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Scheduling Manufacturing with Flexible Recipes to Maximize the Utilization of Renewable Energy

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The production schedule has a direct impact on the periodic utilization and energy consumption of equipment units. Meanwhile, for companies operating small power plants, the available renewable solar or wind energy changes continuously during the day, as does the hourly market price of the energy that can be purchased. Fortunately, the flexibility of production, possible schedules, or alternative recipes allow not only the minimization of costs but also the maximum use of renewable resources.
The novelty of the P-graph-based method proposed here is the integration of three component problems into a single optimization model, namely the production scheduling by discrete event formulation, the management of flexible recipes by process synthesis, and the maximal renewable energy utilization according to discrete-time energy production and market price forecasts by representing them with temporarily available resources. The challenge of formalizing the optimization problem lies in synchronizing the time model of production scheduling with the resolution of market price and renewable energy production forecasts. The results show that the flexibility to alter both the sequence and schedule of operations by the integrated optimization model plays a critical role in optimizing energy usage.

1. Introduction

In today's industrial environment, optimizing production schedules is cardinal for enhancing operational efficiency and reducing costs (Gahm et al., 2016). The periodic utilization of equipment units and their associated energy consumption are directly influenced by the production schedule. This becomes even more complex and critical in scenarios where small power plants operated by companies rely on renewable energy sources like solar and wind (Bertok and Bartos, 2020). The availability of these renewable resources fluctuates throughout the day, as does the hourly market price of energy that can be purchased. This dynamic environment necessitates innovative approaches to scheduling that can adapt to these variations while maximizing the use of renewable energy.
Process Network Synthesis (PNS) offers a powerful framework for designing and optimizing networks of interconnected processes (Friedler et al., 2022). PNS involves identifying and connecting various process units to achieve desired outputs while minimizing costs (Pimentel et al., 2022), risks, and environmental impact (Lim et al, 2022). Advanced mathematical models and optimization algorithms have been developed for parametric models of PNS to identify the N-best solution structures by algorithm ABB (Bertok and Bartos, 2020). By integrating PNS with scheduling (Frits and Bertok, 2021), it is possible to develop schedules that are not only cost-effective but also maximize the utilization of renewable resources. The flexibility inherent in production processes, such as the ability to alter the order of production or use alternative recipes for the same product, plays a crucial role in this optimization. This flexibility allows for adjustments that can align production activities with periods of high renewable energy availability.
Former problem formulations followed fixed time event (Barany et al., 2022), fixed time resolution (Bertok and Bartos, 2020), and precedence-based (Frits and Bertok, 2021) representation of the time horizon. This paper proposes an optimization procedure incorporating fixed-time resolution information into the modeling of fixed-time activities. A real-life furniture manufacturing problem serves as an illustrative example. It underscores the advantages of combining PNS with scheduling and flexible recipes and demonstrates how discrete time-based

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models can be effectively applied to solve complex industrial scheduling problems, paving the way for more sustainable and cost-efficient production processes.

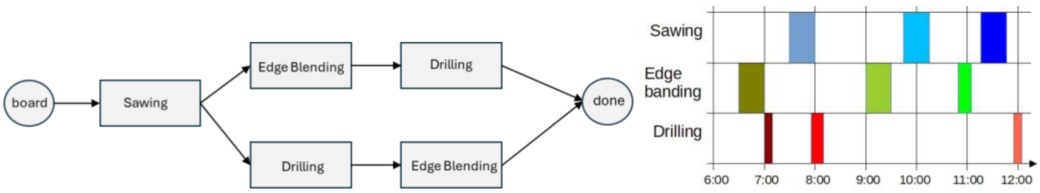
2. Problem Statement

In large-scale manufacturing plants, a significant portion of energy consumption is often attributed to fixed loads such as heating, lighting, and ventilation. These fixed loads remain constant regardless of the production volume. Therefore, the energy demand per unit of product is highly dependent on the utilization rate of the plant. When the plant operates at a higher capacity, the energy consumption per unit of product decreases due to the distributed fixed energy load. Conversely, lower utilization rates result in higher energy consumption per unit of product because the fixed energy load is spread over a smaller production volume. In the examined company, the idle times of the machines are used to perform low-volume subcontractor tasks, e.g., producing parts for laminated cupboards.

