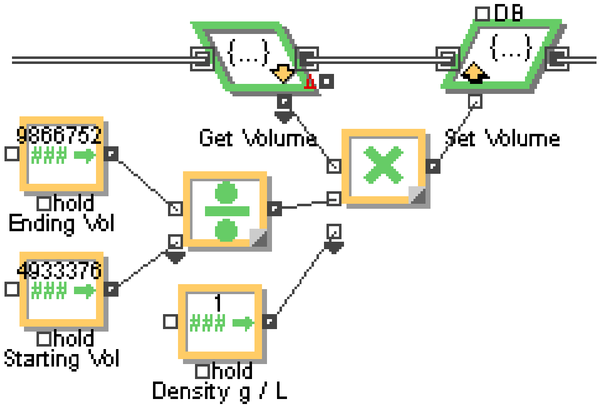


Figure A-19. Item volume set and get attribute blocks as well as value blocks utilized to calculate item volume for each scaling step.

The next block that each item passes through is the `attribute set` block for seasonal yield. The seasonal yield attribute was quantified for determining the process time delay in the growing `activity` block. A seasonal yield `data source` table was constructed which contained different monthly culturing durations correlating to seasonal growth rates. The seasonal yield `data source` table was linked to a `time` block, which conveyed the culturing duration to the value connector of the `attribute set` block. Therefore, as an item passes through the seasonal yield `attribute set` block, the `time` block selects the current time and determines the appropriate culturing duration from the `data source` table. The culturing duration is then set as an attribute for each item upon arriving at each scaling step. Figure A-20 illustrates seasonal yield, seasonal evaporation and CO_2 consumption `attribute set` blocks.

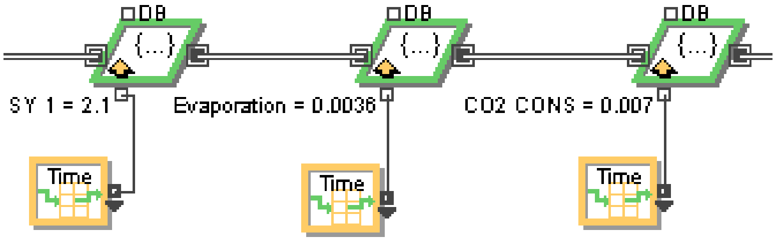


Figure A-20. Attribute set blocks for seasonal yield, evaporation, and CO_2 consumption.

Culturing times were determined on a monthly basis for a 20 yr period and were conveyed to the value connector of the seasonal yield `attribute set` block. The laboratory scale in each model was assumed to have a constant culturing duration of 4 d. This constant culturing duration is based on an assumed growth rate of 20 g m^{-2} d^{-1}, which was justified considering that laboratory culturing takes place in a controlled environment. However, the medium and large raceways would be located outdoors in uncontrolled environments. Therefore, the culturing duration required to double the culture concentration from 0.5 g L^{-1} DW to 1 g L^{-1} DW is seasonal and fluctuates throughout the year. Table 2 summarizes the month, assumed growth rate, and calculated culturing duration. The resulting average yearly growth rate for this analysis was 12.5 g m^{-2} d^{-1}. Becker, (1994) reported an average yield of 8-15 g m^{-2} d^{-1} for the cyanobactria *Spirulina,* which is considered as a slow growing microalgae. Therefore, the seasonal growth rates assumed by this analysis should be regarded as conservative. Culturing process delays were based on monthly growth rates ranging from 5 g m^{-2} d^{-1} to 20 g m^{-2} d^{-1}. The seasonal culturing durations were calculated by first dividing the inoculating concentration (0.5 g L^{-1} DW) by the predetermined seasonal growth rate for each month. The resulting value was then divided by 0.001 m^3 as the inoculating concentration was based on 1 L. This yielded d m^{-1},which was then multiplied by an assumed depth of 0.1524 m. An example of the seasonal culturing duration calculation for a growth rate of 10 g m^{-2} d^{-1} is depicted by equation 1.

$$\frac{.5g}{L} \times \frac{\mathrm{m}^2\ \mathrm{d}}{10g} \times \frac{1L}{.001m^3} \times \frac{.1524\ m}{1} \qquad [1]$$

An attribute for seasonal evaporation rates was also developed to simulate evaporation in outdoor raceways. The evaporation rates considered were indicative of arid regions located in West Texas. Seasonal weather data from a weather station located in Pecos, Texas was interpolated to determine monthly average evaporation rates and incorporated into the model. Weather data from a time period of 8-31-2000 to 8-30-2010, in which 2003 data was not available, was analyzed utilizing Meyer's equation. Monthly evaporation averages were calculated for each year and then averaged across the range of years. This resulted in average monthly evaporation rates over a nine year period. The average monthly evaporation rates are reported in Table A-53 (Ronald Lacey, P.E., personal communication, April 16 2010).

Table A-53. Evaporation rates for Pecos, Texas used for all models.

Month	Evaporation Rate (m d^{-1})
Jan	0.0034
Feb	0.0043
Mar	0.0066
Apr	0.0111
May	0.013
Jun	0.0157
Jul	0.0123
Aug	0.0114
Sep	0.0092
Oct	0.0061
Nov	0.0045
Dec	0.0036

The summer months of May, June, and July yielded the highest evaporation rates compared to other months. An evaporation `attribute set` block was created which utilized a value lookup table for quantification of seasonal evaporation rates. These seasonal evaporation rates were extended for a 20 yr period in the `value lookup` table.

The last attribute attached to each item is the CO_2 consumption attribute. This attribute was derived from seasonal growth rates and CO_2 mass balance calculations. The mass balance formula considered was:

$$6CO_2 + 12H_2O \longrightarrow 6(CH_2O) + 6H_2O + 6O_2.$$

The different compounds and molecular weights are outlined in Table A-54.

Table A-54. CO2 mass balance for algae growth.

Compound	Molecular Weight ($g\ mol^{-1}$)	Mass ($g\ g\ biomass^{-1}$)
CO_2	44	264
H_2O	18	216
$C_6H_{12}O_6$	180	180
O_2	32	192

The CO_2 consumption ratio was determined by dividing the 264 g CO_2 by 180 g of $C_6H_{12}O_6$. This resulted in a ratio of 1.467 g CO_2 required to produce 1 g of biomass DW. The resulting monthly growth rates and CO_2 consumption rates are listed in Table A-55. In a study conducted by Kadam, (1997), the utilization of CO_2 from power plant flue gas resulted in CO_2 consumption rate of 1.49 g CO_2 for each g of biomass. Therefore, the CO_2 consumption rate determined by this analysis is justifiable. The CO_2 consumption rates are constant as they are based on biomass production. Incorporating stochastic variation in the monthly growth rates would also randomize the CO_2 consumption rates, which are dependent on the growth rates.

Table A-55. Seasonal CO2 consumption for all models based on carbon mass balance.

Month	Seasonal Yield ($g\ m^{-2}\ d^{-1}$)	CO_2 Consumption ($kg\ m^{-2}$)
Jan	5.00	0.007
Feb	5.00	0.007
Mar	10.0	0.015
Apr	15.0	0.022
May	20.0	0.029
Jun	20.0	0.029
Jul	20.0	0.029
Aug	20.0	0.029
Sep	15.0	0.022
Oct	10.0	0.015
Nov	5.00	0.007
Dec	5.00	0.007

A CO_2 consumption `attribute set` block was created which attached the CO_2 consumption rates to each item upon arriving at each scaling step. A `value` `lookup` table was created which extended the CO_2 consumption rates for a 20 yr period and was connected to the value connector of the CO_2 consumption `attribute set` block.

Model Process Time Delays and Appropriate Operational Costs

The growing block is the first `activity` block in each scaling step that incorporates a process time delay. This block delays items based on the culturing duration that is determined from the seasonal yield attribute. To prevent simultaneous processing of multiple items, the maximum number of items in the growing `activity` block was limited to one. The growing activity was not directly dependent on the availability of labor resources. The accumulated growing activity time accounts for the greatest time delay for each scaling step in the laboratory, medium and large raceway scales. The growing and transfer `activity` blocks are displayed in Figure A-21.

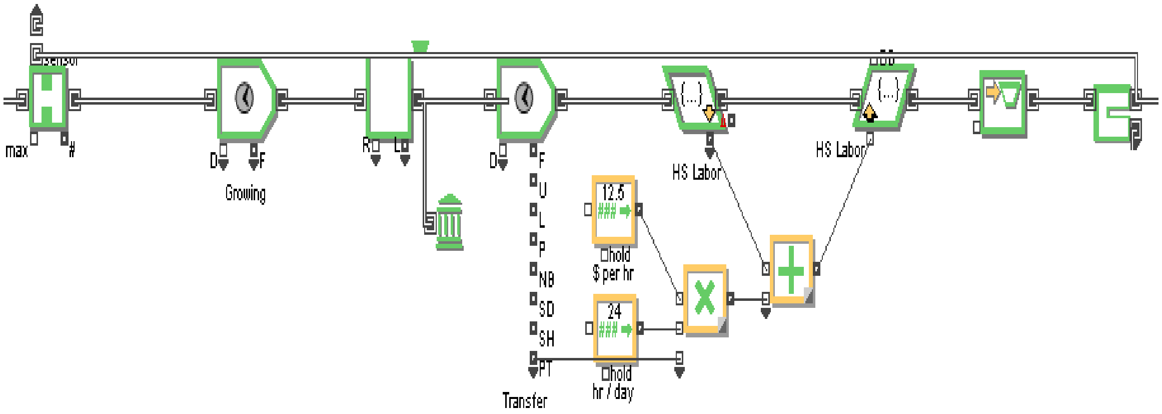


Figure A-21. Growing activity block, shutdown block, and value blocks utilized for calculating shutdown labor costs.

The growing `activity` block is preceded by an `area gating` block. This block restricts the passing of items through a portion of the model by using the sensor connector to monitor how many items are in a section of the model. The sensor connector was linked to the contamination `select item out` block and is depicted in figure 10. The `area gating` block was implemented to simulate the inability of the growing `activity` block to receive another item until the transfer activity has been exhausted.

Culture transfer is a process time delay as microalgae cultures would be transferred from one scale to the next appropriately larger scale. The transfer `activity` block is the second `activity` block depicted in Figure A-21. Since it was assumed that all nutrients were depleted at the end of the culturing period microalgae cultures were assumed to be sustainable but not growing at the time of transfer. Therefore, the time required to transfer the cultures was assumed to delay culture growth and was therefore a process flow time delay. This process time delay was incorporated into the models by utilizing a transfer `activity` block. The maximum number of items allowed in the transfer `activity` block was one and is controlled by the `area gating` block. Therefore, as an item progresses from the growing `activity` block to the transfer `activity` block, only one item is allowed in either the growing `activity` block or the transfer `activity` block.

The culture transfer time for the laboratory scale was determined from personal experience of culturing microalgae in a laboratory setting. The laboratory scale transfer time includes the time required to transfer the microalgae culture from one scaling step to the next, time requirements for preparing glassware, adding media to the culture and other laboratory duties associated with culture transfer. The labor considerations for the laboratory scale utilized lab laborers at a labor rate of \$15 hr^{-1}. The triangular distribution determined for the laboratory scale transfer time was constant for all scaling steps with an average time of 0.30 hrs, a minimum time of 0.15 hrs and a maximum time of 0.45 hrs. This triangular distribution was utilized as the laboratory process time delay in the transfer `activity` block for each model.

