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Framework for evaluating and optimizing algae façades using closed-loop simulation analysis integrated with BIM

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Abstract

According to the U.S. Department of Energy, about 40% of U.S. energy was consumed by the building sector in 2015. Among building components, the façade is critical for minimizing cooling load and optimizing thermal comfort. Related to energy efficiency improvements and waste treatment capabilities, algae façades have been studied to improve the performance of building envelopes. In 2013, an algae façade was applied to a building in Germany, but further applications have not been implemented and its feasibility is still questionable. This study presents a framework to explore the critical factors when deploying algae facades in buildings, analyze energy and waste stream encompassing algae facades, and evaluate the performance considering various building contexts. This research aims to present a framework of closed-loop simulation analysis based on Building Information Modeling (BIM). The framework is composed of: 1) the algae façade is integrated in BIM as one of components, 2) closed-loop energy and waste streams are modelled through a system dynamics model (SDM) for evaluating the impact of algae façades and considering by-product recycling, and 3) algae façade data in BIM is retrieved to be used in the SDM. Contributions from this research are related to promoting more integrated design and construction processes by integrating algae façade components in BIM. Energy and waste flows from the algae façade will be evaluated in a more reliable manner through closed-loop simulation analysis. This framework can also contribute to determine feasibility when the algae façade is applied differently in a building and/or applied in various buildings by running the BIM-integrated SDM simulation iteratively.

Keywords: Sustainable building envelopes; algae façade; energy and waste streams; closed-loop system; BIM;

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1. Introduction

According to the U.S. Department of Energy [1], about 40% of total U.S. energy was consumed in residential and commercial buildings in 2015. With the demand of reducing energy consumption and environmental impacts of buildings, the needs for sustainable buildings have also been increased [2,3]. To achieve a sustainable building, the building façade has an important role for minimizing cooling loads and optimizing thermal comfort [4]. According to the database presented by ASHRAE Fundamentals (SI) 2009, the U-value of walls is distributed from 0.2 to 1.1 (W/m^2K), on the other hand, the U-value of windows is distributed from 0.8 to 6.0 (W/m^2K). It indicates that the heat transfer of windows is much greater than that of walls. In this respect, with an effort of improving the performance of envelopes, the algae façade has been studied for application in buildings [5–8]. Furthermore, in 2013 the first algae-powered building, dubbed the BIQ (Bio-Intelligent Quotient) building, featuring an algae façade, was built in Hamburg, Germany [9,10]. The algae façade has abilities of insulating the building and providing shade from the bright sunlight [10,11]. The south-west and south-east façade can also produce heat and supply energy for the building [11]. Even though this project aimed at presenting the new standard for adopting a bioreactor façade [11], further applications have not been implemented, and its feasibility is still questionable. In this respect, this research explores a framework to apply algae facades by enabling the investigation of building systems requirements in a comprehensive way, analysing energy and waste stream encompassing the algae façade, and evaluating its performance. Therefore, this research aims to develop a framework to evaluate the feasibility of algae façades in the various building contexts.

2. Problem statement

With the demands of a sustainable technology, microalgae systems have been studied for practical use on energy generation possibilities as well as waste treatment capabilities [12,13]. Algae are photobioreactor organisms that generate energy through photosynthesis, being four times more efficient than the typical biofuel such as soybean, flower, and corn, etc. [7,14]. Through photosynthesis, algae produce biomass, which is the source for biogas [14–16]. Algae have been considered as a renewable energy source for sustainable developments in terms of carbon dioxide removal ability, waste treatment capability, organic fertilizer, feedstock for ecosystems, and biological derivatives [14–17]. Algae technology has been studied for application as open, closed, and/or hybrid systems, which is the combined system of open and closed systems [18]. Closed algae systems can be categorized as tubular, flat plate or other design [18]. Among those algae systems, algae façades, which are closed systems formed as flat plat, have been studied for application in buildings with increasing efforts to improve the performance of building envelopes [6,7,19–21]. In terms of closed-loop technology, this concept enables the outputs of the system to activate the inputs [22]. The algae façade, as the closed-loop technology, is expected to enable buildings become a contributor of the ecosystem. The first algae façade applied to a net-zero energy building took place in Hamburg, Germany in 2013. This approach represented an innovative example of applying a sustainable solution in a building, but it has remained at the conceptual stage, which is a pilot project to exhibit a bioreactor façade at the International Building Exhibition (IBA) in Hamburg in 2013 [19,23,24].

