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Energy Consumption Optimization of a Manufacturing Plant by the Application of the P-Graph Framework

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A P-Graph model is developed to address energy supply options of a manufacturing plant. Today's industrial facilities usually have a wide range of options to supply its needs in terms of heat, electricity or water. It is difficult to find the most suitable solution, as several factors must be taken into consideration, including fixed and proportional investment and operational costs, sustainability requirements and variable availability of resources. The P-Graph framework is an effective tool in the synthesis of process networks, which involves the P-Graph modeling tool, rigorous mathematical formulation and algorithms, as well as the utilization of Mixed-Integer Linear Programming models. In this work, the energy supply options of an electronic device manufacturing plant are examined. Decisions can be made about the sources of heat and electricity, including buying energy directly from the market or possibly investing into more economic biogas furnaces, a pelletizer, solar cells, with utilization of several different raw materials as energy sources.

1. Introduction

Energy production is an important part of the economy and critical in terms of operation of firms. Traditionally, large central power plants produce electricity which is transmitted through the grid. However, as environmental regulations play an increasing role, more and more firms become environmentally conscious and use green policy. Therefore, small and medium scale, eco-friendly power plants are on the rise, which can supply or supplement the energy needs of a residential home or a firm. The required investment is considerable but can be advantageous. There is no clear winner method in terms of costs. The decision for firms on supplying their energy needs leads to a complex optimization problem and may coincide with the application of sustainable energy production technologies. Besides electricity, heat demands must also be taken into account.

1.1 Importance of sustainability

The concept of sustainability is basically about finding ways to maintain conditions on the Earth that make civilized human existence possible. The challenge arises because: (1) there is a large and growing human population (US Census Bureau), (2) there is increasing consumption, a fourfold increase in private consumption expenditures from 1960 to 2000 (Worldwatch Institute), and (3) the human population appropriates approximately 38 % of the world terrestrial net primary consumption (Running, 2012), leaving the remainder to support the rest of the planetary ecosystem. One effective way to decrease the human footprint is to provide options to meet the energy needs of manufacturing operations. Note that manufacturing consumed about 2.2E18 J of energy in 2010 (US Energy Information Administration). This is important because increasing population and increasing consumption is likely to result in increasing manufacturing across the globe. Therefore, it is crucial to develop structures of manufacturing processes which reduce energy consumption, and meet energy demands with a mix of available options, all of which remaining economically feasible.

1.2 Process Network Synthesis

Process synthesis is intended to design the structure of a process system. The emphasis is on the system itself, not on the individual processes. Therefore, decisions shall be made about which processes will be part of the system, which will not, and how they are connected. A multitude of alternative systems is often able to produce

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the desired products, because of the combinatorial nature of how these operating units are assembled. Process synthesis seeks the optimal process in terms of an objective function. The objective function can be revenue, cost, profit, emission, etc. The determination of the optimal network structure is usually referred to as flowsheet design or Process Network Synthesis (PNS).

Deciding between the various possibilities is a complex combinatorial optimization problem, as many factors must be investigated before the PNS problem can be formulated. Several available energy sources have to be taken into account. For example, renewables are usually not economical to be transported for a long distance; they have a limited availability and require high investment costs to be processed.

The P-Graph framework, which is a general tool to solve PNS problems, is used in the present work to develop a model for a particular case study. Energy supply options of an electronics manufacturing facility in Hungary were investigated. Naturally, the model is also applicable to other manufacturing firms after collecting the specific data and handling any unique features.

1.3 The P-Graph framework

The P-Graph is a mathematical model for PNS problems. It is based on a bipartite graph with nodes for states like raw materials, intermediates, byproducts or final products, and nodes for operations like production, conversion, transportation, and so on. Arcs are drawn between nodes of states and operations, and vice versa, representing material flow in terms of consumption and production.