The production process of a laminated cupboard serves as a case study for this present work, where the raw material is laminated chipboard, and the product is the assembly-ready parts of the cupboard. There are three operations: sawing, drilling, and edge banding. The order of the last two is interchangeable. The operations in the production recipe are represented in Figure 1(a), and the execution times, together with the energy consumption of each individual operation, are listed in Table 1. In addition, Figure 1(b) illustrates the idle times of machines corresponding to different operations for the morning shift of May 28, 2024, as an example.

Table 1: Fix and proportional energy demands of operations

Name	Power demand [kW]			Duration [minutes]	Energy need [kWh]
	Fix		Proportional		
	Air compressor	Dust remover	Machining		
Sawing	15	9	20	30	22.00
Edge banding	15	9	22	15	11.50
Drilling	15	9	15	5	3.25



(a) (b)

Figure 1: (a) Production process of a laminated cupboard (b) Idle times of operations in the morning shift

Table 2: Energy balance for renewable energy production and consumption

Time	Consumed [kW]	Produced [kW]	Surplus [kW]
6:00	118.00	5.72	0.00
7:00	115.25	40.60	0.00
8:00	126.50	73.38	0.00
9:00	113.00	98.70	0.00
10:00	119.08	117.13	0.00
11:00	117.17	126.12	**8.95**
12:00	127.75	126.70	0.00

Table 3: Available Time Windows for the illustrative example

Equipment units:	w ϵ TimeWindows(eq)	StartTime (w)	EndTime (w)
Saw	WS1	7:00	8:00
Saw	WS2	8:00	9:00
Drill	WD1	8:00	9:00
Drill	WD2	10:00	11:00
Edge Bander	WE1	8:00	9:00
Edge Bander	WE2	11:00	12:00

Table 2 shows the amount of locally produced solar energy, consumption, energy balance, and energy market prices for the morning hours of the same day. The aim of the optimization is to maximize the profit from performing subcontractor tasks while the cost of each individual operation is taken into account as a function of the available renewable energy and actual energy market price.

3. Methodology: Modelling the Scheduling of Furniture Manufacturing Problem by P-graph

In the scheduling of furniture manufacturing, the main goal is to fill the free time slots with useful work, taking into account the previously described manufacturing process. The raw material of the process is the cupboard, which undergoes sawing, drilling, and edge banding. During sawing, the sawn cupboard is produced, and the last two machining phases can be performed in any order. This manufacturing process will be described by P-graph. The initial P-graph model includes all possible solution structures, such as all machining sequences in this example. However, the equipment used in each operation is only available during specified time slots. Therefore, in the P-graph model, as many potential activities are incorporated for each operation, as many time slots are available to perform it. It is important to handle the constraint that an operation associated with a given time slot can only be followed by an operation that is both the next in the recipe and subsequent in time. The following example demonstrates a case where each operation has two time slots, and for the sake of simplicity, each operation lasts for one hour. This is summarized in Table 3.

Based on the table, it is evident that sawing can start at two different times, at 7:00 and 8:00. However, for subsequent operations, the chronological order of the time slots must be observed. For example, sawing at 8:00 can only be followed by drilling at 10:00. Although edge banding at 11:00 is still feasible, there would be no further opportunity for drilling afterward, meaning the product would not be completed. These dependencies must be taken into account when constructing the P-graph model. In the first step, the graph is extended so that for each operation, as many activities are created as the number of time slots in which it can be performed. For example, for sawing, two activities, sawing_0700 and sawing_0800, are added. Each operation will have an input and an output, indicating not only the process materials but the start and end times of the operation as well. For instance, the input for drilling starting at 10:00 (drilling_1000_2) is the semi-finished product already sawed at 10:00 (sawed_1000_2), and the result of the operation is the semi-finished product drilled at 11:00 (drilled_1100_2). These operations are shown in the P-graph depicted in Figure 2, where the prefix 1 indicates the sequence Sawing - Edge banding - Drilling, and the prefix 2 indicates the alternative recipe with the sequence of Sawing – Drilling - Edge banding.

The next step is to determine which operations can follow each other, taking into account both the recipe and the time parameters. For example, sawing completed at 9:00 cannot be followed by drilling starting at 8:00. Possible transitions can be ensured by adding a new operation that performs the necessary links between materials, potentially subsequent in time. For instance, the result of sawing completed at 9:00 (sawed_0900) can be considered as a potential input to drilling starting at 10:00 (sawed_1000_2). The P-graph shown in Figure 2 includes the links representing the potential orders of process materials according to their availability of time by operations I1, I2, …, I9.