The culture transfer time for the medium raceway, large raceway, starvation and harvesting scales was based on an accumulated transfer volume of 24,528,708 L. It was assumed that the accumulated volume would need to be transferred in a time period of 16 hr or less. The raceway volume at each scaling step was divided by the total facility volume of 49,057,416 L and then multiplied by the assumed time constraint of 16 h. The resulting time requirement was the minimum value considered for the triangular distribution. The average value of the triangular distribution was determined by multiplying the minimum value by a factor of 1.25 while the maximum value was 1.5 times the value of the average time requirement. The H.S. Labor resource was utilized for the transfer activity in the medium raceway, large raceway and starvation pond scales. Table A-56 outlines the appropriate triangular distribution for each scaling step.

Table A-56. Transfer time requirements.

			Triangular Distribution		
Scale	Scaling Step	Transfer Volume (L)	Minimum (hr)	Median (hr)	Maximum (hr)
Laboratory	Step 1	2.00	0.15	0.300	0.45
	Step 2	4.00	0.15	0.300	0.45
	Step 3	9.00	0.15	0.300	0.45
	Step 4	19.0	0.15	0.300	0.45
	Step 5	40.0	0.15	0.300	0.45
	Step 6	80.0	0.15	0.300	0.45
Medium Raceway	Step 1	150	0.1	0.125	0.15
	Step 2	301	0.1	0.125	0.15
	Step 3	602	0.1	0.125	0.15
	Step 4	1204	0.1	0.125	0.15
	Step 5	2408	0.1	0.125	0.15
	Step 6	4817	0.1	0.125	0.15
Large raceway	Step 1	9635	0.1	0.125	0.15
	Step 2	19271	0.1	0.125	0.15
	Step 3	38542	0.1	0.125	0.15
	Step 4	77084	0.1	0.125	0.15
	Step 5	154168	0.1	0.125	0.15
	Step 6	308336	0.1	0.125	0.15
	Step 7	616672	0.20	0.25	0.3
	Step 8	1233344	0.40	0.50	0.6
	Step 9	2466688	0.80	1.00	1.2
	Step 10	4933376	1.60	2.00	2.4
	Step 11	9866752	3.20	4.00	4.8
Starvation Ponds	Step 1	9866752	3.20	4.00	4.8
	Step2	9866752	3.20	4.00	4.8
	Step 3	9866752	3.20	4.00	4.8

In order to determine labor costs associated with transfer time, a labor resource `queue` block was placed before the transfer `activity` block. The labor resource `queue` block draws a laborer from the resource pool when an item reaches the transfer `activity` block. The labor resource `queue` block was structured to utilize only one laborer from the labor resource pool. A labor resource `release` block was placed after the lab labor `attribute set` block and is responsible for releasing the labor resource back to the labor resource pool. The labor time associated with the transfer `activity` block was the same as the transfer time; however, the total amount of labor time associated with culture transfer may be less than the total transfer time. This is because laborers will not have to be present for the entirety of the culture transfer process, but will be required to monitor the progression of the activity. The labor cost for the transfer activity is calculated by connecting the activity processing time (PT) connector to a series of `value` blocks. Since the processing time was based on a daily time requirement, the PT is multiplied by a conversion factor of 24 hr d^{-1} and the appropriate labor rate. At the laboratory scale, a labor rate of \$15 h^{-1} was used as lab personnel are responsible for all activities. The outdoor raceways utilized outdoor laborers for culture transfer therefore, the medium, large and starvation pond scales labor rate was \$12.50 h^{-1}. The labor cost calculations is displayed below in equation 2.

$$\frac{.01\,d}{1} \times \frac{24\,h}{d} \times \frac{\$15}{hr} \qquad [2]$$

This value was then added to the labor cost in the previous calculation through the labor cost `attribute get` block value connector. Therefore, the labor cost is an attribute attached to each item and the labor cost value was accumulated as items progressed through the models.

Also, raceways would need to be cleaned periodically to mitigate biological fouling and contamination events. The cleaning `activity` block and manual labor cost calculation are illustrated above in figure 11. Therefore, in the event of raceway contamination, the growing `activity` block must remain inactive until the conclusion of the raceway cleaning activity. A contamination event was assumed to be minute therefore; a probability of 0.001 is considered for this analysis. The `select item` block was employed to determine which items would be contaminated utilizing the previously stated probability. The `area gating` block, depicted above in Figure A-21, was also utilized for this activity. Since the growing and transfer activities were structured to employ one item between the two activities, the cleaning activity would also need to be structured the same way. Therefore, the `area gating` block was structured to allow one item between the growing, transfer and raceway cleaning activities. Likewise, as an item leaves the growing activity, it progresses to the transfer activity. At the completion of this activity, the item is determined to be contaminated or contamination free in the `select item` out block. If the item is free of contamination, it progresses to the next scaling stage and the growing `activity` block receives another item. In the event of a contamination, the contaminated item is sent to the raceway cleaning activity. Upon conclusion of the raceway cleaning activity, the growing activity receives another item. To account for contaminated items the contamination `throw` block was employed which conveyed contaminated items to a contamination `catch` block. The `catch` block catches all of the contaminated items which then progress through a series of cost `attribute get` blocks and finally exit the models through an `exit` block. Therefore, all of the contaminated items and operational costs associated with those items are tabulated for the duration of the models.

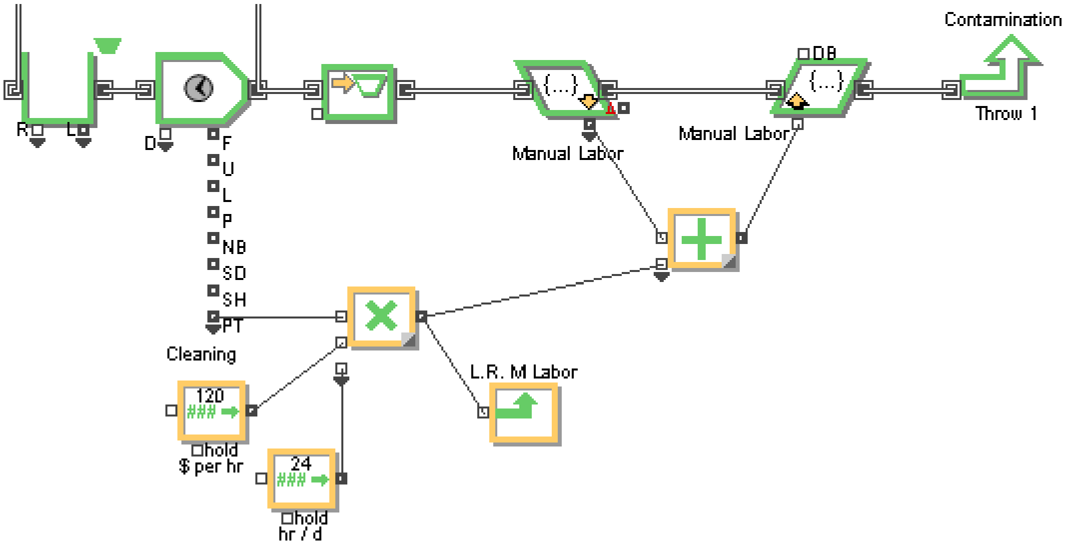


Figure A-22. Cleaning activity block and cleaning labor costs.

Time considerations for raceway cleaning of a contamination event were incorporated in the medium raceway, large raceway and starvation pond scales. The time to clean each raceway was based on current cleaning practices as well as the raceway size. Current cleaning practices include the employment of laborers with portable power washers and hand tools to scrub the liners. The time considerations for raceway cleaning were based on personal field experience for a raceway volume of roughly 30,300 L. These time requirements employed four laborers who were able to clean a 30,300 L raceway in approximately 3 hrs. However, for this analysis it is assumed that a 30,300 L raceway would need to be cleaned in a one hr time period. This would require the utilization of 12 laborers to satisfy the assumed time constraint. Accordingly, it was assumed that it would take one hr for a 12-person crew to clean a raceway volume of 30,300 L or 200 m^2. A triangular distribution for raceway cleaning time for all scaling steps in the medium raceway scales was assumed to have a minimum time of 0.25 hrs, an average time of 0.5 hrs and a maximum time of 1 hr. This triangular distribution was increased linearly in the large raceway scale for each appropriately larger scaling step. The triangular distribution for the raceway cleaning time requirement was determined by dividing the raceway volume by the assumed hourly cleaning volume of 30,300 L. This resulted in the number of hours required to clean a particular raceway. The median value was determined by multiplying the minimum value of the triangular distribution by a factor of 1.25 while the maximum value was determined by multiplying the minimum value by a factor of 1.5. The resulting triangular distribution for each scaling step is depicted below in Table A-57.

Table A-57. Raceway sanitation time requirements.

			Triangular Distribution		
Scale	Scaling Step	Raceway Volume (L)	Minimum (hr)	Median (hr)	Maximum (hr)
Laboratory	Step 1	2.00	0.25	0.50	0.75
	Step 2	4.00	0.25	0.50	0.75
	Step 3	9.00	0.25	0.50	0.75
	Step 4	19.0	0.25	0.50	0.75
	Step 5	40.0	0.25	0.50	0.75
	Step 6	80.0	0.25	0.50	0.75
Medium Raceway	Step 1	150	0.25	0.50	0.75
	Step 2	301	0.25	0.50	0.75
	Step 3	602	0.25	0.50	0.75
	Step 4	1204	0.25	0.50	0.75
	Step 5	2408	0.25	0.50	0.75
	Step 6	4817	0.25	0.50	0.75
Large Raceway	Step 1	9635	1.00	1.25	1.50
	Step 2	19271	1.00	1.25	1.50
	Step 3	38542	1.00	1.25	1.50
	Step 4	77084	2.50	3.13	3.75
	Step 5	154168	5.00	6.25	7.50
	Step 6	308336	10.0	12.5	15.0
	Step 7	616672	20.0	25.0	30.0
	Step 8	1233344	40.0	50.0	60.0
	Step 9	2466688	80.0	100	120
	Step10	4933376	160	200	240
	Step11	9866752	320	400	480
Starvation Ponds	Step 1	9866752	320	400	480
	Step2	9866752	320	400	480
	Step 3	9866752	320	400	480

The labor cost associated with raceway cleaning was calculated utilizing a set of `value` blocks. The process time from the cleaning `activity` block is multiplied by the labor cost of \$120 h^{-1} and a constant of 24 h d^{-1}. The raceway labor cost calculation is depicted in equation 3.

$$\frac{.017\,d}{1} \times \frac{24\,h}{d} \times \frac{\$120}{h} \qquad [3]$$

This value was added to the accumulated manual labor cost in the previous scaling step through the labor cost `attribute` block value connector. Therefore, the manual labor cost associated with raceway shutdown because of cleaning is an attribute that was attached to each item in which the labor cost was accumulated as items progressed through the models.

Another consideration for process time delay is raceway and mixer maintenance. Raceway maintenance was based on the time required for liner inspection and repair as well as mixer inspection and maintenance. A triangular distribution for raceway maintenance was established and utilized in the maintenance `activity` block. The process blocks employed for maintenance duration and labor costs are depicted in Figure A-23.