The P-Graph framework consists of the P-Graph, methods to formulate PNS problems and corresponding algorithms. Rigorous mathematical formulation is used, which proves the effectiveness of this modeling tool (Friedler et al., 1992). The Maximal Structure Generation (MSG) algorithm is used to exclude provably unnecessary parts of the PNS problem (Friedler et al., 1993). The Solution Structure Generation (SSG) algorithm can generate all structurally and combinatorially feasible solutions to a PNS problem, which is a great advantage over purely mathematical programming techniques (Friedler et al., 1995).

To find the optimal solution of larger PNS problems, an underlying Mixed-Integer Linear Programming (MILP) model can be generated, which can be solved by the Accelerated Branch and Bound (ABB) algorithm, designed particularly for P-Graphs to take advantage of their combinatorial nature (Friedler et al., 1996).

P-Graph Studio is a software tool to design PNS problems with P-Graphs and apply the algorithmic framework, used in the present work, which is freely available on the P-Graph official website (p-graph.org).

1.4 Applications of P-Graphs

P-Graphs and corresponding algorithms were used in the past on many different areas, to optimize systems and achieve a greater efficiency, safety, or sustainable operation. Applications of the framework include optimization of polygeneration plants (Tan et al., 2014), synthesis of a biomass corridor (How et al., 2016), utilization of wood processing technologies (Atkins et al., 2016), solution of Separation Network Synthesis problems (Heckl et al., 2010), vehicle allocation (Barany et al., 2011), and even the optimization of a whole renewable supply chain (Lam et al., 2010).

The methodology can be extended to multi-periodical demands and supplies (Tan and Aviso, 2016), and Time-Constrained PNS problems as well (Kalauz et al., 2012), which allows further constraints to be considered in P-Graph models. A thorough review of applications is made by Klemeš and Varbanov (2015).

2. Construction of the P-Graph model

The optimization procedure generally requires the knowledge about demands, possible raw materials and available operations. Investigation of all these kinds of data in the case study is performed, modeled elements being represented by nodes. There are raw material nodes, final product nodes, intermediate product nodes, operating, and conversion unit nodes in this P-Graph. Problem data is assigned to the appropriate attributes of the nodes and arcs.

2.1 Demands in the plant

There are two demands in this case study: electricity and heat requirement during a year. Monthly consumption data of the facility from the past six years were available (Table 1). Fluctuations can be observed between consecutive years, a trend of decreasing consumption for the present time, and changes within a single year also, as most of the heat is required during winter. Therefore, an estimation is made based on a weighted sum of data from the past three years in Equation 1, multiplied by a factor of 1.15 to give room for possible extensions of consumption in the future.

$$\frac{(yr_{n-3} * 0.8 \ + yr_{n-2} * 0.9 \ + yr_{n-1} * 1.0)}{2.7} \cdot 1.15 = yr_n \tag{1}$$

Applying this formula, we made a prediction of 436,045 m^3 gas to be consumed, which is roughly 4,118,206 kWh of heat needed. The analogous procedure was applied in case of electricity as well, resulting in a demand of 5,342,793 kWh. These are modeled as two final products in the PNS problem, which simply define a minimum amount of production for a year.

Note that, as monthly data were also available, it is possible to obtain a multi-periodical model which more accurately describes changing requirements during a single year. This model is currently under development and is not detailed in this work.

Table 1: Monthly natural gas consumption data from the past years in m^3.

Month\Year	2009.	2010.	2011.	2012.	2013.	2014.
1.	133,999	128,744	157,085	123,770	75,782	48,635
2.	123,836	95,406	137,103	124,305	51,407	49,067
3.	120,326	77,536	123,795	83,362	43,560	16,847
4.	37,378	58,464	83,305	61,092	15,452	4,337
5.	35,057	63,719	51,009	37,482	2,785	4,247
6.	37,065	52,094	30,924	17,340	1,919	2,688
7.	30,396	44,485	31,560	12,891	1,554	2,416
8.	34,232	44,628	30,105	20,179	1,534	2,117
9.	28,607	81,730	30,024	19,829	3,072	2,136
10.	82,299	105,612	74,841	25,235	4,208	10,982
11.	105,599	104,195	125,638	50,535	24,273	43,769
12.	116,459	156,139	129,481	73,819	57,240	62,139
Total	885,253	1,012,752	1,004,870	649,839	282,786	249,380

2.2 Raw materials in the model

There are three kinds of raw materials in the model. Heat and electricity purchased from the supplier is available in an unlimited amount, for a given cost. Solar radiation is unlimited and free. On the other hand, different kinds of biomass are available in the region, at a given cost, but only in a limited amount. Transportation of raw materials from larger distances is neither economic nor sustainable. Data for raw materials can be observed in Table 2. Note that energy content conversion factors are also indicated for some raw materials, which are needed for modeling the conversion of different kinds of masses into energy.