When transforming the pilot project to a practical application, the practical implementation of algae façades in buildings can have challenging issues such as environmental, technological, political, economic, or social [21]. For example, there are a number of challenging issues such as competition with other renewables, uncommon alterations for the building envelope, uncertain adaptability to different climates, political issues due to dominant coal and oil industries, uncertain economic value of the end product, and negative perception of algae [21]. In this respect, this research aims at supporting the decision-making process for adopting algae façades by the building sector. Based on the pilot project in the BIQ building, algae façades require a separate water supplier for demanding liquid nutrients and carbon dioxide [9,25]. This supplier system can cause challenges to adopt algae façades because it can lead to additional technical analysis and/or cost. According to Algae World News, the algae façade tested on the BIQ building is producing more heat energy than expected [25]. Although the pilot project was designed as an experiment with pre-determined settings, the performance seems difficult to evaluate before the systems are operated. In this respect, the performance prediction variability can fluctuate more in a common set of buildings, with more uncertainties than the pilot study. In practice, since the design alternatives keep changing, decisions about sustainable building design, including the adoption of algae façades, are conducted with the fluctuation of other constraints at the early design or preconstruction stage [3]. However, the flexible application and evaluation of sustainable design applying algae façades has not been integrated in the process of design and/or construction documents [3].

3. Literature review

3.1. Algae as a renewable energy source in the building sector

With climate changes and the depletion of fossil fuels, biofuels have been studied as a future renewable energy source [26]. Algae is a biofuel that photosynthesizes and its efficiency is much greater (about four times) than the typical biofuel such as soybean, flower, corn, etc. [7,14,16]. Because of its ability for producing huge biomass with a few inputs [21], and due to absorbing the CO_2 from the organic manner [10], the building sector has been considered for the application of algae systems [8,27–30]. Algae systems consist of open, closed, and/or hybrid systems, which combine open and closed systems [18]. Closed algae systems can be categorized as tubular, flat plate or other design [18]. Among those algae systems, the algae façade, a closed system with a formed flat plat, can be applied to improve the performance of building envelopes [7,19–21]. However, complex interactions with various subsystems and difficulties of assessing the performance make it difficult to adopt algae façades for the building sector [15,29,31,32]. Therefore, the requirements for implementing algae façades in buildings should be investigated and defined.

3.2. Sustainable buildings with BIM

Early design decisions about sustainable design enable more cost-effective and efficient process in a construction project [33]. Currently, the role of sustainable analytic tools consists of providing information for the evaluation of design alternatives through visualization and lean process [34]. In this respect, BIM tools enable us to make sustainable decisions time- and cost- efficiently [33]. With its widespread technical development, BIM can facilitate sustainable design and construction practices [33,35]. To achieve sustainable design and construction by using BIM, the sustainable design considerations should be conducted as early as possible in the design phase process [2,3]. With the increasing BIM detail, the integrated information can used for sustainable design decisions [35]. On the other hand, users require different partial data for analysis [3,36]. In this respect, the early integration of sustainable design options with BIM will contribute to sustainability. Generating and/or extracting required information seems inevitable to meet the users' data demand. Therefore, this research integrates the algae façade into BIM for consideration at the early design stage. At the same time, a way of accessing specific data is also required for extending the usability of information about the algae façade.

3.3. System dynamics approach for decision-making

System Dynamics (SD) support the integrated decision-making process for complex and multiple disciplines [37], and has been applied for the holistic analysis of various systems [38]. In terms of how every decision can influence the systems where the decision was made, system dynamics models have been applied for considering iteration and feedback processes [39,40]. Despite the ability of supporting integrated decision-making, the application of SD has barely been conducted in building design [41]. In this respect, SD models can support the decisions of applying algae façade systems in the building design, and also in terms considering multiple subsystems and food-energy-water (FEW) feedback processes. Furthermore, this application can expand the use of SD into the sustainable building field.

4. Research approach

Using a SD simulation method with BIM, the potential adaptability of algae façades and its holistic performance are evaluated considering the initial involvement of the systems at the early design phase with data from a comprehensive literature review. To achieve the research objective, a closed-loop simulation analysis is used based BIM. The framework is composed of: 1) the algae façade is integrated in BIM as one component, 2) closed-loop energy and waste streams are modelled through a SDM for evaluating the impact of algae façades and considering by-product recycling, and 3) algae façade data in BIM is retrieved to be used in the SDM.