The energy consumption of each equipment in the process is specified in Table 1, and it should preferably be supplied from renewable energy sources, such as the energy produced by a solar panel system installed on the factory building. Since the amount of energy produced by renewable sources is uncertain, it is necessary to ensure supply from the grid as well with its hourly varying energy prices. Accordingly, two new raw materials are introduced hourly: renewable energy and grid energy, with the former being limited according to estimated production and the latter having a cost. The two energy sources are converted into a material node describing the energy available at the given hour, as shown on the sides of Figure 2.

The material nodes describing the energy produced on an hourly basis are connected to the activity corresponding to that hour, with the edge weights set based on the consumption of the associated equipment. Thus, in the given hour, the free renewable energy is used first, followed by the costly grid energy if necessary. As a result, both consumption and the price of energy available in the time slot influence which tasks are assigned to each time slot.

The constructed P-graph model is capable of resulting in a production schedule based on the given available time slots, taking into account the recipe while minimizing energy costs. In the next section, a case study will be solved by applying the model-building steps introduced in this section. Note that the time resolution of the model can be easily increased, but practically, neither the forecast of renewable energy production nor the energy market price estimate has a resolution higher than a quarter of an hour.

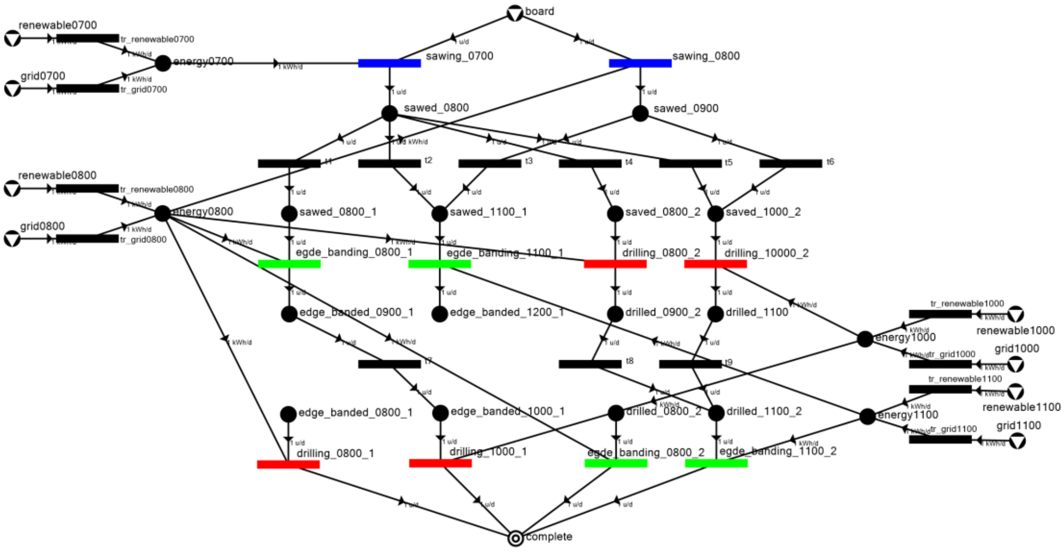


Figure 2: The generated structure for the illustrative example

Table 4: Available Time Windows for the Case Study

Equipment units	TimeWindows	StartTime	EndTime
BeamSaw	WS1	7:30	8:00
BeamSaw	WS2	9:45	10:15
BeamSaw	WS3	11:20	11:50
Edge_Bander	WEB1	6:30	7:00
Edge_Bander	WEB2	9:00	9:30
Edge_Bander	WEB3	10:50	11:05
Drill	WD1	7:55	8:10
Drill	WD2	7:00	7:10
Drill	WD3	11:55	12:05

Table 5: Expected renewable energy productions and energy prices on May 28, 2024 in Veszprém, Hungary

Hour	Remained Renewable Energy	Grid Energy Cost
06:00	0 kW/h	0,090 EUR/kWh
07:00	0 kW/h	0,115 EUR/kWh
08:00	0 kW/h	0,125 EUR/kWh
09:00	0 kW/h	0,105 EUR/kWh
10:00	0 kW/h	0,088 EUR/kWh
11:00	8,95 kW/h	0,075 EUR/kWh
12:00	0 kW/h	0,073 EUR/kWh

4. Case Study

The steps for generating the P-graph model, which were presented in the previous section, as well as the results provided by the model, are also demonstrated through a real case study, in which data provided by Balaton Bútor Ltd were used. In the Problem Definition section, the manufacturing process was already introduced, along with the time and energy requirements for each operation, which are fixed parameters for every generated model. However, during daily planning, the available time windows for each piece of equipment, the expected energy amount from renewable energy, and the hourly breakdown of energy prices change. Taking these variable parameters into account, the P-graph model can be generated algorithmically, capable of providing the optimal solution, with the goal of efficiently utilizing empty time slots with minimal consumption.

