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Energy Integration of Vertical Farms for Higher Efficiency and Sustainability

Jean Pimentel[a], Ferenc Pongrácz[b], Zoltán Sejpes[b], Zsolt Bukodi[b], György Ágoston[c], István Kenyeres[d], Ferenc Friedler[e,*]

[a]Budapest University of Technology and Economics, 1111 Budapest Műegyetem rkp. 3, Hungary
[b]Tungsram Operations Ltd, 1044 Budapest, Vaci ut 77, Hungary
[c]University of Dunaújváros, 2400 Dunaújváros, Táncsics M. utca 1/A., Hungary
[d]The Biopolus Institute, 1082 Budapest, Futó u. 37, Hungary
[e]Széchenyi István University, 9026 Győr, Egyetem tér 1, Hungary
f.friedler@ga.sze.hu

As a result of the increasing human population, the availability of resources per capita has been vastly diminished in the last decades. Naturally, the depletion of valuable environmental assets such as water and arable land, poses a threat to mankind's sustainable development. In this regard, various novel ideas have been proposed for processing agricultural products ecologically and sustainably; one of such ideas is vertical farming (VF). VF is a novel production technology that aims at enhancing both the yield and the product quality, by growing them in highly packed, high energy-density systems with high mass-flow rates and in a controlled environment. The technologies required for VF have been developed and successfully tested, thereby producing crops that meet the requirements of food safety, adequate nutrient content, and maximum yield. However, the extremely high biomass densities and high turnover rates employed to give rise to challenges regarding to energy efficiency and homogeneity patterns.

In this work, a P-graph model is presented for the integration of VF systems. The algorithmic approach is employed to evaluate options for process integration and intensification of VF with plausible synergetic production processes into a dense urban environment. As a result, 115 integrated process alternatives are identified for the base case, with the best structure exhibiting a total cost of 41,920 EUR/y, thereby yielding reductions up to 11% for the total cost of the integrated network. The pareto front of economic performance and CO_2 emission is presented to illustrate the potential benefits of integration, and the capability of the methodology to evaluate alternative designs.

1. Introduction

According to the United Nations Food and Agriculture Organization (FAO), there were 0.42 hectares (ha) of arable land per person in 1961; this figure has dropped to 0.23 ha in 2002 (Al-kodmany, 2018). The reduction of arable land endangers the food security for future generations, consequently, numerous efforts have been made to ensure the sustainability of production. Vertical farming (VF) is a technique for cultivating crops that aims at reducing the land and resources required for their generation. VF is characterized by growing produce in a vertical orientation employing an indoor system of multiple layers with controlled conditions of light, nutrients supply, water, and other environmental variables (Rizal et al., 2019).

Ideas on the vertical growth of crops have been proposed numerous times during human history. However, the concept of VF has been recently propagated by the work of Despommier (2011), who proposed the integration of agriculture facilities inside urbanized cities for the mass production of fruits and vegetables in skyscrapers. The popularity of this concept has increased during the last decade, and various companies have been established based on it. Such increment can be explained by the reduction of cost of LED lighting technologies, and the general demand for healthy and quality products. Currently, commercial enterprises based on VF focus their production on vegetables such as lettuce, spinach, basil, and microgreens, as well as fruits such as

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strawberries (Beacham et al., 2019). Regarding the production scale of commercial facilities, assorted sizes of growing space have been reported in the range of 160 m^2 for the denominated “container facilities”, up to 8000 m^2 for big plant factories. VF is expected to have a huge potential in the near future, but currently it is still in a research phase and a wide range commercial applications are about to come. Therefore, the overview of the companies involved changes periodically, for recent information about companies in the US, the reader is referred to the work of Al-kodmany (2018), whereas realizations of enterprises in Europe are described by Butturini and Marcelis (2019).

VF can be regarded as a technique that intensifies the generation of horticultural products by grouping a diverse number of subsystems, such as the controlled/modified environment, the plants, and the water and nutrients, in a small portion of land. Thus, VF constitutes a system with an elevated density of mass and energy per unit of area and a high packing factor. Because of this nature, VF not only entails savings in required land, but it can also reduce the water consumption and CO_2 emissions of the operation. Moreover, controlled environment of VF ensures a higher quality of products free of infestations, polluted water, and pesticides; artificial light can be employed to control and optimize the production of secondary metabolites, which enhance organoleptic, dietary or functional value (SharathKumar et al., 2020). Besides, the indoor installation permits a constant production that increases reliability of the farm, and because of the proximity between the production facilities and the final consumer, the carbon footprint and cost of transportation are decreased (Benke and Tomkins, 2017).