This research defines the requirements of algae façade systems to evaluate the applicability of the algae façade into the building systems. Then, based on the required systems of the algae façade, the algae façade is modelled as a BIM component to integrate the algae façade into the design alternatives by visualizing and generating information. Afterwards, the closed-loop flow of the energy and waste is modelled by SDM to evaluate the effectiveness of the algae façade, then find the optimized algae façade by running the SDM simulation considering various scenarios. The requirements for applying the algae façade are obtained by generating BIM components and building the SDM as reference information.

5. Framework of closed-loop simulation based on BIM

The framework of closed loop simulation analysis based on BIM for evaluating the adaptability of algae façades is presented in Fig. 1. In the first step, the research defines the requirements of applying algae façade in the building sector by comprehensive literature review and accessible data from the pilot project (IBQ building in Hamburg, Germany). Based on the requirements and the pilot projects data, this research defined the properties of algae façades including geometry information and mechanical requirements to install the systems while considering current building physics. For the next step, prerequisite information is converted into the 3D component, which architects can utilize in a BIM environment. By utilizing and modifying the existing family component, which is defined as a window family, this the algae façade component is presented. This will contribute to visualize the design by adapting the algae façade systems and increase the attraction of BIM data at the early design stage. Since specific algae façade data are used for evaluating performance, API commands are developed to retrieve specific data from the integrated BIM to into a semi-automatic process. The SD model will be built to evaluate the feasibility in terms of energy performance and waste treatment capabilities, then an optimization process will be conducted to present the optimal size and location of the algae façade for potential adoption by the building sector.

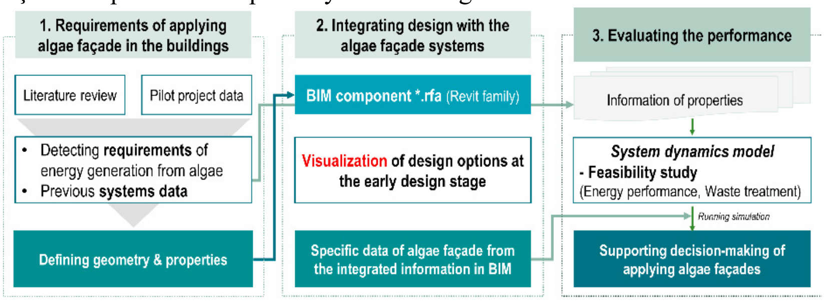

Fig. 1. Presented framework for evaluating the adaptability of algae façades in the building sector

5.1. Defining requirements of applying algae façade in the buildings

Based on literature review, the system compositions for algae façades can be organized in five categories; algae panel, aluminum framing for four sides, intake systems, discharging systems, and sunlight availability [7]. According to the pilot project in Germany [10], one façade is known to be 70 cm wide, 270 cm high and 8 cm thick, and 129 modules were installed on the southeast and southwest. The bioreactor façade module is filled with waste containing microalgae. Through photosynthesis, these algae captured Carbon Dioxide (CO_2), produce heat and biomass, then produced biomass can be used for biogas. The applied algae façade can remove 6 tons CO_2 per year, produce heat about 150kWh/m^2year, and produce 30kWh/ m^2year biomass [10]. The produced biomass can be converted into methane, up to 80%. Since the algae façade was applied about 243.8m^2, it can reduce 67.4g of CO_2 every day per a unit square meter. The information for the algae façade is presented in Table 1.

Table 1. Required information for the algae façade.

Information category	Information types	Investigated values
Compositions [7]	Physical Compositions	Panel, aluminum frames (4 sides), pipes (intake and outtake)
Geometry [10]	Width	70cm (2’ 4”)

	Height	270cm (8' 10")
	Thickness	8cm (3")
Performance [10]	CO_2 reduction	67.4g/ m^{2}day (6.3 g/ft^2/day)
	Biomass production	30kWh/ m^{2}year (7.6 Wh/ft^2/day)
	Heat production	150kWh/m^{2}year (38.2 Wh/ft^2/day)
Properties [10,15,42]	Resources	CO_2, Nutrients (N, P), Water, Sunlight

5.2. Integrating design with algae façade systems

Based on the preliminary investigation of required information, the algae façade is integrated as a BIM component in this section by building a 3D component. This research modified the existing window component, which is determined through a comparison between the current curtain wall component and the window component.