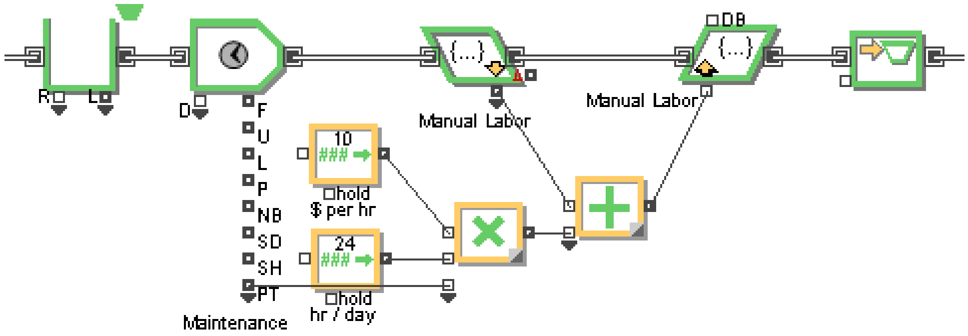


Figure A-23. Resource queue block, maintenance activity block, value blocks connected to the activity process time (PT) connector to calculate labor costs, get block for lab labor costs, set block for lab labor costs and the resource pool release block.

The medium raceway triangular distribution for raceway maintenance resulted in a constant distribution with an average time of 2 h, a minimum time of 1 h and a maximum time of 3 h. Beginning in the large raceway scale, the triangular distribution was increased linearly by adding 0.5 hr to the previous scaling stage time delay. The maximum value was increased by adding 1 hr to the maximum time delay of the previous scaling step. The resulting triangular distribution and scaling steps are displayed in Table A-58.

Table A-58. Maintenance time requirements.

			Triangular Distribution		
Scale	Scaling Step	Raceway Volume (L)	Minimum (hr)	Median (hr)	Maximum (hr)
Medium Raceway	Step 1	150	1.00	2.00	3.00
	Step 2	301	1.00	2.00	3.00
	Step 3	602	1.00	2.00	3.00
	Step 4	1204	1.00	2.00	3.00
	Step 5	2408	1.00	2.00	3.00
	Step 6	4817	1.00	2.00	3.00
Large Raceway	Step 1	9635	1.00	2.50	4.00
	Step 2	19271	1.00	3.00	5.00
	Step 3	38542	1.00	3.50	6.00
	Step 4	77084	1.00	4.00	7.00
	Step 5	154168	1.00	4.50	8.00
	Step 6	308336	1.00	5.00	9.00
	Step 7	616672	1.00	5.50	10.0
	Step 8	1233344	1.00	6.00	11.0
	Step 9	2466688	1.00	6.50	12.0
	Step 10	4933376	1.00	7.00	13.0
	Step 11	9866752	1.00	7.50	14.0
Starvation Ponds	Step 1	9866752	1.00	7.50	14.0
	Step2	9866752	1.00	7.50	14.0
	Step 3	9866752	1.00	7.50	14.0

The maintenance labor cost attribute and value calculation is structured similar to the transfer time labor cost attribute and values calculations. A resource `queue` block was utilized to acquisition a laborer from the resource pool when an item entered the maintenance `activity` block. The resource `queue` block was structured to allow one laborer to be released from the appropriate resource pool. A resource `release` block was incorporated to release the labor resource. To determine the labor cost, the maintenance PT was connected to a series of `value` blocks. The laboratory scale utilized the lab labor resource at a labor rate of \$15 h^{-1} while the medium raceway, large raceway and starvation pond scales utilized the manual labor resource at a rate of \$10 h^{-1}. Since the maintenance process time is determined by the number of days, a conversion factor of 24 h d^{-1} and the appropriate labor rate were multiplied together. The resulting maintenance cost formula is displayed below in equation 4.

$$\frac{.07\,d}{1} \times \frac{24\,h}{d} \times \frac{\$15}{hr} \qquad [4]$$

Through the labor `attribute get` block, this value was added to the previous labor cost. The resulting total cost was conveyed to the labor `attribute set` block in which the accumulated labor costs could be attached as an attribute for each item.

The starvation pond scale contained the same array of blocks as the final scaling step in the large raceway scale. The only difference was that the growing `activity` block was replaced with a starvation `activity` block. Starvation was assumed to have a constant period of 21 d. A data source table was employed, which contained a starvation period of 21 d for each month for the duration of 20 yr. The data source table was linked to the `time` block, which transferred the 21 d starvation period to the seasonal yield `attribute` block. This attribute was then utilized in the starvation `activity` block.

Three sets of starvation ponds were assumed to maximize the number of items progressing through the models. Therefore, the starvation pond scale contained a `select item out` block which delegated the dispersal of items upon arrival. The sequential selection condition was chosen for the `select item out` block so that each starvation pond would have the same probability of receiving any one item. The starvation ponds were constructed as three different series of similar processes. The composition of these blocks included `attribute set` blocks as well as `activity` blocks. The `attribute set` blocks utilized included seasonal yield, evaporation and CO_2 consumption. The `activity` blocks employed included: starvation period, transfer and maintenance blocks. The starvation, transfer and cleaning `activity` blocks were structured similar to the blocks displayed in Figure A-21. Likewise, the maximum number of items allowed between the starvation, transfer and raceway cleaning activities was one.

After items progress through the series of `activity` blocks, items were directed back to a single array of `attribute cost` blocks. Since the seasonal yield, evaporation and CO_2 consumption attributes are set at the beginning of each of the three process series, items could be routed into a single network of `attribute cost` blocks. Therefore, items were conveyed back into a single process series through a `select item in` block. The item input was selected to merge items together; this resulted in items merging into the same network of blocks to determine operational costs associated with each item.

The harvesting time requirement was based on item volume, culture growth rates and centrifuge processing rates. Since the optimal growth rate resulted in a time delay of 3.8 d, it was assumed that harvesting would need to be achieved in less than 3.8 d. Therefore, harvesting was assumed to be accomplished by employing a total of three centrifuges, each with a processing rate of 90,000 L hr^{-1}. The process blocks for centrifugation are illustrated in Figure A-24.

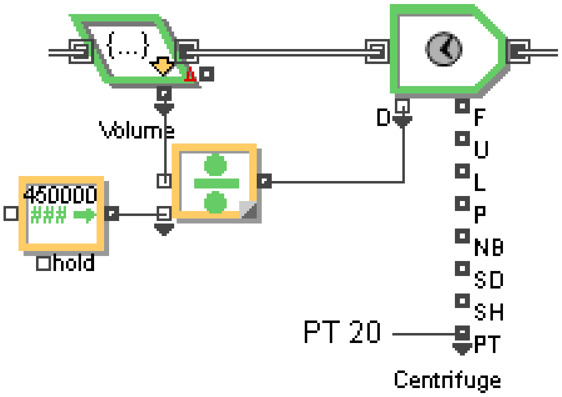


Figure A-24. Centrifuge activity block that utilizes the volume attribute block and centrifuge process rate to determine the delay time.

The harvesting scale contained a centrifuge `activity` block, which simulated the centrifugation of microalgae culture received from a single set of starvation ponds. The delay time for centrifugation was determined through an array of `value` blocks and a volume `attribute get` block. The value derived from the volume `attribute get` block, which was the total item volume from the starvation ponds, was divided by the accumulated centrifuge process rate. The resulting delay time value was then conveyed to the centrifuge `activity` block through the process time (PT) connector. The resulting centrifuge process time calculation is displayed in equation 5.

$$\frac{9{,}866{,}752\,L}{1} \times \frac{1\,h}{300{,}000\,L} \qquad [5]$$

It was also assumed that each centrifuge had an operating efficiency of 85%. There were three centrifuges in the harvesting stage, which resulted in an overall process efficiency of 99.66%. The high process efficiency suggests that minimal breakdowns would occur for this process. Therefore, there was no time delay consideration for centrifuge breakdowns in the harvesting process. It was assumed that if time was required for centrifuge maintenance or repair, it would occur between harvesting periods.

Operating Costs

Operational costs play a pivotal role in the economics of microalgae cultivation. Given the nature of the models described thus far, the models quantify process durations for culturing/mixing, culture transfer, maintenance, and raceway sanitation. Identifying costs associated with the previously mentioned time delays would allow for quantification of operational costs. Therefore, the models developed were structured to allow precise determination of various operating costs. These operational costs included electricity for mixing and water, media costs, CO_2 costs and labor costs.
Mixing costs were recorded by a mixing cost attribute which accrued the total mixing costs associated with each item. To determine the culture mixing cost, the culturing duration attribute was utilized to quantify the mixing time required for each item. The culturing duration is multiplied by the power requirement of the mixing devices and a conversion factor of 24 hr d^{-1}. This resulted in the number of kilo-watt hours which was multiplied by the 2009 Texas average electrical rate for an industrial entity. This electrical cost calculation for mixing is displayed in equation 6.

$$\frac{15.2\,d}{1} \times \frac{.003\,kW}{1} \times \frac{24\,h}{d} \times \frac{\$.0804}{kWh} \qquad [6]$$

The resulting value was connected to the mixing costs `attribute set` block. Therefore, as items progressed through the model, the mixing cost attribute was accumulated and attached to each item. The process blocks utilized for mixing costs are depicted in Figure A-25.

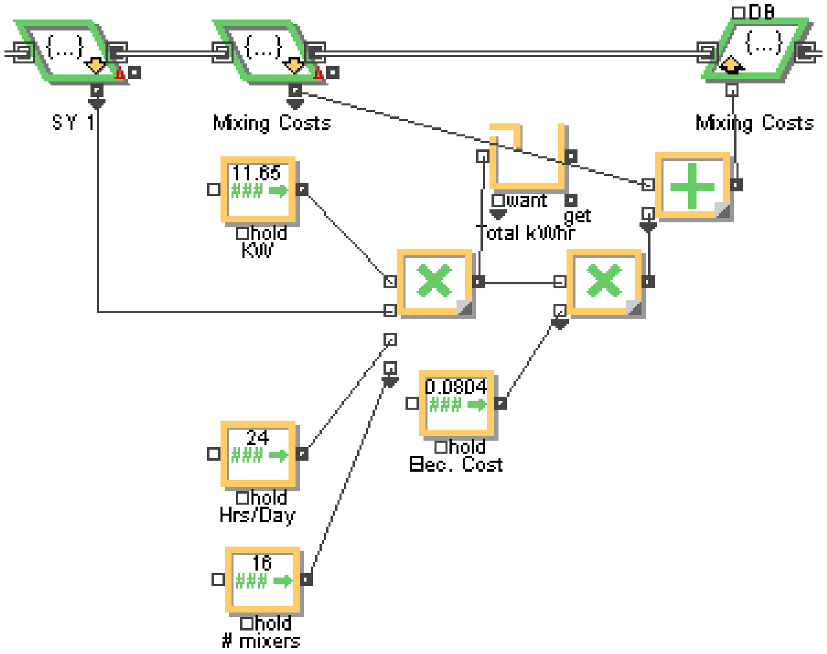


Figure A-25. Mixing costs attribute get and set blocks. Associated value blocks and seasonal yield attribute block required to calculate mixing costs.

Water costs were determined from media composition and evaporation rates. As items advanced to new scaling steps, the inoculating culture was half of the raceway volume. Raceway filling was accomplished by adding water and media to the inoculating culture to achieve full raceway capacity at a culture concentration of 0.5 g L^{-1}. Therefore, the volume of water added in each scaling step was equal to the inoculating volume of microalgae culture received from the previous scaling step. The process blocks employed for water cost calculations are portrayed in Figure A-26.