In spite of its advantages, VF is not a mature technique, and has presented various drawbacks for its practical implementation. Moreover, some of its benefits have been refuted. For instance, the enhanced sustainability of VF is still a matter of discussion in the scientific community, and it seems to have a strong dependency on the specific conditions and location of the project (Butturini and Marcelis, 2019). The most significant barrier is the uncertain economic feasibility, as cases of high production costs have been reported. High investment costs, in addition to elevated consumption of energy may result in a non-competitive operation (Banerjee and Adenaeuer, 2014). Hence, the products derived from VF need to have a high added value for the operation to be cost-effective.

One strategy that has been proposed is the integration of VF systems within the infrastructure of additional systems, so that components of the latter complement the drawbacks of the former. For instance, the integration of aquaculture with hydroponic vegetables, where fish provide nutrients for the plants whereas the plants clean water for the fish; or the incorporation of anaerobic digestors capable of generating power and heat for the farm by employing food waste. In this work, a graph-theoretic approach is employed to systematically identify plausible candidate systems to be integrated with VF. This aims at finding alternative structures of closed-loop productive systems that have a reduced cost for crops and the valuable products derived from them. The closed-loop system employs the outputs from some subsystems as the inputs for the others, consequently, the amount of resources consumed by the entire network, as well as the global cost of production are reduced.

2. Methodology

The determination of subsystems that may exhibit benefits when integrated must be performed based on a judicious evaluation of the components’ individual performance, as well as the properties of the global network. From the engineering point of view, this constitutes a problem of synthesis (or design) where the elements of the most suitable system are determined, as well as the mass and energy flows among them. The decision of including a subsystem in the closed-loop network may be performed by resorting to optimization techniques that identify the most convenient schemes of production. However, optimization problems derived from synthesis are combinatorial by nature, which complicates their solution. These problems are usually formulated as Mixed Integer Non-linear (or Linear) Programming problems (MINLP/MILP), and represent the construction of a reducible superstructure that encompasses the best design. It is worth noting that formulation of the superstructure and its model by hand may result in errors that lead to wrong results. Moreover, the generation of a single solution is usually not enough to provide sufficient information about the problem, because of the differences between the mathematical models and the real world and the possible changes in the parameters of the problem (Voll et al., 2015).

The P-graph framework rests on an algorithmic methodology for process synthesis introduced by Friedler et al. (1992). The framework takes its name from the process graph representation (P-graph representation), which depicts the problem by resorting to two types of nodes. The first type of node, the M-type node, depicts the materials involved in the synthesis problem by means of circles. The second type, the O-type node, illustrates the operating units of the problem as horizontal bars. Both types of nodes are connected by arcs, i.e. arrows, indicating the direction of materials within the network. Moreover, the M-type nodes are also partitioned into raw materials, intermediate materials, and desired products. This representation permits the unambiguous depiction of the original network. Figure 1 shows a comparison of the conventional representation, and the P-graph representation of a system that transforms 2 raw materials into a product and a byproduct.

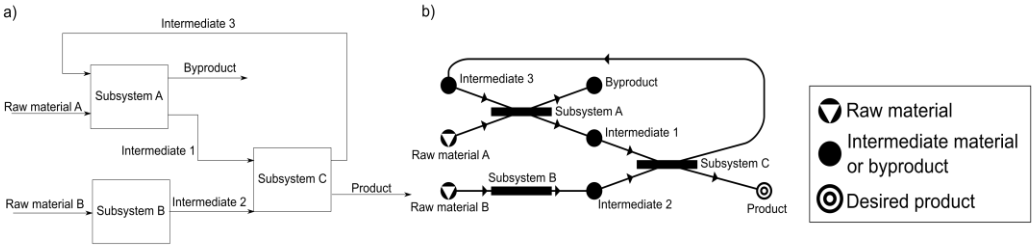

Figure 1: Representation of systems in conventional representation (a) and P-graph representation (b)