- Comparison of generating the algae façade in different family components

Based on the compositions of the algae façade (see Table 1), the window family is more appropriate to generate the algae façade components than the curtain wall family (Fig. 2.). While the curtain wall system's panel is divided by mullion and transom and there is no enough space for installing pipes between panels, the window family can have space between panels for pipes as well as it can have frames characterized as aluminum. Moreover, window families have analytic properties such as thermal resistance, heat gain coefficient, etc., so a window component has more potential adaptability to convert the component of algae facades.

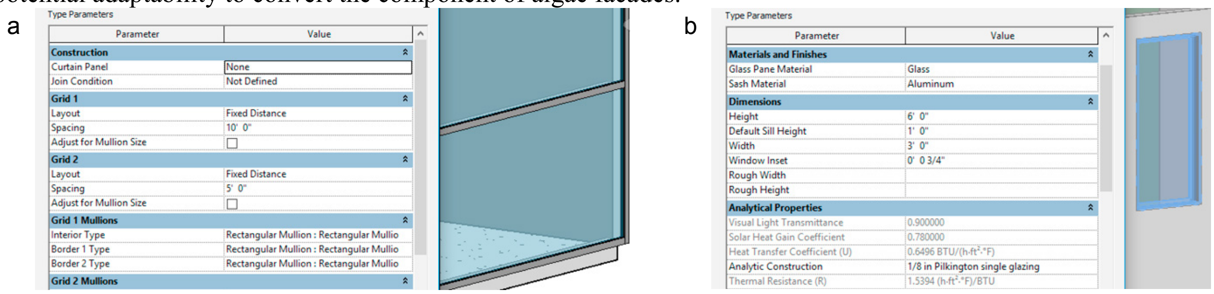

Fig. 2. Comparison of family components in BIM (Revit 2016) (a) Curtain wall; (b) Window

- Modelling family component of the algae façade using current window family

The algae façade BIM component was modeled (see Fig. 3.) based on the previous studies of geometry and property information in Table 1. The performance information, which is carbon reduction, biomass production, and heat production, was generated under the new property named Green Building Properties. The performance information can be modified in the modeling environment, and the initial values (Fig. 3. b) were assigned a performance value per a unit square footage (see Table 1). The algae façade component was modeled in Autodesk Revit 2016 environment and the family file (.rfa) was exported for the general use, as shown in Fig. 3. (c).

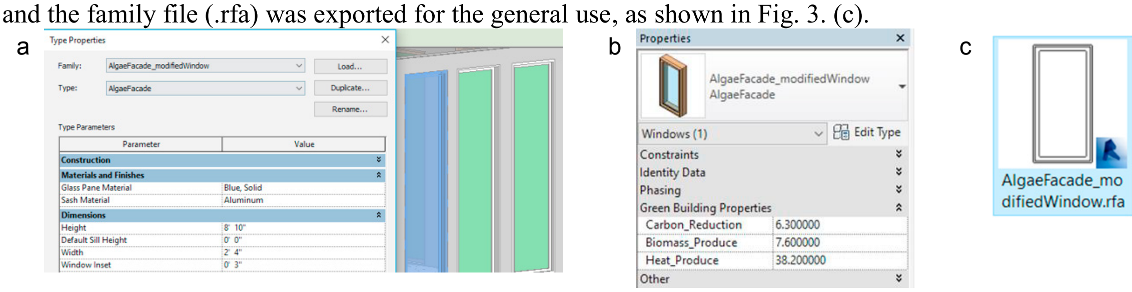

Fig. 3. Modeling algae façade component (Revit 2016) (a) Geometry information and modeling view; (b) Properties; (c) .rfa file

5.3. Evaluating the effectiveness of algae façade systems in difference building context.

Based on the literature review and the available information from the pilot project [14,15,23], the preliminary SDM was modelled in Fig. 4. The algae inside facades perform photosynthesis through sunlight and feeding on CO_2 and nutrients contained in wastewater. Then, by producing biomass, it turns into biogas within a reactor. According to the pilot project data discussed in *5.1*, the biomass produced 7.6 Wh/ft^{2}day and heat produced 38.2 Wh/ft^{2}day. Since that the assumption was that 1 second in simulation is 6 minutes in real, the daily data was divided by 240 simulation seconds. The carbon dioxide reduction rate (6.3 g/ft^{2}day) was also considered. The unit area was applied to the data from the pilot case, and the number of applied unit is assumed as 1. Other variables such as wastewater, photosynthesis efficiency, and solar availability were assumed sufficient not to interrupt the process, then all were assigned a 100%.