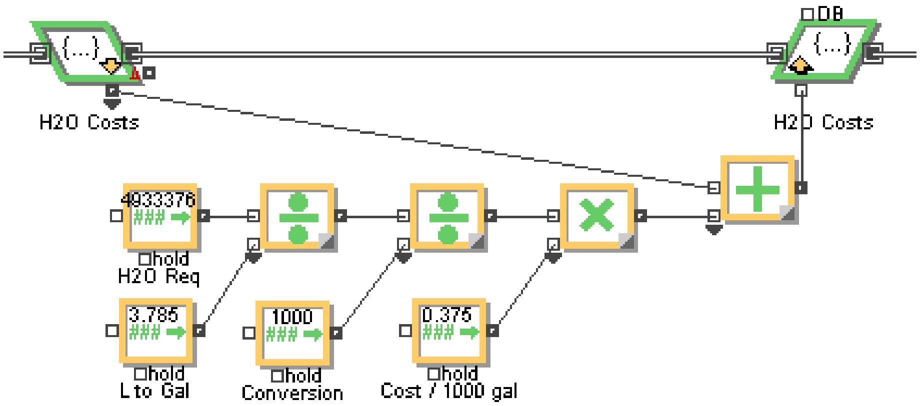


Figure A-26. H_2O cost get and set attribute blocks. Value blocks employed to calculate H_2O costs.

Water costs were calculated through a series of `value` blocks with the resulting value added to each item as an H_2O cost attribute. Each item passes through the H_2O costs `attribute get` block, which yields the water cost from the previous scaling stage. The volume of water required for each scaling stage is divided by a conversion factor of 3.785. This value was then divided by a factor of 1,000 as water costs were based on 1,000 gal increments. The resulting value was then multiplied by a water well cost of \$0.37/1,000 gallons. Equation 7 illustrates the calculation to determine H_2O costs.

$$\frac{9{,}866{,}752L}{1} \times \frac{1\,gal}{3.785\,L} \times \frac{\$0.375}{1{,}000\,gal} \qquad [7]$$

Water costs associated with seasonal evaporation rates were also considered. Seasonal evaporation rates were determined from yearly data located in the western part of Texas. This yearly data was duplicated for a 20 yr period and entered into a `data source table` block. An evaporation attribute was created to incorporate the seasonal evaporation rates which could be quantified based on the time of year. The process blocks employed for evaporation costs are depicted in Figure A-27.

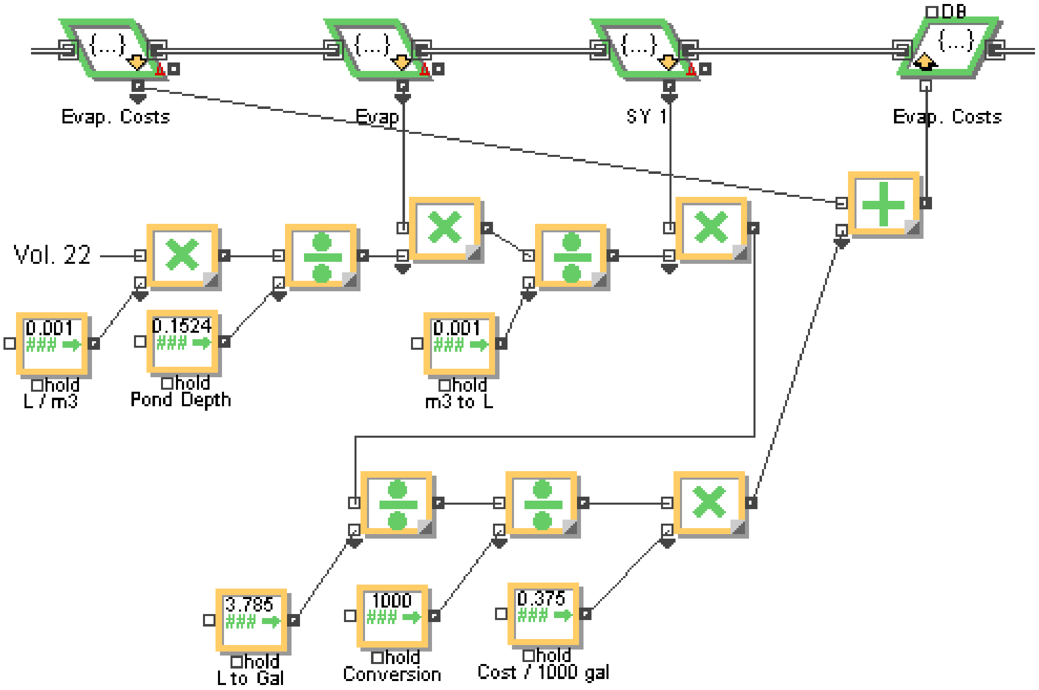


Figure A-27. Evaporation costs get and set attribute blocks. Evaporation attribute and seasonal yield get blocks utilized in unison with value blocks to calculate evaporation costs.

Evaporation costs were calculated by first determining the raceway surface area. Raceway surface area was determined by multiplying the raceway volume by a conversion factor of 0.001. This value was then divided by the assumed raceway depth of 0.1524 m, which yielded the raceway surface area in m^2. The resulting value was then multiplied by the determined evaporation rates, which were quantified in an evaporation `data source table` block. Data source tables were developed for the medium raceway, large raceway and starvation pond scales. Evaporation rates were not considered for the laboratory scale as these evaporation quantities would be minute compared to the overall process. The daily evaporation volume was then multiplied by a conversion factor of 0.001. Determination of the evaporation duration for each item required the employment of the seasonal yield `attribute get` block. The evaporation duration for each item would be equal to the culturing duration in each scaling step. Therefore, the culturing duration value from the seasonal yield `attribute get` block was multiplied by the daily evaporation rates pertaining to the time of year items are processed. To actuate the evaporation cost, the total volume of evaporation for each item is divided by a conversion factor of 3.785. This value is then divided by a conversion factor of 1,000 and multiplied again by a water usage cost of $0.37/1,000 gal. The resulting calculation is represented in equation 8.

$$\frac{9{,}866{,}752\,L}{1} \times \frac{0.001\,m^3}{L} \times \frac{depth}{.1524\,m} \times \frac{0.007m}{d} \times \frac{L}{0.001\,m^3} \times \frac{15.2\,d}{1} \times \frac{gal}{3.785\,L} \times \frac{\$0.375}{1{,}000\,gal} \qquad [8]$$

The calculated value was then added to the previous scaling step water evaporation cost which was derived from the evaporation cost `attribute get` block. The accumulated evaporation cost was then set as the new evaporation cost attribute. As items progressed through each model, media costs were calculated for each scaling step. Media costs were based on proprietary media recipes and bulk quantity costs. The laboratory media recipe and costs were different from both the medium and large scale raceways. A cost of \$0.07 L^{-1} was determined for the laboratory scale while the medium and large raceway scale media recipe yielded a cost of \$0.00484 L^{-1}. A media cost attribute was implemented for each scaling step through a pair of media cost `attribute get` and `set` blocks. The media `set` and `get attribute` blocks are illustrated in Figure A-28.

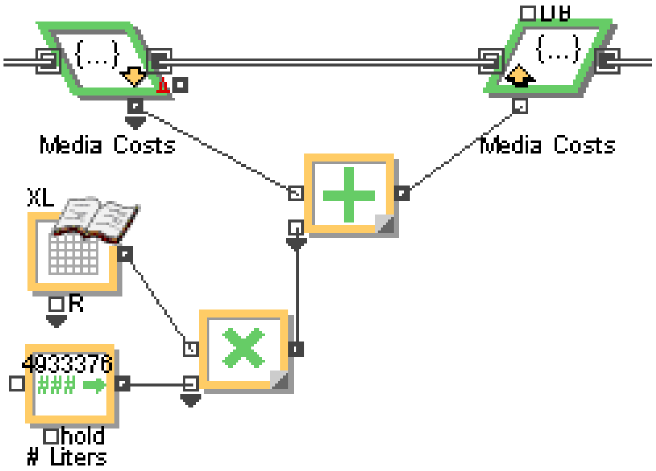


Figure A-28. Media costs attribute get and set blocks. Value read block and other value blocks required to calculate media costs.

Media costs for each scaling step were calculated through a series of `value` blocks. The media recipe and costs for the laboratory, medium raceways, large raceways and starvation ponds were recorded in an Excel spreadsheet and linked to a `read` `value` block which imported the appropriate media cost for each scale. Since the inoculating culture volume was diluted from 1 g L^{-1} to 0.5 g L^{-1}, the media cost value derived from the `read value` block was multiplied by the inoculating volume of culture. This amount was then added to the value derived from the media cost `attribute get` block. The resulting accumulated media cost was then set as the new media cost attribute through the `attribute set` block.

CO_2 was not included in the media recipes mentioned in the previous paragraph. Therefore, carbon dioxide costs were tabulated for each scaling step separately from the media costs. The process blocks employed for CO_2 consumption and costs are depicted in Figure A-29.

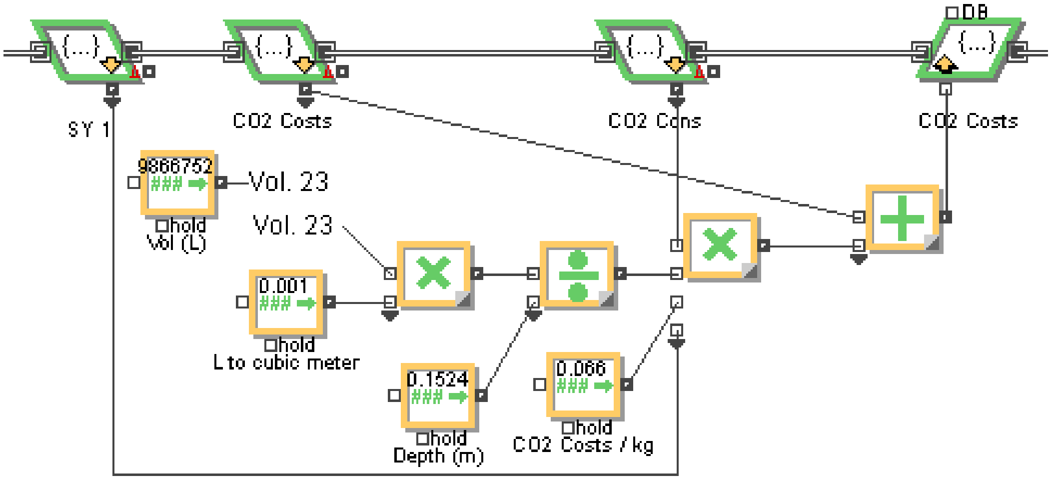


Figure A-29. CO2 costs get and set attribute blocks. CO_2 consumption attribute and seasonal yield get blocks utilized together with value blocks to calculate CO_2 costs.

CO_2 costs were calculated by first determining the raceway surface area. The raceway volume is multiplied by a conversion factor of 0.001. This value was then divided by an assumed pond depth of 0.1524 m which yields the raceway surface area in m^2. The raceway surface area was then multiplied by seasonal CO_2 consumption rates, and the assumed CO_2 cost of \$0.066 kg^{-1}. The resulting CO_2 cost calculation is portrayed in equation 9.

$$\frac{9{,}866{,}752\,L}{1} \times \frac{0.001\,m^3}{L} \times \frac{depth}{.1524\,m} \times \frac{0.007\,kg}{depth} \times \frac{15.2\,d}{1} \times \frac{\$0.066}{kg} \qquad [9]$$

Daily monitoring of all outdoor microalgae cultures was assumed to be necessary in order to evaluate culture quality. This would be accomplished through measurement of pH , optical density of the culture, electrical conductivity, ash free dry weights, nitrate concentration, and dissolved oxygen concentration. These measurements would be executed for each scaling step and would be conducted by laboratory personnel. Therefore, lab labor costs are calculated for daily culture testing and were implemented into the models. The blocks utilized for daily culture testing labor costs are illustrated in Figure A-30.