As the representation is unambiguous, the set of algorithms of the P-graph framework can handle the problem. Initially, algorithm Maximal Structure Generation (MSG) systematically creates a rigorous superstructure, or maximal structure, from the set of units initially selected by the designer (Friedler et al., 1993); this algorithm removes the infeasibilities given by the structure of the problem, and eliminates the human errors in formulation of the model. Subsequently, algorithm Solution Structure Generation (SSG) enumerates the logical processes comprised in the maximal structure. Finally, algorithm Accelerated Branch-and-Bound (ABB) finds the best structure, and set of the next n-best alternative designs according to the objective function (Friedler et al., 1996). The set of alternative designs represents a valuable tool for decision making during the design step, because it provides additional information about the behavior of the problem, as well as secondary objectives in the process, such as reliability or flexibility. The identification of units that can be integrated to VF is performed by recognizing systems whose outputs (or inputs) can generate the materials required (or produced) by the farming system. For instance, productive systems that employ horticultural crops to generate valuable products. Usually, these processes involve the internal generation of heat and electricity that could be readily employed to reduce a fraction of the energy required by the growing operation. Once these subsystems are determined, they are represented as operating units (horizontal bars) of the P-graph framework considering their required inputs and outputs as materials (circles). It is worth noting that despite their name, material nodes are also used to depict the energy flows such as heating and electricity.

In this work, the total amount of CO_2 is gathered in a single material node (termed as Residual_CO2). The placement of an upper bound constraint to this node enables the identification of cost-effective networks that also minimize the carbon emissions. First, the algorithm MSG is employed to generate the superstructure of the problem. Subsequently algorithm ABB is used to identify the set of n-best alternatives of integration for the selected subsystems and interactions. Then, solutions are classified according to pareto dominance for minimization of total annualized cost (TAC) and CO_2 emission, thus determining the Pareto front. Finally, the upper limit for CO_2 is reduced and the algorithm ABB is implemented again to complement the set of non-dominated solutions.

3. Case study

In this work, seven subsystems are selected as feasible options for integration with VF. Specifically, an electrical substation that operates based on gas turbines, named as “Electricity_producer”; a centralized plant for distribution of industrial and residential heating, termed as “District_heating”; a system of aquaculture coupled with a biofilter that has a symbiotic relation with hydroponic crops; a combined heat and power cycle, named “CHP_unit”; an industrial facility that corresponds to the generation of valuable products from vertical farming crops, represented here by extraction of essential oils; an industrial wastewater treatment system (WWTP) that removes organic matter from the water of the industrial process. These systems are represented by means of O-type nodes in the P-graph framework. Naturally, the vertical farming system is also represented as an operating unit for the synthesis problem. Table 1 presents the inputs and outputs of the mentioned operations relevant to this work. Here it is assumed that the input for WWTP comes only from the facilities that generate valuable products.

Furthermore, the mass and energy balances, as well as the investment costs of the systems, are estimated from information available in the literature. For instance, information for small systems (Somerville et al., 2014), estimations for large facilities (Banerjee and Adenaeuer, 2014), as well as laboratory-scale experiments (Meziane et al., 2020) and measurements performed at the R&D facilities of Tunsgram in Budapest, Hungary. Also, information was retrieved from the life cycle assessment database Ecoinvent3 by resorting to the software SimaPro®. It is worth noting that the general characteristics of the performance of VF still need to be determined by long term experiments. Data related to the consumption and efficiency of VF systems reported in the literature are irregular as they depend on the crop, growing system and particular conditions of the farm. For instance, data for energy consumption have been of 377 kWh/y (Banerjee and Adenaeuer, 2014) up to more than 1404 kWh/y per square meter (iFarm, 2020) . For the estimations of this work, average values of representative systems were considered.

Table 1: Main systems identified for integration in the case study

Name	Input	Output
Electricity_producer	Natural_gas	CO_2_Combustion, Electricity
District_heating	Fresh_water, Natural_gas	Heat, CO_2
CHP_unit	Natural_gas, Fresh_water	Heat_EO, Electricity, CO_2
Vertical_Farming	Electricity, Available_nutrients, WaterVF, Heat, CO_2	Plants,Water_from_VF
Essential_oil_production	Plants, Heat_EO, Electricity, Fresh_water	Added_value_products, Wastewater
WWTP	Wastewater	Treated_Water
Biofilter	Water_from_AQ	WaterVF, Available_nutrients
Aquaculture_system	Recond_water_from_VF, Feed	Fish, Water_from_AQ

In addition to the O-type nodes that represent the subsystems in Table 1, fourteen secondary operations were included in the initial problem. Some of these operations represent the purchase of resources from external providers or intermediary stages among the systems, such as conditioning or transport of materials. It is assumed that the cost of these secondary steps is negligible compared with those of the main subsystems. Finally, the operating costs of the units are calculated considering the price and quantity of raw materials required for the utilities of the different operations. Figure 2 shows the maximal structure generated by algorithm MSG for the case study.