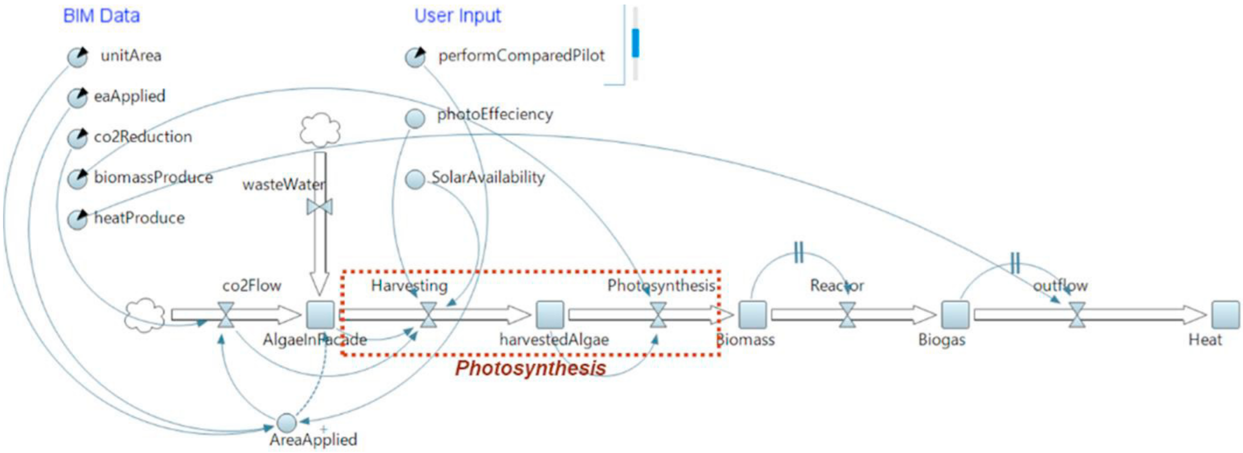

Fig. 4. The preliminary System Dynamics Model (SDM).

6. Results and findings

When we apply one algae façade, 1.89 m^2 (20.3 sf^2), we can produce a certain amount of heat from photosynthesis of the algae façade, in Fig. 5. (b). Although some variables in the SDM model were assumed, the occupied portion of the time stack chart can be accountable in terms of the rates from algae to biomass, from biomass to biogas, and from biogas to heat, and were estimated from the performance data of the pilot case in Germany mentioned in *5.1*. In Fig. 5. (a), we could identify that harvesting rate will decrease along with the previous stocks, 'Algae in façade' decrease. Also, we could observe time gaps between algae to biomass, biomass to biogas, and biogas to heat. In Fig. 5. (b), we could explore the productivity from the photosynthesized algae to heat is still very low.

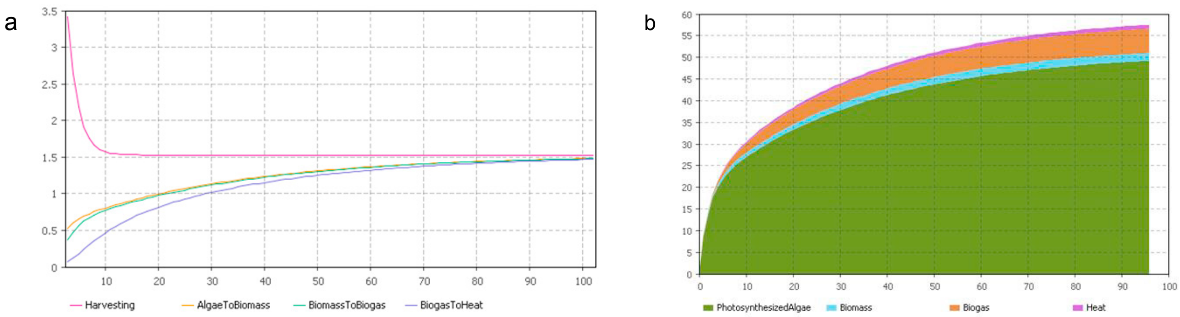

Fig. 5. Preliminary results of running the SDM (a) rates between stocks; (b) the time stack chart of stocks