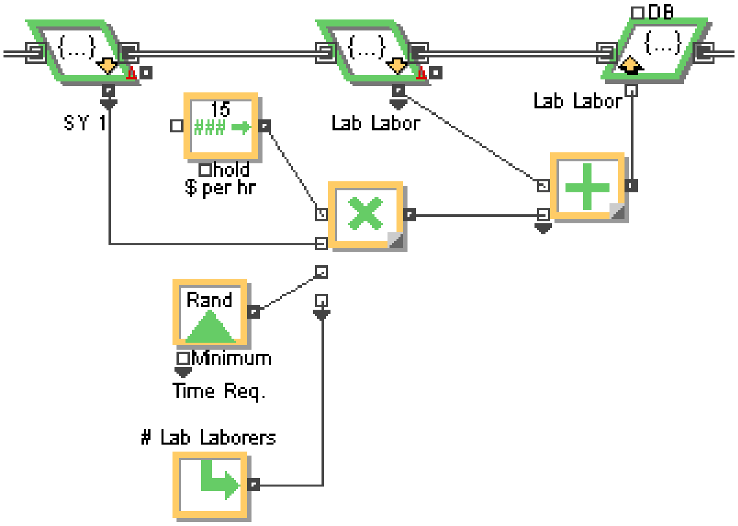


Figure A-30. Laboratory labor cost get and set attribute blocks. Seasonal yield, random distribution time requirement block and value block utilized to enumerate laboratory labor costs.

The time required to collect, prepare and evaluate culture samples was determined by a triangular distribution in a `random value` block. The required time was assumed to be consistent for all scaling steps in each model. The triangular distribution time increments consisted of a minimum time of 15 min, an average time of 30 min and a maximum time of 45min. Samples would be collected on a daily basis therefore; the number of samples collected for each item was determined by culture duration through the seasonal yield `attribute get` block. This value is multiplied by the labor rate of \$15 hr^{-1} and the average collection time determined from the triangular distribution. The culture monitoring labor cost is represented in equation 10.

$$\frac{15.2\ d}{1} \times \frac{.52\ h}{1} \times \frac{\$15}{h} \times \frac{1\ laborer}{d} \qquad [10]$$

The resulting amount was then added to the collection and analyzing cost from the previous scaling step. The final value was then attached to each item through the lab labor `attribute set` block.

The labor requirement for centrifugation was calculated through a series of `value` blocks depicted in Figure A-31.

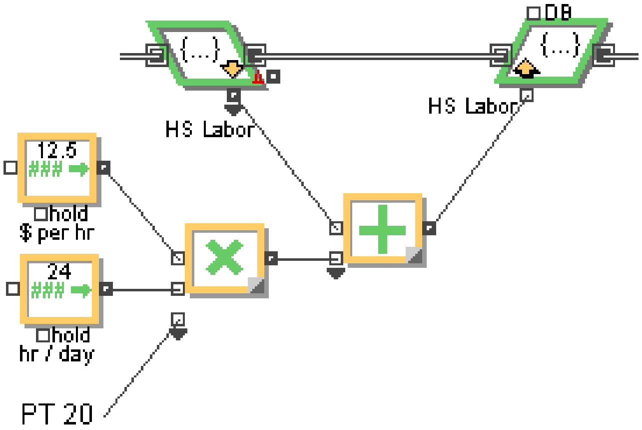


Figure A-31. High school labor cost get and set attribute blocks. Value blocks employed to calculate centrifuge labor costs.

The harvesting labor cost is calculated by multiplying the processing time from the centrifuge `activity` block by the labor rate of \$12.50 hr^{-1} and a conversion factor of 24 hr d^{-1}. The resulting value was then added to the value from the high school labor `attribute get` block. The labor for centrifugation is illustrated in equation 11.

$$\frac{.07\ d}{1} \times \frac{24\ h}{d} \times \frac{\$10}{hr} \qquad [11]$$

The accumulated value was then set as the new H.S. Labor cost through the H.S. Labor `attribute set` block. As each item exits the model, the accumulated costs associated with that item pass through a series of `attribute get` blocks. The values derived from the cost `attribute get` blocks are conveyed to a value holding tank in which the cost specific to that `attribute` block are summed together for all the items. The resulting value was then transferred to a `throw value` block, which conveys the value to a `catch value` block. The blocks utilized for this process are depicted in Figure A-32.

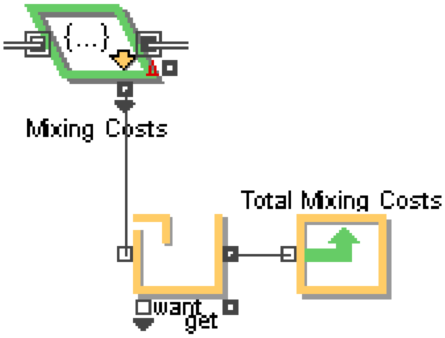


Figure A-32. Mixing costs attribute get block connected to a holding tank and then a value throw block.

The initial operational costs derived from the models include: mixing power costs, harvesting power costs, water supply power costs, media costs, CO_2 costs and labor costs. Subsequent operational costs included: other power costs and maintenance, tax and insurance costs. Other power costs were assumed to be 1% of the accumulated mixing, harvesting and water supply power costs. Maintenance, tax and insurance costs were assumed to be 5% of the net capital costs.

Once the value was received by the `catch` block, it was rounded to three significant figures. The value was then transferred to an excel spreadsheet through a `value write` block. This allowed all the costs resulting from the model to be imported into an Excel spreadsheet. The `value` blocks utilized for this process are depicted in Figure A-33.

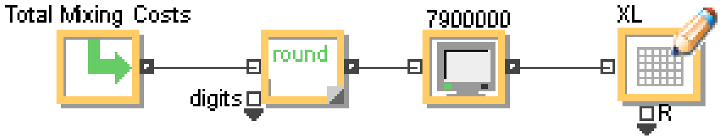
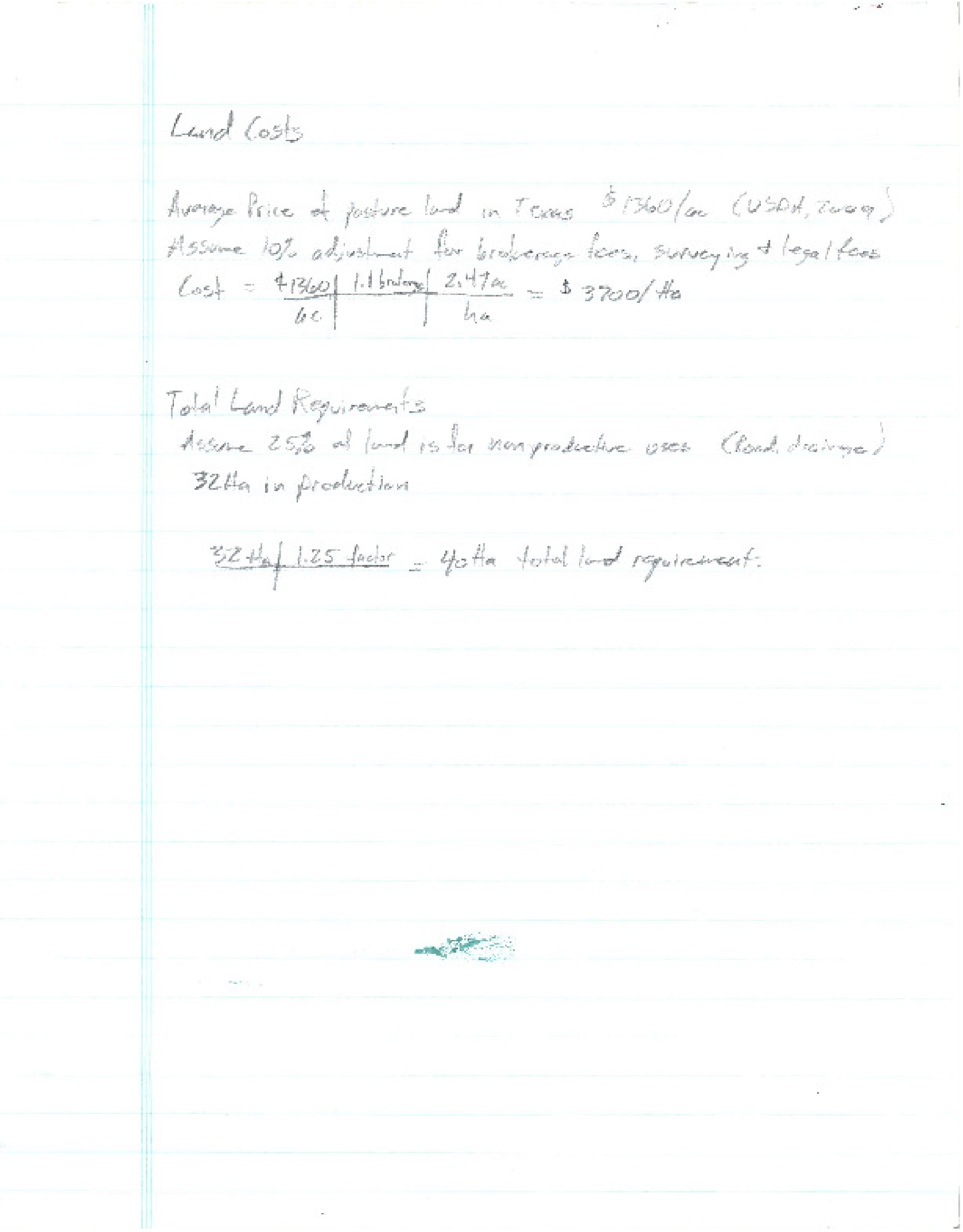


Figure A-33. Total mixing costs catch block, a round value up block, a display block and a value write block linked to an excel spreadsheet.

