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Synthesis of Integrated Vertical Farming Systems with Multiperiodic Resource Availability

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Vertical farming (VF) has been proposed as an approach to decrease the land required for growing agricultural products. This technique consists of growing produce in vertical orientation within a controlled environment. However, one of the most significant barriers for its implementation is the uncertain economic feasibility, derived from the elevated consumption of energy and the high investment costs. A strategy to enhance VF efficiency proposes its integration with municipal infrastructure, thus establishing closed-loop systems where VF seizes organic waste, manure, CO_2, and excess energy from productive plants and local power stations. Because of the economic uncertainty of its development, the optimal synthesis of such a closed-loop system (i.e., the selection and specification of its components, and their connections) is of utmost importance for the implementation of this strategy. The difficulty of the synthesis task arises from the combinatorial nature of the problem and the variability of the resources and market conditions in time. This work employs a graph-theoretic approach for the synthesis of a closed-loop system of VF considering the variability of the resources during multiple periods of operation. The proposed method relies on the P-graph framework which permits the identification of the n-best alternatives for the system's design, employing the properties of the problem's structure to enhance the effectiveness of the solution procedure. Consequently, the most cost-effective systems are identified together with their policy of operation for the different periods. This method constitutes a powerful tool for the assessment of systems for VF integration that enhance the sustainability of agricultural activity.

1. Introduction

The rapid decrease of the arable land's availability jeopardizes the food safety for humankind, especially, considering that the world population is expected to increase in about 2 billion people for 2050 (United Nations, 2019). Consequently, ensuring the generation of agricultural products has become a relevant topic for researchers in numerous areas. Vertical farming (VF) is an interesting alternative for growing crops reducing the resources consumed in cultivation and harvesting phases; specifically, it is characterized by a low requirement of the arable land, and it has been proposed as an option for a safer and more reliable food supply (Despommier, 2011). The reduction of required arable land is a result of employing a vertical orientation for the crops by stacking layers of growing media in a controlled environment. This is performed in an indoor system where the relevant growing factors, such as light, temperature, humidity, carbon dioxide (CO_2) concentration, water, and nutrients, are monitored. Figure 1 shows a typical VF installation with artificial UV lighting, which permits a uniform control of photosynthesis of the plants. Because of the controlled conditions the quality of produce is uniform and can be guaranteed, since pests, pollutants, and harmful factors are more easily restrained. Moreover, regardless of the weather, the indoor system permits a consistent production during the year, which enhances the reliability of the production facilities (SharathKumar et al., 2020) and enhances the food safety.

VF intensifies the generation of produce by integrating distinct systems in a reduced fraction of land. Therefore, this kind of systems have a high density of mass and energy per unit of area. Thus, its implementation results not only in a reduction of the required arable land, but also may derive in a reduction of CO_2 and a decrement of water consumption. Because of these advantages, numerous organizations have shown interest on VF, such

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as the US department of agriculture (Federman, 2021), the association for vertical farming (2017) and companies such as Tungsram kft. (2021).

Figure 1: Installation of VF in the Netherlands (Bates, 2017)