7. Conclusion and future work

In this research, the framework to evaluate feasibility of applying algae façade in a building sector was presented. The generated 3D component of algae facades will help to integrate the considerations of algae façade at the early design stage. Although the implementation should be conducted in the future, the framework can support the initial performance evaluation of algae façades. The relative amount of generated heat visually compared to the amount of biomass and biogas from applied algae façades can be evaluated, as shown in Fig. 5. Future research will investigate the implementation of the framework. The implementation of the presented framework is still being developed. While the information of the algae façade integrated in BIM is being manually entered in the SDM, application programming interface (API) commands will be developed to extract data and input the data into SDM semi-automatically for implementing the framework. The presented system dynamics model will be also developed along with data collection.

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References

[1] DOE. How much energy is consumed in residential and commercial buildings in the United States? US Dep Energy 2016. http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1 (accessed February 27, 2016).
[2] Autodesk I. Building Information Modelling for Sustainable Design Conceptual Building Performance Analysis Overview. Autodesk 2005. http://www.autodesk.com (accessed March 16, 2017).
[3] Azhar S, Brown J, Farooqui R. BIM-based Sustainability Analysis: An Evaluation of Building Performance Analysis Software. Proc. 45th ASC Annu. Conf., 2009.
[4] Manz H, Frank T. Thermal simulation of buildings with double-skin façades. Energy Build 2005;37:1114–21. doi:10.1016/j.enbuild.2005.06.014.
[5] Yang PP-J, Quan SJ, Castro-Lacouture D, Rudolph C, Stuart B. GIS-based Planning Support System for Waste Stream and Algal Cultivation in Residential Construction. Constr. Res. Congr. 2014 Constr. a Glob. Netw., 2014, p. 2385–94.
[6] Kim T, Han S. Analysis for Energy Efficiency of the Algae Façade-Focused on Closed Bioreactor System. KIEAE J 2014.
[7] Kim K. Beyond green: growing algae facade. ARCC Conf Repos 2014.
[8] Castro-Lacouture D, Quan SJ, Yang PP-J, Marshall T. GIS-BIM Framework for Integrating Urban Systems, Waste Stream and Algal Cultivation in Residential Construction. Proc. Int. Symp. Autom. Robot. Constr. Sydney, Aust., 2014.
[9] IBA Hamburg. IBA Hamburg – BIQ. IBA 2013. http://www.iba-hamburg.de/en/themes-projects/the-building-exhibition-within-the-building-exhibition/smart-material-houses/biq/projekt/biq.html (accessed March 27, 2017).
[10] The European Portal For Energy Efficiency In Buildings. The BIQ House: first algae-powered building in the world | Build Up. Eur Portal Energy Effic Build 2015. http://www.buildup.eu/en/practices/cases/biq-house-first-algae-powered-building-world (accessed March 27, 2017).
[11] IBA Hamburg GmbH, Roedel C, Peterson J-P. Smart Material House BIQ. 2013.
[12] Demirbas MF. Biofuels from algae for sustainable development. Appl Energy 2011;88:3473–80. doi:10.1016/j.apenergy.2011.01.059.
[13] Gnansounou E, Raman J. Life cycle assessment of algae biodiesel and its co-products. Appl Energy 2016;161:300–8.
[14] Sheehan J, Dunahay T, Benemann J, Roessler P. A look back at the US Department of Energy's aquatic species program: biodiesel from algae. Natl Renew Energy Lab 1998;328.
[15] Mata TM, Martins AA, Caetano NS. Microalgae for biodiesel production and other applications: a review. Renew Sustain Energy Rev 2010;14:217–32.
[16] Subhadra B, Edwards M. An integrated renewable energy park approach for algal biofuel production in United States. Energy Policy 2010;38:4897–902.
[17] Yang J, Xu M, Zhang X, Hu Q, Sommerfeld M, Chen Y. Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance. Bioresour Technol 2011;102:159–65.
[18] Demirbas A. Use of algae as biofuel sources. Energy Convers Manag 2010;51:2738–49. doi:10.1016/j.enconman.2010.06.010.
[19] Chalcraft E. Arup unveils world's first algae-powered building. Dezeen | Archit Des Mag 2013. https://www.dezeen.com/2013/04/15/arup-unveils-worldsfirst-algae-powered-building/ (accessed March 27, 2017).
[20] Kim K. A Feasibility Study of an Algae Façade System. Proc. Int. Conf. Sustain. Build., Seoul, South Korea: 2013, p. 333–41.
[21] Wlkinson S, Stoller P, Ralph P. Feasibility of Algae Building Technology in Sydney. 2016.
[22] Ranieri VM. Optimization of patient-ventilator interactions: closed-loop technology to turn the century. Intensive Care Med 1997;23:936–9. doi:10.1007/s001340050434.
[23] Miceli M. Microalgae prove ideal for green facades | Arup | A global firm of consulting engineers, designers, planners and project managers. ARUP 2012. http://www.arup.com/news/2012_09_september/14_sep_micro_algae_prove_ideal_for_making_green_facades (accessed