APPENDIX B

CAPTIAL ITEM COST CALCULATIONS



Land Costs

Average Price of pasture land in Texas \$1360/ac (USDA, 2009)
Assume 10% adjustment for brokerage fees, surveying + legal fees

$$\text{Cost} = \frac{\$1360}{\text{ac}} \Big|\ 1.1\ \text{brokerage} \Big| \frac{2.47\ \text{ac}}{\text{ha}} = \$3700/\text{Ha}$$

Total Land Requirements
Assume 25% of land is for nonproductive uses (Road, drainage)
32Ha in production

$$\underline{32\ \text{Ha} \,\big|\, 1.25\ \text{factor}} = 40\ \text{Ha}\ \text{total land requirement.}$$

SITE PREPARATION

① Primary Clearing
- Average cost of site clearing $470/ha (USDA, 2008), Texas

② Site Plowing
- Custom plowing rate for Texas $50/ha

③ Site Leveling
- Cost of Laser leveling $240/ha (Salassi, 2001)
- Assume 2 passes required

$$\frac{\$240}{\text{Ha}} \bigg| \frac{2\text{ passes}}{} = \$480/\text{Ha}$$

④ Site Compaction
- Highes farm custom rate $25/Ha (Edward, 2009)
- Assume 2 passes required

$$\frac{\$25}{\text{Ha}} \bigg| \frac{2\text{ passes}}{} = \$50/\text{Ha}$$

⑤ Site Surveying
- Surveying costs $2134/day (RSM, 2009)
- Assume 5 Ha could be surveyed in an 8 hr day

$$\frac{\$2134}{\text{day}} \bigg| \frac{1\text{ day}}{5\text{ Ha}} = \$425/\text{Ha}$$

TOTAL = $1475/Ha

RACEWAY LEVEES AND DIVIDERS

- Assume 1 hr to complete a .4 ha raceway for each step

① Plowing
- Custom Moldboard Plowing $17.51/ac (USDA, 2008)

$17.51 (2.47 ac/ha) = $45/ha

② Construct Levees

$45/ha

③ Levee Compaction

$45/ha

TOTAL = $135/ha

RACEWAY LEVELING

- Assume to be done with 13.6 MT grader w/ laser level
- Assume a grader could level .4 ha/hr
- Cost $1494/day (RSM, 2009) CREW B-11L

$$\frac{\$1494}{\text{day}} \Big| \frac{1\ \text{day}}{8\ \text{hr}} \Big| \frac{1\ \text{hr}}{.4\ \text{ha}} = \$470/\text{Ha}$$

- Assume raceway dividers constructed while pond is leveled.

SUMP CONSTRUCTION

Sump 1: (Media, H_2O, CO_2 + Drainage)

- Assume sump is width of raceway + approx. .31 m deep.
- Assume .4 ha raceway sump is constructed in 1 hr.

Cost $1212.38/day (excavation of soil)

$$\frac{\$1212.38}{\text{day}} \cdot \frac{1\text{ day}}{8\text{ hr}} \cdot \frac{1\text{ hr}}{.4\text{ ha}} = \$380/\text{ha}$$

UB Model = (11,495)(31.90)

= $366690 / 83 sumps = $4417/sump (x2)

366690 − 8835 = 357,855/30.9

≈ $11,220

Sump 2: (Electric Mixer Sump)

- Excavation Soil, Construct Forms, Concrete
- Excavation: $1268/Day (RSM, 2009) <u>CREW B11M</u>
- Construct Forms $2963/day (RSM, 2009) <u>CREW C-14H</u>
- Concrete

Sin = O/H

Cos = A/H

Tan = O/A

4" thick, .33 ft

4ft wide

Wall Area = 100' x 6 x .33' = 198 ft^3

x 2

396 ft^3

Floor Area = 70' + (16.15 x 2) x 4' x .33'

Floor Area = 135 ft^3

National Avg Cost Concrete = $\frac{\$75/\text{cu yd}}{(\$98/\text{m}^3)}$ (concrete only) TOTAL = 531 ft^3

$$\frac{531\text{ ft}^3}{} \cdot \frac{\text{cu. yd}}{27\text{ ft}^3} \cdot \frac{\$75}{\text{cu. yd}} = \$1475/\text{ac}$$

(1,475)(2.5 ac/ha) = $3690/ha

20 cu yd / sump

= 15.3 m^3

Excavation Assume: 1 hr / .4 ha = ($1268/day) (.125 day / .4 ha) = $395/ha

Construct Forms Assume: Construct 1 Form/day = ($2963/sump)(1 sump/.4 ha) = $7410/ha

Concrete Assume: 15.3 m^3 / .4 ha = ($1475/sump)(1 sump/.4 ha) = $3,690/ha

TOTAL = 11,495/ha

POND LINER

Liner Bare Costs = $4.74 m² (RSM, 2009)

Reevaluation of Installation Costs:

1 Foreman, 4 laborers	$ 1985/day	CREW B-2
1 operator, 1 laborer, 1 grader	$ 1495/day	CREW B-11L
1 operator, 1 Forklift	$ 380/day	CREW B-68
TOTAL	$3860	

Assume: .4 ha of liner is installed in 1 day

$$\frac{\$3860}{day}\Bigg|\frac{1\,day}{.4\,ha}\Bigg|\frac{1\,ha}{10{,}000\,m^2} = .965/m^2$$

$$\begin{array}{rl} \text{Total Cost} = & 4.74 \\ & \underline{+\,.965} \\ & 5.70/m^2 \longrightarrow \$57{,}000/ha \end{array}$$

31.90 ha

ELECTRIC MIXERS

VB Model subtract $17,582 (127,110 /ha)

FPR Model subtract $97,783 (127,585) 31.95 ha

Pond Size (ha)	Pump Size (hp)	Cost	# Ponds	TOTAL
.0032	2.5	17,582	1	17,582
.0063	2.5	17,582	1	17,582
.0126	2.5	17,582	1	17,582
.0253	4	18,190	1	18,190
.0506	8.3	26,847	1	26,847
.1012	15	31,749	1	31,749
.2023	20	43,092	1	43,092
.4047	40	52,373	78	$4,085,094

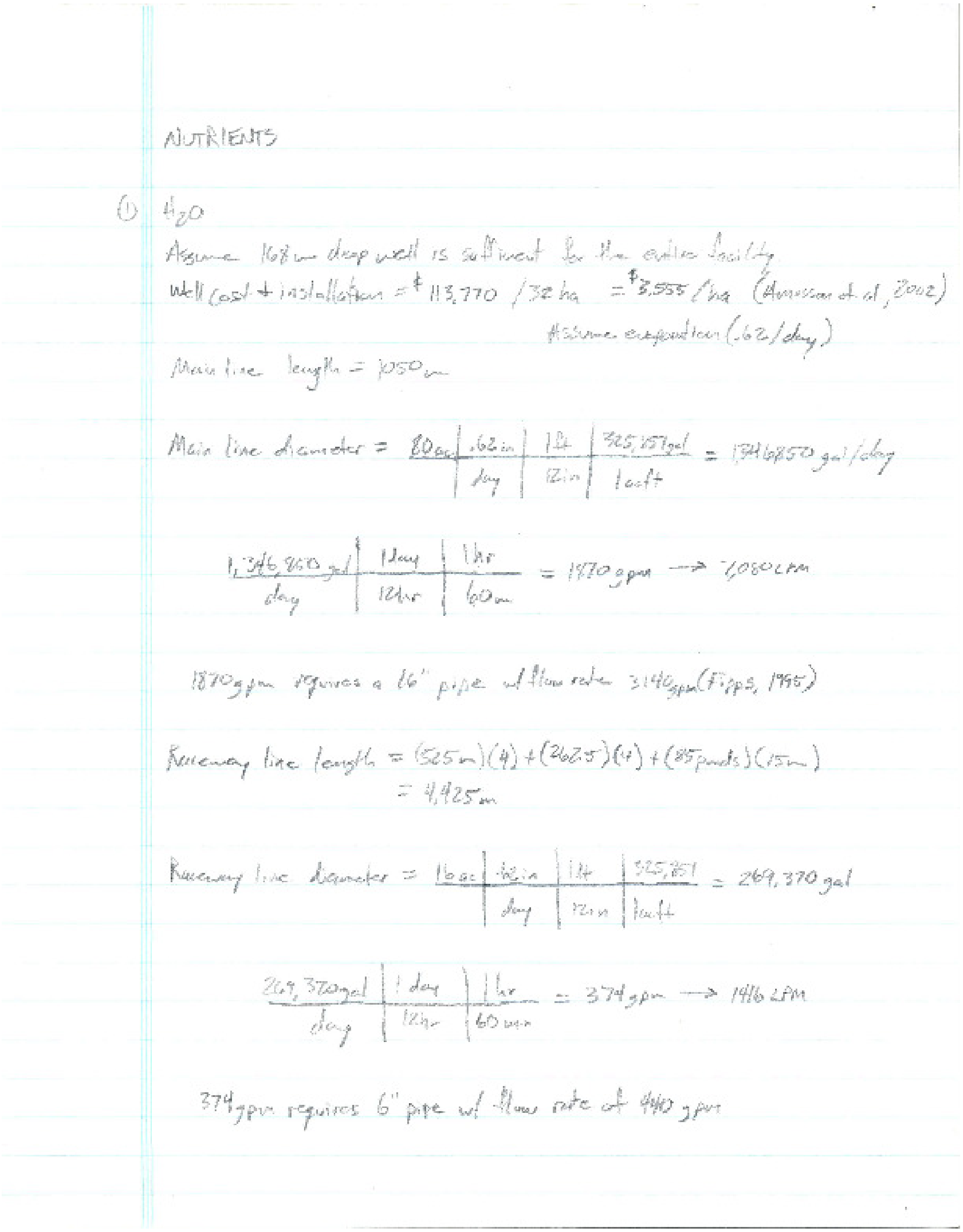
TOTAL $4,257,718

= $133,055/ha

40 hp pump was assumed effective for a .4 ha raceway
Since raceway size is reduced by ½, pump size was reduced by ½

(Flygt, 2010)

* FPR
- Compressor –
- Chiller – 17,700 w



NUTRIENTS

① H_2O

Assume 168 m deep well is sufficient for the entire facility

Well cost + installation = $113,770 / 32 ha = $3,555/ha (Amesson et al, 2002)

Assume evaporation (.62/day)

Main line length = 1050 m

$$\text{Main line diameter} = \frac{80\,\text{ac}}{} \bigg| \frac{.62\,\text{in}}{\text{day}} \bigg| \frac{1\,\text{ft}}{12\,\text{in}} \bigg| \frac{325,851\,\text{gal}}{1\,\text{ac ft}} = 1346850\ \text{gal/day}$$

$$\frac{1,346,850\,\text{gal}}{\text{day}} \bigg| \frac{1\,\text{day}}{12\,\text{hr}} \bigg| \frac{1\,\text{hr}}{60\,\text{m}} = 1870\ \text{gpm} \rightarrow 7,080\ \text{LPM}$$