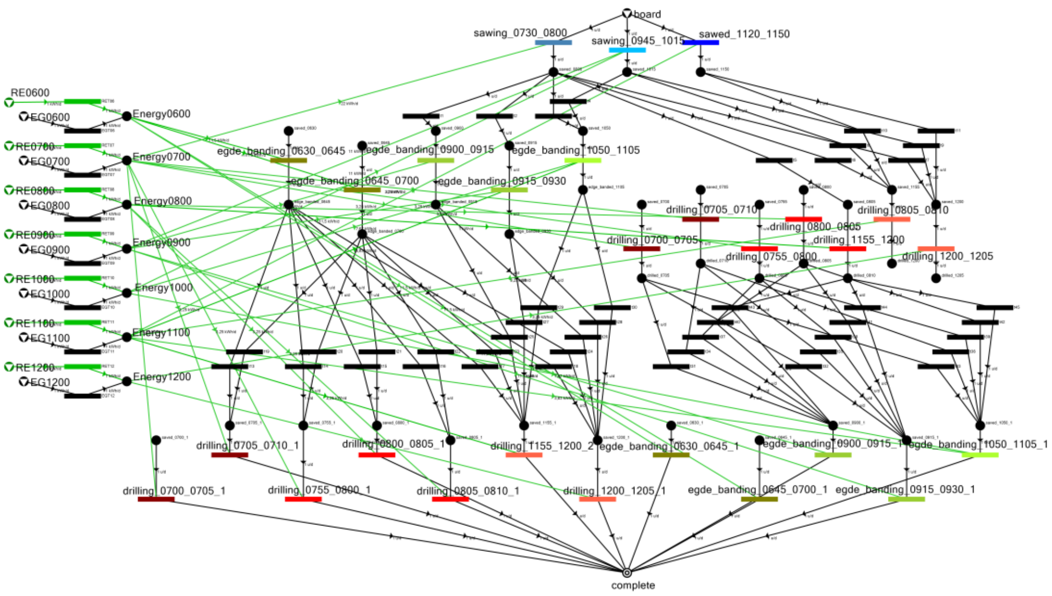


Figure 3: P-graph model of the Case Study

The manufacturing process includes three main activities: sawing, drilling, and edge banding, which can be performed on dedicated equipment. The free time slots of the equipment featured in the case study are summarized in Table 4. In the example, we only schedule production for a morning shift, for which the estimated energy production and energy prices for these hours can be found in Table 5.

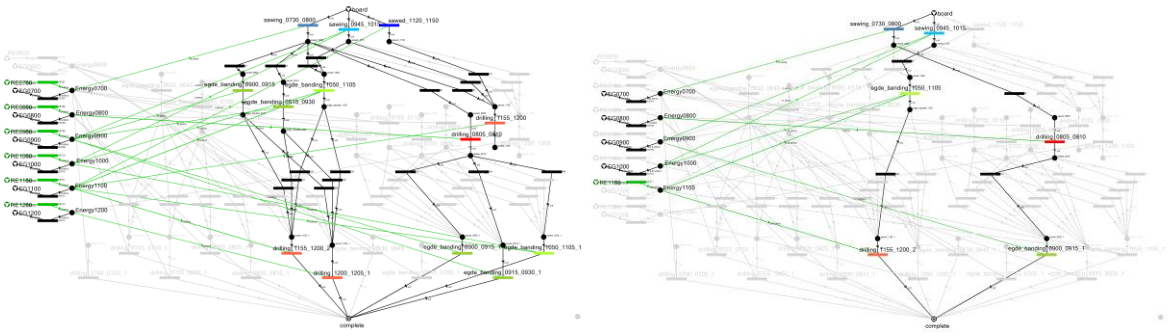
Based on the above parameters and the already described model-building steps, the P-graph model related to the case study can be generated automatically. In the first step, an activity must be created for each time slot listed in Table 4, along with the corresponding inputs and outputs. It is important to ensure that, according to the recipe, the order of drilling and edge banding is flexible, so all time slots must be created for the operation performed first, as well as for the same operation performed second. Naturally, this will result in some infeasible cases, which the MSG (Maximal Structure Generator (Friedler et al., 2022)) algorithm will filter out, but the generating algorithm can also be implemented in a way that excludes impossible combinations from the graph. In the next step, activities are added to the graph to ensure the transition between the output of one operation and the input of a subsequent operation. During the generation process, the recipe and the times assigned to the nodes are also managed, so transitions that are not possible in reality are not added to the graph.