March 27, 2017).
[24] Miceli M. World first bio-reactive façade debuts in Hamburg | Arup | A global firm of consulting engineers, designers, planners and project managers. ARUP 2013. http://www.arup.com/news/2013_03_march/22_march_hamburg_debut_for_first_bio_reactive_facade (accessed March 27, 2017).
[25] ALGAE WORLD NEWS. This Algae-Powered Building Actually Works -. ALGAE WORLD NEWS 2014. http://news.algaeworld.org/2014/07/algae-powered-building-actually-works/ (accessed March 27, 2017).
[26] Alam F, Date A, Rasjidin R, Mobin S, Moria H, Baqui A. Biofuel from Algae- Is It a Viable Alternative? Procedia Eng 2012;49:221–7. doi:10.1016/j.proeng.2012.10.131.
[27] Pei-Ju YANG P, Jige QUAN S, Castro- Lacouture D, Rudolph C, Stuart B. GIS-based Planning Support System for Waste Stream and Algal Cultivation in Residential Construction. Proc. 2014 ASCE Constr. Res. Congr., Atlanta, GA, USA: 2014, p. 2385–94.
[28] Shipeng L, Castro-Lacouture D. Holistic Modeling of Microalgae for Powering Residential Communities. Energy Procedia 2016;88:788–93. doi:http://dx.doi.org/10.1016/j.egypro.2016.06.129.
[29] Tijo-Lopez S, Castro-Lacouture D. Selection of the Design and Construction Parameters for Energy Efficient Housing Using System Dynamics. Constr. Res. Congr. 2016, 2016, p. 1244–53.
[30] Yang PP-J, Quan SJ, Castro-Lacouture D, Rudolph C, Stuart B. Performance Metrics for Designing an Algae-powered Eco Urban District: A Geodesign Perspective. Energy Procedia 2014;61:1487–90. doi:10.1016/j.egypro.2014.12.153.
[31] Grant W, Pedersen E, Marín S. Ecology and natural resource management: systems analysis and simulation. 1997.
[32] Singh R, Sharma S. Development of suitable photobioreactor for algae production–A review. Renew Sustain Energy Rev 2012.
[33] Wong JKW, Zhou J. Enhancing environmental sustainability over building life cycles through green BIM: A review. Autom Constr 2015;57:156–65. doi:10.1016/j.autcon.2015.06.003.
[34] Bynum P, Issa R, Olbina S. Building information modeling in support of sustainable design and construction. J Constr Eng 2012.
[35] Eastman C, Eastman CM, Teicholz P, Sacks R, Liston K. BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons; 2011.
[36] Azhar S, Hein M, Sketo B. Building information modeling: Benefits, risks and challenge. 44th Annu. Int. Conf. Assoc., 2008.
[37] Sterman JD. System dynamics modeling for project management. Unpubl Manuscript, Cambridge, MA 1992.
[38] Bank L, McCarthy M, Thompson B. Integrating BIM with system dynamics as a decision-making framework for sustainable building design and operation. Proc First 2010.
[39] Sterman J. Business dynamics : systems thinking and modeling for a complex world. Irwin/McGraw-Hill; 2000.
[40] Sterman J, Rahmandad H. Introduction to System Dynamics | Sloan School of Management | MIT OpenCourseWare. MIT OpenCourseWare 2013. https://ocw.mit.edu/courses/sloan-school-of-management/15-871-introduction-to-system-dynamics-fall-2013/# (accessed April 4, 2017).
[41] Thompson BP, Bank LC. Use of system dynamics as a decision-making tool in building design and operation. Build Environ 2010;45:1006–15. doi:10.1016/j.buildenv.2009.10.008.
[42] Singh A, Olsen SI. A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. Appl Energy 2011;88:3548–55.