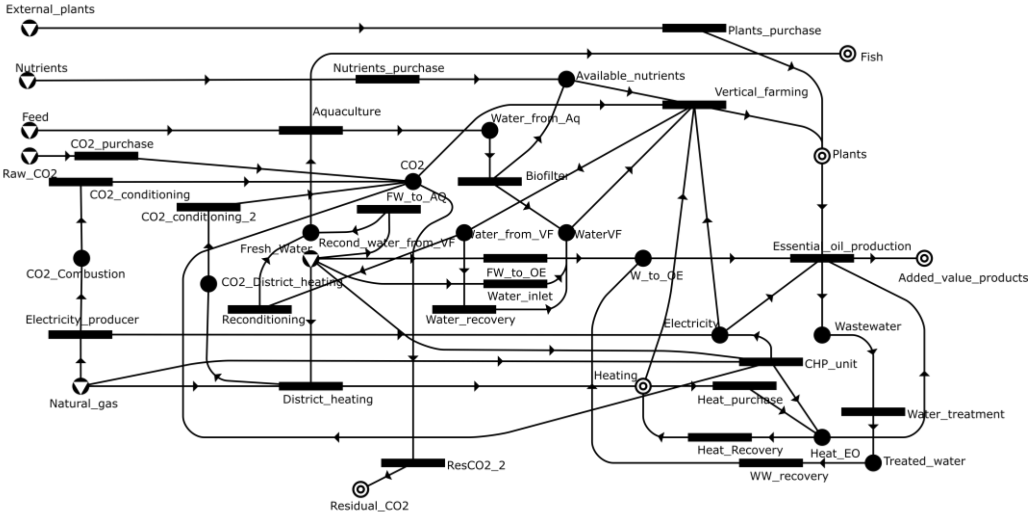

Figure 2: Maximal structure for the integration of VF

The algorithm ABB identifies 115 feasible solutions for the base case where no upper bound is defined for production of CO_2. In all cases, a demand of 100 kg/y of plants and 135 kg/y of valuable products is assumed. The best solution presents a total annualized cost of 41,920.1 EUR/y and would correspond to a growing space of 2,750 m^2, assuming an average yield of 20 t/ ha for the crops. The CO_2 emissions equivalent to 340.1 t/y, This structure displays the integration of 7 subsystems which provides the network autonomous operation in terms of CO_2 and electricity. In addition, it reduces the consumption of fresh water by including aquaculture in the system. This network is depicted in Figure 3, the excluded units are shown in grey. Conversely, solution number 41 constitutes a network where the produce, the electricity and the heating are purchased from external providers, i.e., structure with no integration. This network has a total annualized cost of 48,269.5 EUR/y and is depicted in Figure 4. This result demonstrates that the integration of VF has the potential of reducing the TAC of the network by 13% compared with the scenario where all the raw materials are purchased. By decreasing the maximum allowable emission of CO_2 in the system, it is possible to identify a set of non-dominated solutions that represents the Pareto front for the problem. In this set of solutions, the minimum TAC is exhibited by the network in Figure 3. On the other hand, the solution with the lowest rate of CO_2 emissions has a cost of 48,047.8 EUR/y. A selection of the best structures in terms of TAC (<80,000 Eur/y) and CO_2 emissions (< 46 tCO_2/y) are depicted in Figure 5. The identified non-dominated solutions are shown with red markers.