Table 2: Available energy sources in the region.

Name	Price (HUF)	Unit	Available amount	Energy content conversion factor
Saw dust	24	kg	150,000	0.90
Wood chips	22	kg	600,000	0.85
Sunflower stem	5	kg	500,000	0.75
Vine stem	7	kg	600,000	0.82
Corn cob	6	kg	1,200,000	0.80
Energy grass	8	kg	1,600,000	0.96
Wood	20	kg	2,000,000	0.83
Solar energy	0	kWh	infinite	N/A
Natural gas	114	m^3	infinite	N/A
Electricity from the grid	38	kWh	infinite	N/A

2.3 Operating units in the model

The different kinds of biomass that can be pelletized or processed in a biogas plant may greatly differ in terms of heating value. However, the same equipment may work for all of them, or possibly for a mix of them. For this reason, converter operating units are introduced for each type of biomass and the solar radiation, which is just a modeling tool to convert these raw materials into energy values, which is then used as inputs and outputs for the operating units modeled. The converter operating units take one material each, produce the input for some equipment of the facility, in a ratio of the energy content of the raw material. These converters are placed just below each raw material in the P-Graph, as raw materials are given in kg or kWh, but all other material nodes in the model are represented in kWh values (see Figure 1).

Purchase of energy is modeled by two operating units. The actual technologies available for energy production inside the plant are solar cells with corresponding electric heater and electric transporter, a pelletizer, a biogas plant and a corresponding biogas furnace and combined heat and power (CHP) plant. Note that sustainable technologies require high investment costs, both fixed and proportional to the required capacity, and also considerable operational costs (see Table 3).

Table 3: Estimated financial parameters considered for the energy conversion technologies. Proportional costs are with respect to heating values of the biogas or solar power to be produced finally.

Name	Investment cost, fixed	Investment cost, proportional	Operating cost, fixed	Operating cost, proportional
Solar power plant	50,000,000 HUF	400,000 HUF/kWh	none	25,000 HUF/kWh
Pelletizer	5,000,000 HUF	2 HUF/kWh	none	0.8 HUF/kWh
Biogas plant	20,000,000 HUF	48 HUF/kWh	none	2 HUF/kWh
Biogas furnace	10,000,000 HUF	20 HUF/kWh	6,000,000 HUF	4 HUF/kWh
Biogas CHP plant	20,000,000 HUF	36 HUF/kWh	6,000,000 HUF	6 HUF/kWh