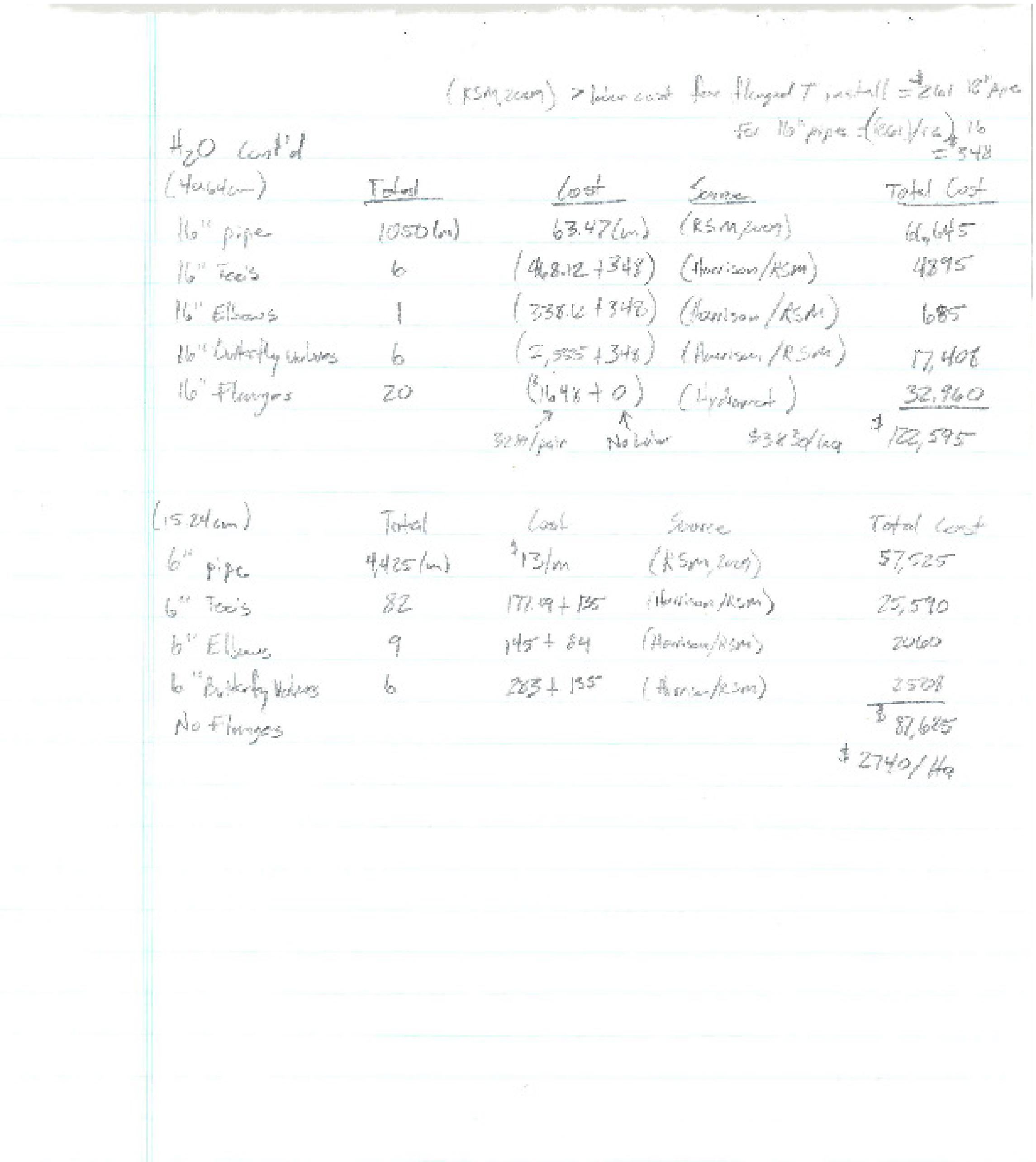
1870 gpm requires a 16" pipe w/ flow rate 3140 gpm (Fipps, 1995)

$$\text{Raceway line length} = (525\,\text{m})(4) + (262.5)(4) + (85\,\text{ponds})(15\,\text{m})$$
$$= 4,425\,\text{m}$$

$$\text{Raceway line diameter} = \frac{16\,\text{ac}}{} \bigg| \frac{.62\,\text{in}}{\text{day}} \bigg| \frac{1\,\text{ft}}{12\,\text{in}} \bigg| \frac{325,851}{1\,\text{ac ft}} = 269,370\ \text{gal}$$

$$\frac{269,370\,\text{gal}}{\text{day}} \bigg| \frac{1\,\text{day}}{12\,\text{hr}} \bigg| \frac{1\,\text{hr}}{60\,\text{min}} = 374\ \text{gpm} \rightarrow 1416\ \text{LPM}$$

374 gpm requires 6" pipe w/ flow rate of 440 gpm

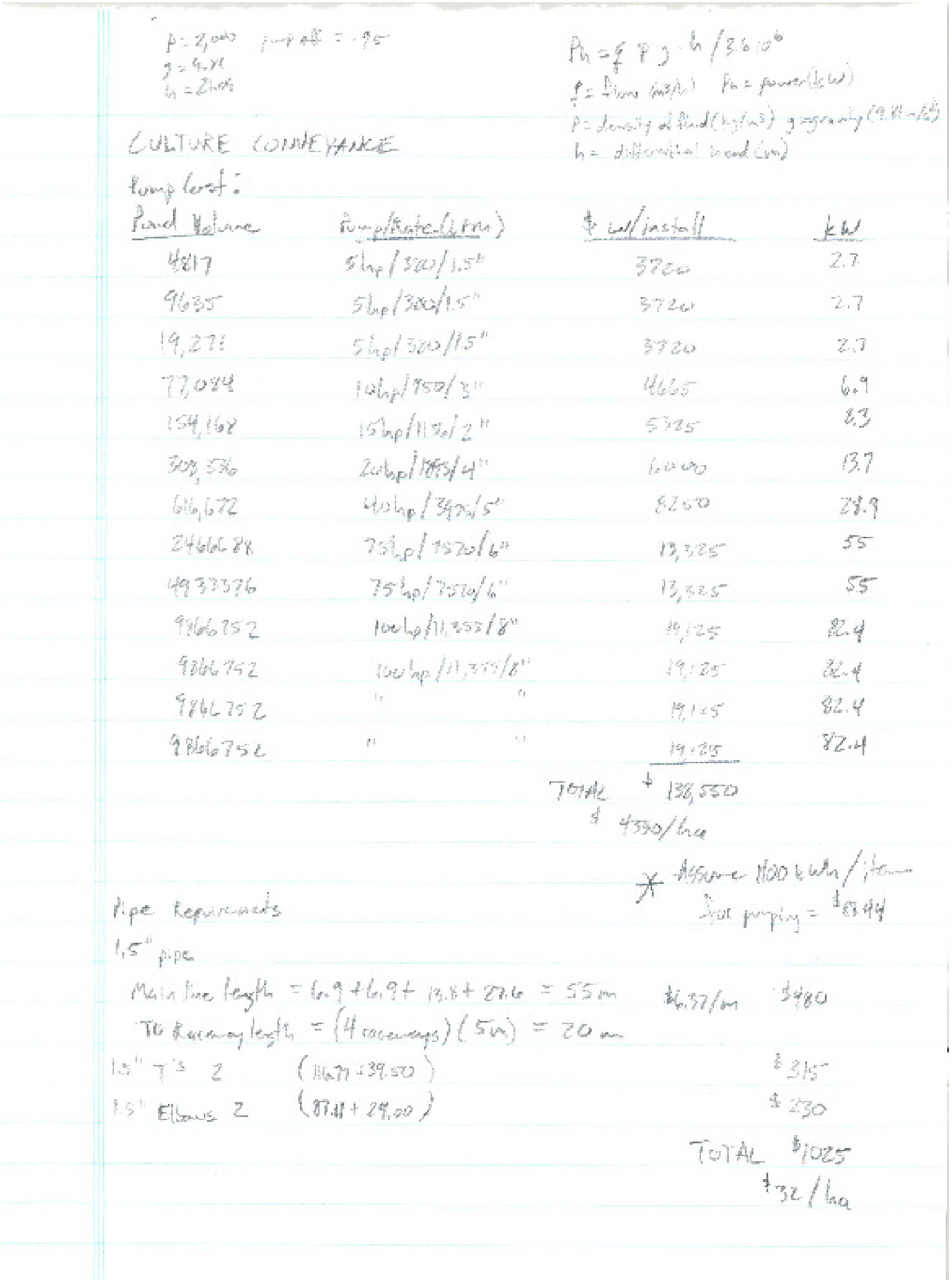


(RSM, 2009) > labor cost for flanged T install = $391 18" pipe
for 16" pipe = (391/18) 16
= $348

H₂O Cont'd

(40.64cm)	Total	Cost	Source	Total Cost
16" pipe	1050 (m)	63.47 (m)	(RSM, 2009)	66,645
16" Tee's	6	(468.12 + 348)	(Harrison/RSM)	4895
16" Elbows	1	(338.6 + 348)	(Harrison/RSM)	685
16" Butterfly valves	6	(2,555 + 348)	(Harrison/RSM)	17,408
16" Flanges	20	($1648 + 0)	(Hydromart)	32,960
		3296/pair No Labor	$3830/ha	$ 122,595

(15.24cm)	Total	Cost	Source	Total Cost
6" pipe	4,425 (m)	$13/m	(RSM, 2009)	57,525
6" Tee's	82	177.09 + 135	(Harrison/RSM)	25,590
6" Elbows	9	145 + 84	(Harrison/RSM)	2060
6" Butterfly Valves	6	283 + 135	(Harrison/RSM)	2508
No Flanges				$ 87,685
				$ 2740/Ha



ρ = 1,000 pump eff = .95
g = 9.81
h = 21.06

$Ph = q\,\rho\,g \cdot h / 3.6 \cdot 10^6$
q = flow (m3/h) Ph = power (kW)
ρ = density of fluid (kg/m3) g = gravity (9.81 m/s2)
h = differential head (m)

CULTURE CONVEYANCE

Pump Cost:

Pond Volume	Pump/Rate (LPM)	$ w/install	kW
4817	5hp/300/1.5"	3720	2.7
9635	5hp/300/1.5"	3720	2.7
19,271	5hp/300/1.5"	3720	2.7
77,084	10hp/950/3"	4665	6.9
154,168	15hp/1130/2"	5325	8.3
308,336	20hp/1885/4"	6000	13.7
616,672	40hp/3475/5"	8250	28.9
2466688	75hp/7570/6"	13,325	55
4933376	75hp/7570/6"	13,325	55
9866752	100hp/11,355/8"	19,125	82.4
9866752	100hp/11,355/8"	19,125	82.4
9866752	" "	19,125	82.4
9866752	" "	19,125	82.4

TOTAL $ 138,550
$ 4330/ha

* Assume 1100 kWh/item for pumping = $88.44

Pipe Requirements

1.5" pipe

Main line length = 6.9 + 6.9 + 13.8 + 27.6 = 55 m $6.37/m $480
To Raceway length = (4 raceways)(5 m) = 20 m
1.5" T's 2 (116.79 + 39.50) $315
1.5" Elbows 2 (87.41 + 29.00) $230

TOTAL $1025
$32/ha

6" pipe

Main line length = 82.9 + 110.6 + (525/2) + (15 · 3) + 152.4 + (525/2)
+ (15 · 4) + (150) + (525/2) + (15 · 2) + (150 · 2)
= 1700m

Flanges for T's & Butterfly valves

	TOTAL	COST	SOURCE	TOTAL COST
6" pipe	1700m	$13.00	(KSM, 2009)	$22,100
6" T's	17	177.09 + 135.00	(Harrison, KSM)	$5305
6" Elbows	3	145.00 + 84.00	(Harrison, KSM)	$687
6" Flanges	34	$93.36 + No Labor	(Hydromat)	$3175
6" Butterfly valves	17	$283 + 135	(Stockham)	$7105
				$38,370
				$1200/ha

8" pipe

8" pipe length = (1050 + 4425) − (70 + 1700) = 3705m

	TOTAL	Cost	Source	Total Cost
8" pipe	3705m	19.02	(KSM, 2009)	70,470
8" T's	63	255.56 + 174.00	(Harrison, KSM)	27,060
8" Elbows	5	162.67 + 116.00	(Harrison/KSM)	1395
8" Flanges	130	158.57 + No labor	(Hydromat)	20,615
8" Butterfly Valves	67	402 + 174.00	(Stockham)	12,060
				$131,600
				$4110/ha

CULTURE CONVEYANCE TOTAL COST $5340/ha
PUMP COST $4330/ha

NUTRIENT STORAGE (FPR MODEL)

Transfer Volume = 15,996 + 154,168 + 308,336 + 616,672 + 1233344 + 2466688 + 4933376 (4) = 24528708 (L)

Starvation Ponds = 4933376 (3) = 14,800,120 (L)