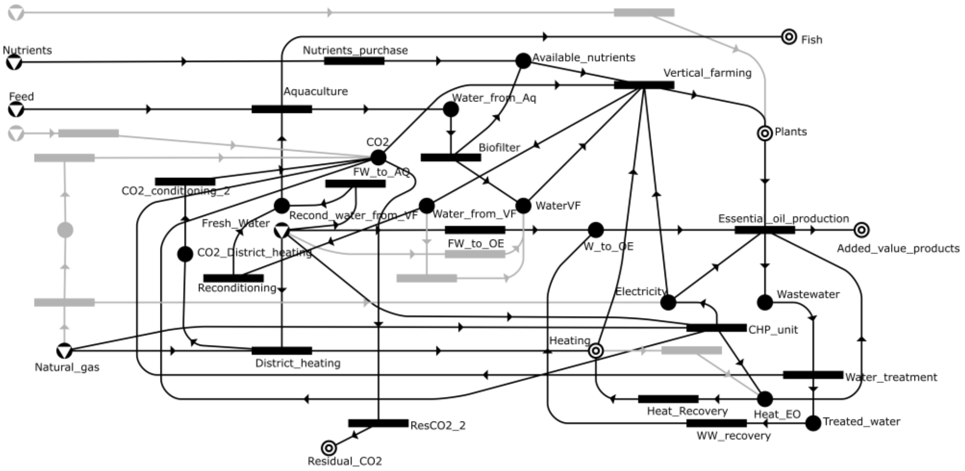

Figure 3: Best solution in terms of total annualized cost for the case study

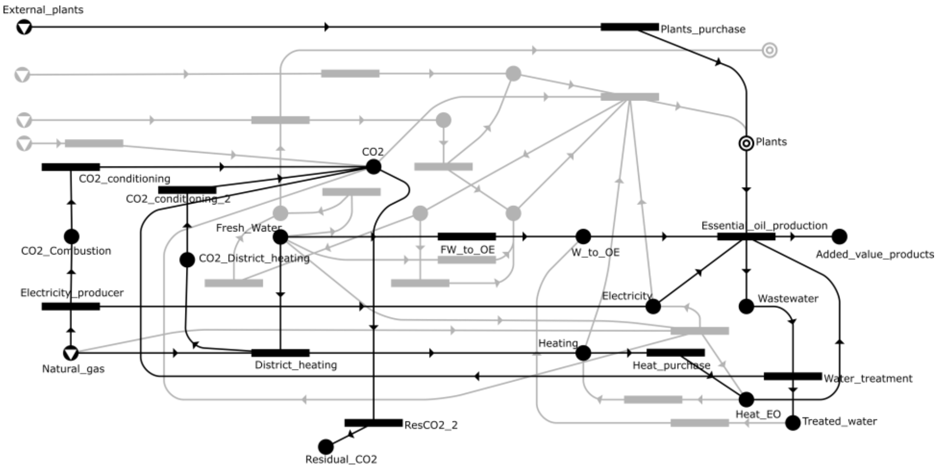

Figure 4: Solution #41. Solution with no integration

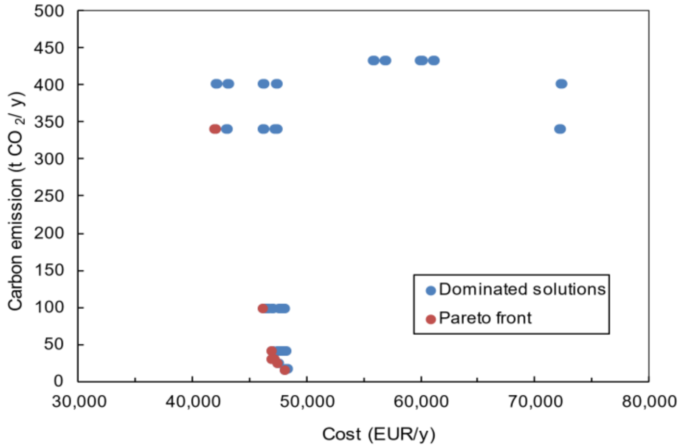

Figure 5. Set of best solutions in terms of cost and CO_2 emission.(The non-dominated solutions are denoted by red markers)

4. Conclusions

A method for the systematic design of an integrated network for enhancing the efficiency of vertical farming has been presented. The analysis by means of P-graph framework shows that integration of VF within closed-loop systems has the potential of reducing the total annualized cost of the entire system. The implementation of algorithmic design constitutes a valuable tool for decision making that permits the evaluation of multiple scenarios under numerous criteria. This tool can be used effectively with more complex mathematical models, or with artificial intelligence rules that derive the parameters of the network based on data evaluation and statistical learning for different systems. Vertical farming is still a young technique that requires further evaluation and modelling, to be able to conclude about its benefits. Under the assumptions presented here, it exhibits promising features by integrating it within dense urban and industrial systems. Future work can focus on determining more accurate data for the systems and subsystem, that can represent the behaviour of VF with different crops and under assorted conditions.

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