Despite its advantages, VF still has numerous barriers to overcome as its economic feasibility remains uncertain. Various commercial facilities are operating worldwide in various scales of production, with areas up to 9000 m^2 (Kalantari et al., 2018), and numerous projects are expected to be finished in the upcoming years; however, the landscape remains dynamic with players constantly entering and leaving this line of business (Butturini and Marcelis, 2019). The elevated initial cost required by the infrastructure and additional costs involved in the controlled conditions, e.g., energy required for lighting and heating, may lead to not cost-effective operations. Hence, additional research effort is required to unveil more efficient production techniques, or to generate strategies for integration of these systems with further enterprises (Banerjee and Adenaeuer, 2014).
Because of this, the strategy of integrating the VF within the municipal infrastructure has been proposed, aiming at rendering closed-loop systems capable of minimizing the common costs. This strategy consists in merging systems, such as with the VF productive system, trying to emulate the natural ecosystems that work as closed-loop schemes; where the waste of some subsystems (or units) is employed as raw material for the others (Al-Kodmany, 2018). Figure 2 illustrates this concept in a general diagram, where VF may be integrated with systems of agricultural production, industrial processes, or generators of utilities. For instance, the combination of VF with an aquaculture system in Figure 2 enables the capacity of recycling the water. There, the fish can provide a fraction of the nutrients required by the plants whereas the hydroponic vegetables clean the water for the fish. In these closed-loop agricultural systems, nearly all waste-elements of the farming process, such as water, sewage, and nutrients, can be harnessed by other units of the network, thereby leading to a close-to-zero-waste operation. Additionally, the CO_2 required by the plants in VF may constitute a sink for the emissions of other units, thus, not only the land necessary for crops growing is decreased, but also the general footprint of the global system is reduced. One example of this kind of systems is the VF system named “The Plant”, located in Chicago (The Plant, 2020). This project intends to improve the energy efficiency of the farm by including anaerobic digestors, which permits the transformation of organic waste (e.g., organic matter from the farms, or the aquaculture systems) into biogas to produce power and heat. In this project, the farm is integrated with aquaculture, anaerobic digestors and production of Kombucha tea (Al-Kodmany, 2018).
However, because of their nature, the demands and availabilities of the products exchanged by the different subsystems in the closed-loop system may vary with factors such as the seasons and the weather. Although VF is capable to produce the plants throughout the year, the energy, heating, products required by the consumers, as well as the prices of raw materials may differ in time. Consequently, for some periods of the year the systems may be used with a partial capacity to save in costs of labor, operation, and storage. The design of these closed-loop agricultural systems, as well as the definition of the employed capacity for each period, must be performed systematically; and their structure needs to be synthesized resorting to algorithmic methods that generate the most cost-effective integration scheme. The systematic design of structures for closed-loop productive systems has been previously explored (Pimentel et al., 2021), however, variation of the system’s conditions with time had not been explored yet.
In this work, the P-graph framework is employed to generate plausible structures for closed-loop agricultural systems considering plausible variations in time. A multiple period formulation is deployed to represent the variation of demands, availabilities, and prices for some materials in the network. This type of evaluation identifies the subsystems (i.e., units) suitable for integration, in addition to the policy of production (i.e., fraction of the maximal capacity employed for each period) that fulfills the requirements of the market.

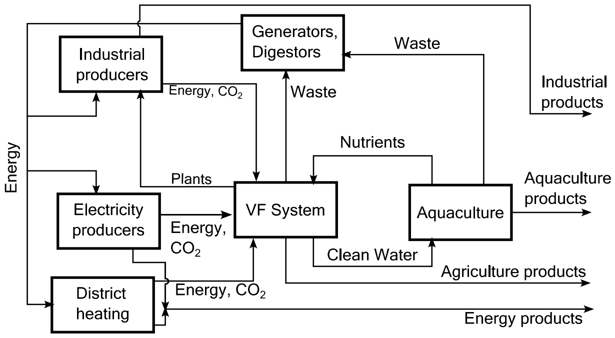

Figure 2: Illustration of closed-loop system for VF

2. Methodology

The P-graph framework is a graph-theoretical approach capable of accelerating the solution of design problems where the structure of the process is to be determined (i.e., synthesis problems), by resorting to the properties of the networks that represent them (Friedler et al., 2022). P-graph relies on a bipartite representation where the units and streams are portrayed as horizontal bars and circles, respectively. Based on this representation, the framework depicts the network of a process unambiguously, thereby making it suitable for exploiting its structural properties. Figure 3 shows the closed-loop system of Figure 2 in terms of the P-graph representation. The streams are substituted by M-type nodes (i.e., circles), and the units are depicted by O-type nodes (i.e., horizontal bars). Figure 2 also shows the different sub-types of M-type nodes employed in P-graph representation.