Culturing Ponds = 24,528,708 - 14,800,120 = 9,728,588 (L)

Compound	Total (kg)/L	367,930 Total Weight (kg)	170.51 Total (kl)
A	.015	(24528708 x .015)	(367930 x 2.2)/17.97/264.17)
B	.0002414	2349.48	1.78
C	.000025	613.22	.63
D	.000075	1839.65	1.90
E	.00000436	106.95	.11
F	.000129	3164.2	3.27
G	.000033	321.04	.33
H	(.07 mL/L)		.213
I	(.005 mL/L)		.015

Fertilizer Density: NaHCO$_3$ 17.97 lb/gal
N 11 lb/gal
P 8.07 lb/gal
K 8.07 lb/gal

Density Assumed for All other compounds = 8.07 lb/gal

Nutrient Storage Cost

.5g/L → 1g/L

Depth = .1524 m

Assume 37g/m² /day growth Rate

1L = .001 m³

$$\frac{37\,g}{m^2\text{-}day}\;\Big|\;\frac{.001\,m^3}{.1524\,m}\;\Big| = .243\,g/d \longrightarrow (.243\,g/day)/(.5\,g/L) = 2.06\text{ days}$$

Assume 1 week supply on hand = 8 days / 2.06 = 4x Original Amount

Compound	Volume (kl)	Total Volume (kl)
A	170.51	(170.51)(4) = 682.04
B	1.78	7.12
C	.63	2.52
D	1.90	7.6
E	.11	.44
F	3.27	13.08
G	.33	1.32
H	.213	.852
I	.015	.06

Compound	Tank Size (kl)/gal	# Tanks	Cost/Tank w/stand	Total Cost
A	31.23 / 8250	22 (15% [illegible])	$7555	$166,220
B	10.15 / 2500	1	$2060	→
C	3.78 / 1000	1	$1290	→
D	10.15 / 2500	1	$2060	→
E	.75 / 200	1	$530	→
F	17.41 / 4600	1	$4545	→
G	1.89 / 500	1	$860	→
H	1.32 / 350	1	$655	→
I	.75 / 200	1	$530	→

TOTAL COST (178,240)

Nutrient Storage Cost

Tank agitation: 2" Outlets (5.08cm)

(RSM, 2009)

Tank Size	Pump (Hp/$\overset{\text{GPM}}{\text{Rate}}$)	# Pumps	Total Cost
31.23/8250	10/200	22	93,060
10.15/2500	3/50	1	1190
3.78/1000	3/50	1	1190
10.15/2500	3/50	1	1190
.75/200	3/50	1	1190
17.41/4600	7.5/100	1	2155
1.89/500	3/50	1	1190
1.32/350	3/50	1	1190
.75/200	3/50	1	1190

TOTAL Cost $103,545

$3235/ha

Nutrient Conveyance

Assume 2" or 5.08cm pipe for nutrient transfer.

* Assume Culture Conveyance Infrastructure used for nutrient conveyance.

CO_2 CONVEYANCE

Assume 2" (5.08cm) pipe is sufficient

	Total	Cost	Source	Total Cost
2" pipe	5475 (m)	6.37	(RSM 2009)	$ 34,875
2" Tees	76	2.44 + 39.50	(Home Depot/RSM)	$ 3190
2" Elbows	10	1.80 + 29.00	(Lowes/RSM)	$ 308
2" ball valves	84	6.35	(RSM, 2009)	$ 535

No flanges

TOTAL COST $ 38,908

$ 1215 / ha

CO_2 Storage

C	H	O	N	S
12	1	16	14	32

$$6CO_2 + 12H_2O \longrightarrow 6(\underset{\text{glucose}}{CH_2O}) + 6H_2O + 6O_2$$

Compound	MW (g/mol)	Mass g's biomass
→ CO_2	44	264
H_2O	18	216
→ $C_6H_{12}O_6$	180	180
O_2	32	192

$$\frac{264g\ CO_2}{180g\ \text{biomass}} = 1.467g$$

$PV = nRT$

p = pressure (Pa)

V = volume m^3

n = # moles

R = constant

T = kelvin (K)

$$\frac{37g}{m^2 \cdot d} \left| \frac{1.467g}{1g} \right| \frac{1\ \text{mole}}{44g} \left| \frac{10,000\ m^2}{1\ ha} \right| 32\ ha = 394,756\ \text{mol/d}$$

Assume tank pressure of 250 psi = 1,723,500 pa

$$1,723,500\,(V) = (394,756)(8.314)(273)$$

$$V = 519\ m^3/\text{day}$$

CO_2 Storage con't

519 m^3 of CO_2 / day

Tank size 9300 gal @ 250 psi Cost = \$75,000

9300 gal = 35.2 m^3

Assume 2 day storage

$$\frac{519\ m^3}{day}\bigg|\frac{1\ tank}{35.2\ m^3}\bigg|\frac{2\ day}{storage} = 30\ tanks$$

Assume 15% discount on bulk purchase

TOTAL Cost = \$1,912,500

HARVESTING

Centrifuge capacity 900 hL/hr

$$\frac{900\,\text{hL}}{\text{hr}} \left| \frac{100\,\text{L}}{1\,\text{hL}} \right| \frac{1\,\text{hr}}{60\,\text{min}} = 1500\,\text{L/min}$$

Centrifuge

Harvest volume 9,866,752 L

Shortest Culturing Period 3.8 days. Centrifuges can be added easily

10 lb/gal Density of Paint = 4536 g/gal ≈ 1200 g/L

$$\frac{9,866,752\,\text{L}}{\text{Harvest}} \left| \frac{\text{Culturing period}}{2\,\text{days}} \right| \frac{1\,\text{day}}{12\,\text{hr}} \left| \frac{1\,\text{hr}}{60\,\text{min}} \right| \frac{\text{Centrifuge rate}}{1500\,\text{L/min}} = 5\text{ centrifuges}$$

Centrifuge Cost: $229,268/unit (via Green Hill)

Volume after centrifugation = 986675 L @ 10 g/L

Drum Dryer

$$\frac{986,675\,\text{L}}{} \left| \frac{\text{Batch}}{3.5\,\text{days}} \right| \frac{\text{Drum Size}}{134\,\text{m}^2} \left| \frac{\text{m}^2\text{-hr}}{20\,\text{L}} \right| \frac{}{24\,\text{hr}} = 5\text{ dryers}$$

1440 ft² Dryer Cost: $325,000/unit (matche.com)

Evaporation (20 L/hr·m²) → 3200–6500 kJ/kg evaporated H_2O (Handbook of industrial drying)

Natural gas = 1055 kJ

$$\frac{3200\,\text{kJ}}{\text{kg}\,H_2O} \left| \overset{\text{Density } H_2O}{\frac{3.785\,\text{kg}}{1\,\text{gal}}} \right| \frac{1\,\text{gal}}{3.785\,\text{L}} \left| \frac{986675\,\text{L}}{\text{Harvest}} \right| = 3,155,691,646\,\text{kJ}$$

eia.doe.gov (Nov, 2010)

$$\frac{3,155,691,646\,\text{kJ}}{\text{Harvest}} \left| \frac{\text{m}^3}{38,300\,\text{kJ}} \right| \frac{\$4.51}{28.32\,\text{m}^3} \right| = \$13,120/\text{Harvest}$$

or $1.33/kg DW

Natural Gas eia.gov industrial: $4.51/1,000 ft³ = 28.32 m³

HARVESTING Con't

Assume: 986675 L will be transported to process facility by pipeline
Infeasible to ship by truck, rail too slow

Truck

$$\frac{25\text{ ton}}{\text{truck}} \Big| \frac{2{,}000\text{ lb}}{\text{ton}} \Big| \frac{\text{gal}}{8.34\text{ lb}} = 5{,}995\text{ gal}$$

Tank Capacity only 5,995 gallons

$$\frac{9{,}866{,}752\text{ g}}{986{,}675\text{ L}} \Big| \frac{3.785\text{ L}}{\text{gal}} \Big| \frac{5{,}995\text{ gal}}{\text{load}} \Big| \frac{1\text{ kg}}{1{,}000\text{ g}} \Big| \frac{2.2\text{ lb}}{1\text{ kg}} \quad 5200\text{ lb DW/load}$$

$$\frac{986{,}675\text{ L}}{} \Big| \frac{1\text{ gal}}{3.785\text{ L}} \Big| \frac{}{5{,}995\text{ gal}} = 44\text{ loads/harvest}$$

POWER HARVESTING
5 centrifuges, 100 kW power input, $.0804/kWh, 900 hl/hr

$$\frac{5\text{ cent}}{5\text{ cent}} \Big| \frac{100\text{ kW}}{} \Big| \frac{9{,}866{,}752\text{ L}}{90{,}000\text{ L/hr}} \Big| \frac{.0804}{\text{kWhr}} \Big| = \$\ 880\text{ /harvest}$$

POWER H_2O SUPPLY

Assume 168m deep well (Amosson et al. 2001)

Operating Costs: (SAI 168m well) ($\$2.71/\text{MCF}$) $\text{MCF} = 1{,}000\ \text{ft}^3$

Fuel: $\$3.33/2.71 = 1.23\%$

Updated fuel cost: $\$(4.53)(1.23) = \$5.57/\text{ac-in}$

(Labor/Maintenance/Repair) LMR 65% of fuel cost

$\text{LMR} = (\$5.57)(.65) = \$3.62$

$\text{Labor} = (.59/3.33) = (.18)(5.57) = \$1.00/\text{ac-in}$

Total Operating cost $= \$10.19/\text{ac-in}$

$$\rightarrow \quad \frac{\$10.19}{\text{ac-in}}\ \Big|\ \frac{12\text{in}}{1\text{ft}}\ \Big|\ \frac{1\text{ac-ft}}{325{,}851\text{gal}}\ \Big|\ \frac{1000\text{gal}}{\$} = \$.375/1{,}000\text{gal}$$

POWER SUPPLY OTHER

$3600/ha as determined by Beavans + Oswald, (1996) NUTRIENT COST (Refer to spreadsheet)

.00787/L Lab Media Costs

.00434 / L Outdoor Media Costs

.00410/L Starvation Pond Media Costs

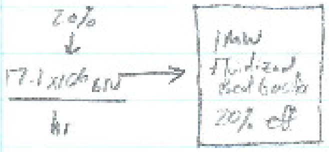
Transfer Volume = 24,594,753 L

Current transfer volume: (9,866,757 L) ($.00787/L) = $77,651

APPENDIX C

LEA FOR POWER GENERATION

LEA for Power Generation



$$\frac{1{,}000 \text{ kwh}}{\text{hr}} \times \frac{3412 \text{ BTU}}{\text{kwh}} = \frac{3.41\times10^6 \text{ BTU}}{\text{hr}}$$

Assumptions:

Algae oil = 30%

LEA = 70%

Energy content = $\frac{22{,}000 \text{ BTU}}{\text{kg}}$

Electricity value = $\frac{\$0.15}{\text{kWh}}$

$$\frac{17.1\times10^6 \text{ BTU/hr}}{22{,}000 \text{ BTU/kg}} = 777 \text{ kg/hr of LEA}$$

$$\frac{1{,}000 \text{ kwh}}{\text{hr}} \left| \frac{\$0.15}{\text{kwh}} \right. = \$150/\text{hr}$$

$$\frac{\$150/\text{hr}}{777 \text{ kg/hr}} = \$0.19/\text{kg of LEA}$$

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    2010