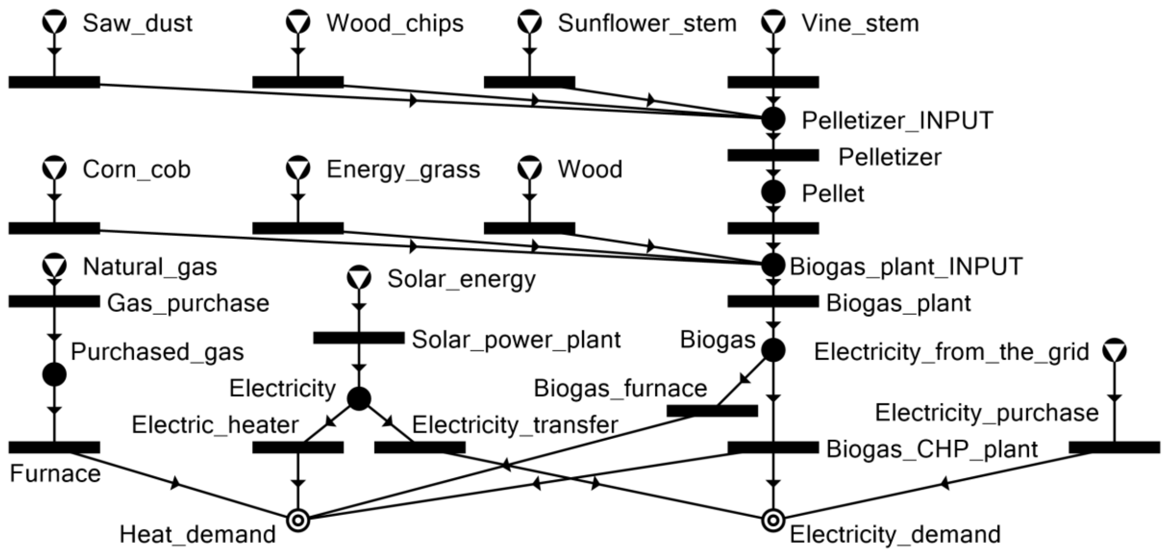

Figure 1: Maximal structure of the formulated PNS problem.

3. Results of the Case Study

The P-Graph model along with the problem data was implemented in the P-Graph Studio software (Figure 1). The maximal structure generated by the MSG algorithm is the same as the original P-Graph, as there are neither operating units nor materials that can be provably excluded. The ABB algorithm was executed, with the objective of the optimization being the total annual cost. A 20 years long payback period was supposed for the investments.

Table 4: Cost data for the optimal solution structure.

Cost type	Cost (HUF/y)
Raw material cost	24,053,870
Operating unit cost	196,991,130
Total cost	221,045,000

The problem with all the factors considered was solved by the P-Graph Studio in a very short time by the solution procedure. After a manual review of some solution structures found (see Figure 2), the following remarks are made. Note that each solution in this list is described relatively to the previous one.

- The optimal solution for the problem yields approximately 221.05 M HUF total cost for a single year. Most of the costs are due to investment, as renewable raw materials are usually cheap (see Table 4). Vine and sunflower stems are pelletized, and together with energy grass and corn cobs, biogas is produced and used in a combined heat and power plant. Although it may be dangerous to rely purely on renewable sources, theoretically we do not need to buy electricity from the grid or heat in this case.

- The second best solution has an objective of 221.58 M HUF, by omitting pellets at all and using solar power to supply the electricity needs partially.
- In the third best solution, an annual cost of 221.90 M HUF is achieved by using sunflower stems and electricity bought from the supplier again instead of solar power.
- In the fourth best solution, sunflower stem is exchanged to vine stem, the objective of 222.05 M HUF is still not much worse than the optimal.
- The original, business as usual solution only includes buying the required energy from the suppliers, and no investments are used, which results in an annual cost of 269.25 M HUF.