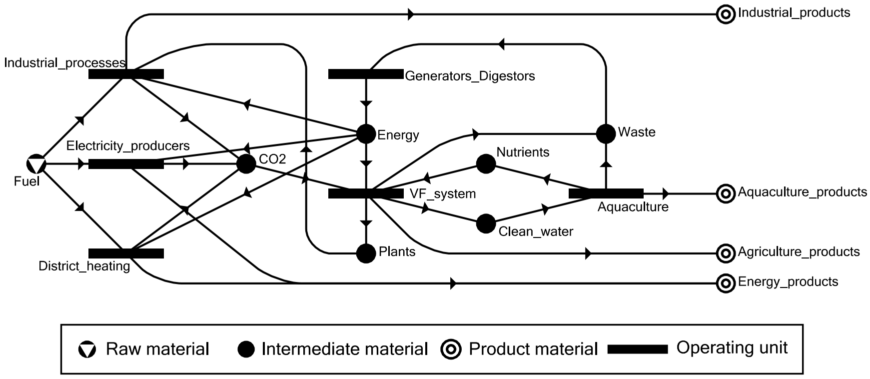

Figure 3: Representation of closed-loop system in Figure 2 as P-graph

The P-graph framework is employed here as it exploits the structural properties of the synthesis problem to accelerate its optimization and generates the n-best solutions for it. Such a capability comes from a set of combinatorial algorithms, which are based on a set of axioms that determine the combinatorial feasibility of a particular network (Friedler et al., 2022). The method of solution employed here uses two of these algorithms. First, the algorithm Maximal Structure Generation (MSG) renders a rigorous superstructure (termed as the maximal structure) by connecting the units specified by the designers. Then, the algorithm Accelerated Branch-and-Bound (ABB) uses the combinatorial feasibility axioms to accelerate the problem solution by means of the reduction in the search space, and the simplification of the optimization subproblems (Friedler et al., 2022).
The formulation of synthesis problems involving multiperiod constraints in P-graph was first presented by Heck et al. (2015). In this formulation, the initial structure for a single period was generated. Thereafter, the nodes whose conditions change in time (i.e., multiperiodic operation) were replicated as many times as periods were considered. These nodes represent the activity of the operations in the distinct intervals of time. The nodes replicated were connected to form the superstructure for the entire operation. Various contributions can be found in the literature of the implementation of this method in the software P-Graph Studio (P-graph community, 2015), such as the work of Bertók and Bartos (2018).
This work explores the synthesis of closed-loop systems for VF with integration to municipal infrastructure and multiperiod operation. Such exploration is illustrated by means of a case study of a closed-loop system where

the demands of products and the price of raw materials are modified. Initially, the set of units selected to conform the closed-loop system are specified by the designer, which involves the definition of material balances of the units and their cost relationships depending on their size. Then, the number of periods to be examined is determined by evaluating the variation in time of conditions for materials or units selected. Subsequently, the initial structure is constructed and extended to consider the multiple periods required. Finally, the synthesis problem posed by the extended structure is solved via algorithm ABB, which generates the installed capacity and the scheme of operation.

3. Case Study

For illustration, the case study presented by Pimentel et al. (2021) is examined in a more realistic scenario, considering the change of conditions with time by means of a multiperiod formulation. Here, in addition to the VF system, seven main units are considered to constitute the structure of the closed-loop system. Figure 4 shows the initial structure for one period with a total of nineteen units, where the eight main units are shown in green, whereas the auxiliary units are depicted in black. The subsystems represented by the main units account for the VF system; an electricity production facility; a plant for distribution of district heating; a system for aquaculture; a biofilter for sending the water to the VF system and a system for valorization of plants generated in VF. The latter is represented by three units and is considered here as an industrial facility that generates essential oils (EO) from the plants. In this case. The first unit of this subsystem represents the main process of extraction and purification of the oils, whereas the other two are complementary processes required for the correct working of the last. Namely, a combined heat and power cycle, (CHP_unit), proposed to deliver heat and power to the valorization process; and the industrial wastewater treatment system that removes organic matter from the water of the process.
These units can be interconnected to exchange energy in the form of power and heat, water, CO_2, and materials. Here it is assumed that the input for WWTP comes only from the facilities that generate valuable products, and this water is not reused in the system. Furthermore, materials such as the fish, the plants, the added value products, and the energy are the desired products required by the consumers.