In the final step, energy management is implemented. During this step, renewable and grid energy resources for the hours within the given period are generated and then connected to the respective operations. The weights of the edges are set according to the consumption data provided in Table 1; the result of this step can be seen in Figure 3.

The P-graph structure generated in three steps appropriately describes the problem defined in the case study, but it contains many nodes that will certainly not be part of the solution. For example, there are activities linked to time slots that have no inputs connected to them. During the solution process, these nodes must be eliminated, which is implemented by the MSG (Maximal Structure Generator) algorithm of the PNS framework. The result can be seen in Figure 4(a), where nodes and edges that will certainly not be part of any solution structure are marked in gray.

The solution structure for the optimal solution of the case study is shown in Figure 4(b), which provides the basis for determining the manufacturing sequence and schedule with minimal energy requirements while maximizing the utilization of idle times of the manufacturing equipment. The computation time required to generate the 10 best processes and schedules was less than 0.1 s on an Intel i7-9750HF processor laptop. Thus, the solution procedure is fast enough to incorporate it into daily decision support.

In the optimal solution, idle time was utilized to schedule two furniture productions. For the first piece of furniture, the schedule was as follows: 7:30 sawing, 08:05 drilling, and 09:00 edge banding. For the second piece of furniture, the schedule was 9:45 sawing, 10:50 edge banding, and 11:15 drilling.



(a) (b)

Figure 4: (a) Maximal structure (b) Optimal structure for the case study

5. Conclusions

The study presents a method for optimizing production schedules in manufacturing to maximize the use of renewable energy. As a novelty, it includes three component problems in a single optimization model: the scheduling of production by discrete event formulation, the management of flexible recipes by process synthesis, and the maximal renewable energy utilization according to discrete-time energy production and market price forecasts by representing them with temporarily available resources. This approach addresses the challenges posed by the fluctuating availability of solar and wind energy, as well as varying hourly market prices for purchased energy. By integrating Process Network Synthesis (PNS) with flexible scheduling, the proposed method creates production schedules that align with periods of high renewable energy availability. This is demonstrated through a case study in furniture manufacturing, where the production process includes sawing, drilling, and edge banding. The study shows that the flexibility to alter the sequence of operations and use alternative production recipes plays a critical role in optimizing energy usage. The case study results highlight the method's effectiveness in generating optimal production schedules that minimize energy costs and maximize the utilization of renewable resources. In summary, this study shows that integrating PNS with flexible scheduling can significantly enhance the utilization of renewable energy in manufacturing, leading to cost savings and more sustainable production processes.

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References

Barany M., Bertok, B., Kovacs, Z., Friedler, F., Fan, L. T., 2011, Solving vehicle assignment problems by process-network synthesis to minimize cost and environmental impact of transportation. Clean Technologies and Environmental Policy, 13, 637-642.

Bertok B., Bartos A., 2020, Renewable energy storage and distribution scheduling for microgrids by exploiting recent developments in process network synthesis. Journal of Cleaner Production, 244,118520.

Friedler F., Orosz Á. and Losada J.P., 2022, P-graphs for process systems engineering. Springer International Publishing, Cham, Switzerland, ISBN 978-3030922153.

Frits M., Bertok B., 2021, Routing and scheduling field service operation by P-graph. Computers & Operations Research, 136, 105472.

Gahm C., Denz F., Dirr M., Tuma A., 2016, Energy-efficient scheduling in manufacturing companies: A review and research framework. European Journal of Operational Research, 248(3), 744-757.

Lim J.Y., Orosz A., How B.S., Friedler F. and Yoo C., 2022, Reliability incorporated optimal process pathway selection for sustainable microalgae-based biorefinery system: P-graph approach. In Computer Aided Chemical Engineering, 49, 217-222.

Pimentel J., Rodríguez G., Gil I., 2020, Synthesis of alternative cost-effective process flowsheets for lactic acid valorization by means of the P-graph methodology. Industrial & Engineering Chemistry Research, 59(13), 5921-5930.