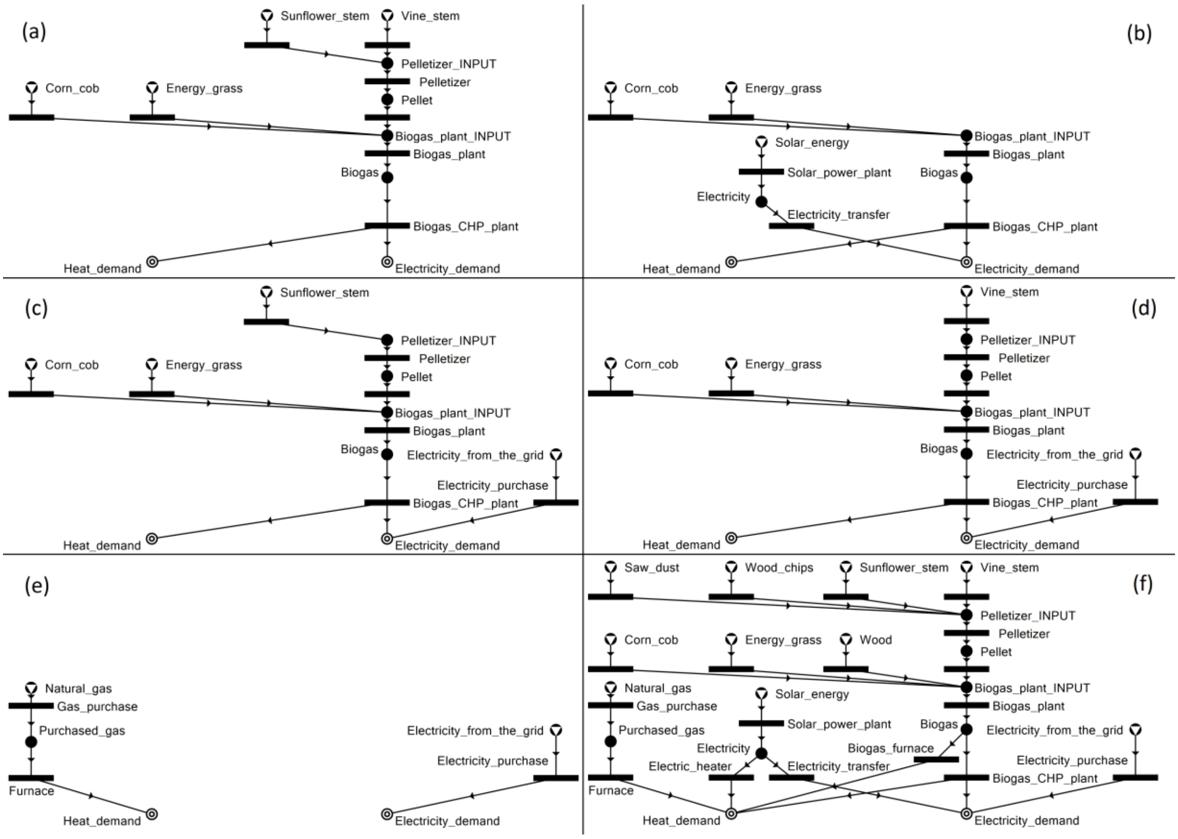

Figure 2: Solution structures of the PNS problem, the optimal or 1st best (a), the 2nd best (b), the 3rd best (c), the 4th best (d), "business as usual" solution (e), and the original maximal structure for reference (f).

The first best solutions were close together, and far from the original one, showing us that the P-Graph tool can be successfully used to optimize such demand and supply scenarios. It should be noted that all of the possible energy sources are used in some solutions structures found.

Apparently some parameters like availability, raw material cost, and especially investments have a very large influence over the solution structure. If we change the payback period to 5 years, which is still considered as a long-term investment in business practice, the optimal solution becomes the one with purchasing energy only, no investments are economic in this case. This indicates that the usage of alternative, renewable energy sources is economic, but only in very long-term scenarios.

4. Conclusions

A PNS problem was formalized as a P-Graph model to optimize energy options of an electronics manufacturing plant, where heat and electricity were considered as the desired products. Required amounts were estimated for a year. Solar cells, a pelletizer, biogas plants and furnaces, different kinds of biomass were considered as possible alternatives to purchasing energy from the suppliers.

The ABB algorithm was applied to find the sequence of the best solutions with the lowest total annual costs. Many structurally different solutions exist with approximately 221 M HUF/y cost; however, all are much better than the business as usual solution of 269.25 M HUF/year. A high payback period of 20 years is used here to

achieve these results. If much sooner payback is required for the investments, the original solution becomes the best in short term, without investments into sustainable technologies. Various government projects that endorse usage of these technologies are helpful to address this problem in the future, as well as other options to improve energy efficiency. Further Technological development in renewables is also expected.
The P-Graph framework was demonstrated to be working well for modeling different kinds of inputs, energy conversions and technologies in this case study. Other components should be investigated to be included in the P-Graph of the PNS problem where similar plants are to be optimized, like other renewable energy sources, and economic technology upgrades of the electric system, lights, insulation, heating and water system, etc. The current development includes the extension of the existing model with multi-periodical demands and supplies, which more accurately describes real-world situations where circumstances change over the course of the year, or consecutive years.

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