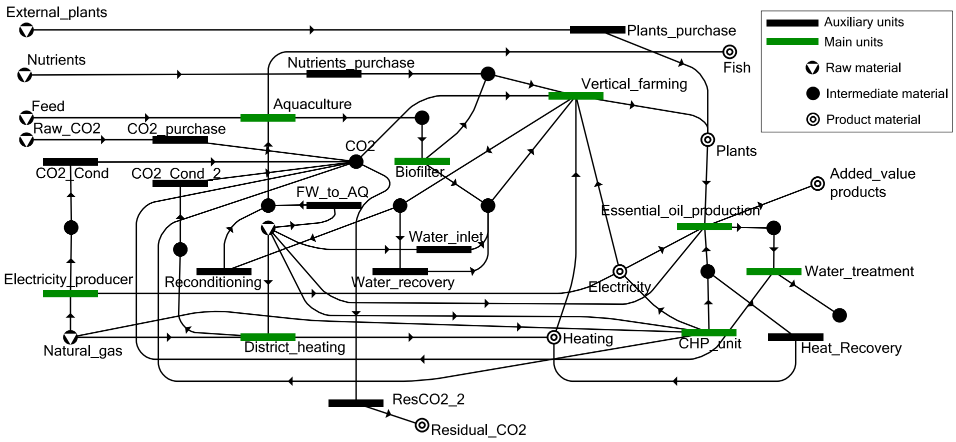

Figure 4: Initial structure for a single period of case study of closed-loop system for VF integration

These units are selected since they are regarded as systems whose inputs or outputs may be seized by VF, or other members of the closed loop and the structure is created in P-Graph Studio. It is worth noting, that the estimation of mass balances and costs for the units greatly depend on the characteristics assumed for their operation. For instance, VF depends on the plant species selected since different species have different yields and require distinct conditions. The selection of the species may be also considered in the synthesis problem by including various “VF units” as O-type nodes, where each of them would represent the performance of the selected crop. Here, the mass and energy balances, and the cost of the units, are estimated as representative values for illustration retrieved from information available in the literature, naturally, a different case study would require to re-determine the value of these parameters. For instance, the estimations for cost of large VF facilities (Banerjee and Adenaeuer, 2014), and technical databases such as Ecoinvent3 in SimaPro®. The evaluation is performed by dividing the year in four periods of three months each, equivalent to the four seasons of continental climate. The amount of heating, electricity, and food demanded by the users varies according to their necessities for each season, whereas the demand of EO (added value product) remains constant (33.75 kg/period). Additionally, the price of the gas is also assumed to change in time, to illustrate the possibility of examining scenarios with variability in the price of raw materials. Table 1 shows the value of the key materials, whose parameters vary throughout the year. With these conditions, the multiperiod formulation of the P-graph framework is employed via software P-Graph Studio to identify the optimal maximum capacities of the units, and the policy of operation for the four seasons in various alternative solutions. Initially, the algorithm MSG identifies the maximal structure for the four periods, which comprises 95 operating unit nodes, and 165 material nodes.

Table 1: Demands and changes of prices for the four periods considered in the case study

Material	Electricity	Fish	Heating	Natural gas	Plants
Period name	Demand (kWh)	Demand (kg)	Demand(kWh)	Price (USD/m^3)	Demand (kg)
Winter	4500	50	27000	0.0540	65
Spring	2500	50	10000	0.0499	41
Summer	9500	30	8000	0.0540	30
Fall	3500	20	15000	0.0457	25

Subsequently, the algorithm ABB identifies the maximum capacity of the units, and their policy of operation for each period in the form of the partial work capacity. Figure 5 illustrates the policy of operation for the 12 months of the year for the main units in the best network identified, i.e., the scheme of operation for the best solution found. Since the problem was modelled for 4 periods, each group of three consecutive months exhibits the same value in the Figure 5. This figure shows that units such as aquaculture and district heating are operated at partial capacity for months 7 to 12, and 4 to 12, respectively. On the other hand, the production of EO and the water treatment are always operated at total capacity as they are related to the demand of EO (assumed invariant in this case study).

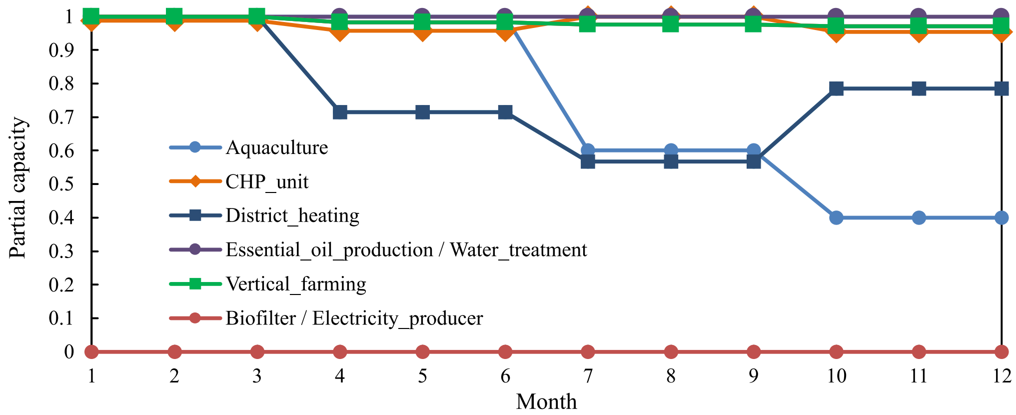

Figure 5: Policy of operation for the main units included in the best solution identified by algorithm ABB for the four periods in Case Study

As illustrated in Figure 5 biofilter is not included in the best solution. This because of the low price assumed for the fresh water, however, its inclusion becomes advantageous if this parameter increases in 27 %. The electricity producer is not included either, consequently, the system's power is independent from external providers and is satisfied uniquely by the CHP, whose policy of operation is related to the variation of the electricity demand. The heat required is produced by both the CHP and the district heating. The latter is fully employed during the first period (winter), then, it is operated at 70 %, 56 %, and 78 % of its capacity for the next periods, following the behavior of the heating requirement. Additionally, VF generates the totality of plants required for the demand, and for the manufacture of EO. This unit is always operated above 97% alongside its auxiliary units. In this solution no CO_2 is purchased as the entire amount required is produced within the network. Also, the aquaculture operates at full capacity for the first half of the year, and then it decreases to 60 % and 40 % for the last periods, as a response to the behavior assumed for the fish demand in the case study.
This network presents a total annualized cost of 44,087 USD. The algorithm ABB renders the same information for the best 100 solutions in less than 3 seconds, resulting in annual operating costs between 44,087 and 46,771 USD. Therefore, a diverse range of solutions, including the optimal and some near-optimal alternatives that are

close in profit, can be identified in short time. These structures can provide additional insights about the problem to be solved, and can exhibit useful features such as reliability, robustness, or resilience.

4. Conclusions

The multiperiod formulation of the P-graph has been implemented to determine the best network of closed-loop systems integrating vertical farming considering variation of conditions with time. The framework permits the unambiguous modelling of the problem by means of the bipartite representation of P-graph, which enables the combinatorial handling of the problem. The capability of the framework is demonstrated by means of a case study of 19 plausible units for the construction of an integrated system for enhancement of sustainability. The methodology successfully determines the maximum capacity to be installed for the design of the network, as well as the scheme of operation of the selected units all over the year. Therefore, the formulation employed constitutes a powerful design tool for closed-loop systems, considering the changes of conditions during the time of operation.

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