




ETHOS.PeNALPS: A Tool for the Load Profile Simulation of Industrial Processes Based on a Material Flow Simulation

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Summary

ETHOS.PeNALPS (Petri Net Agent-based Load Profile Simulator) is a Python library for simulating the load profiles of industrial manufacturing processes for arbitrary energy carriers. It is part of [ETHOS \(Energy Transformation Pathway Optimization Suite\)](#). Load profiles are energy demand time series. Processes that can be simulated using ETHOS.PeNALPS include, for example, steel, paper, and industrial food production.

Figure 1 shows the main conceptual objects of ETHOS.PeNALPS which are:

- Generic model objects
- Material flow simulations
- Production plans
- Result load profiles

The model of the material flow simulation is created by users based on generic simulation objects. After the material flow simulation is completed, a set of production orders is passed to the model to start the simulation. The simulation generates a production plan that tracks the activity of each node to fulfill the requested set of orders. Based on the activity in the production plan, the load profiles are created for each node in therein.

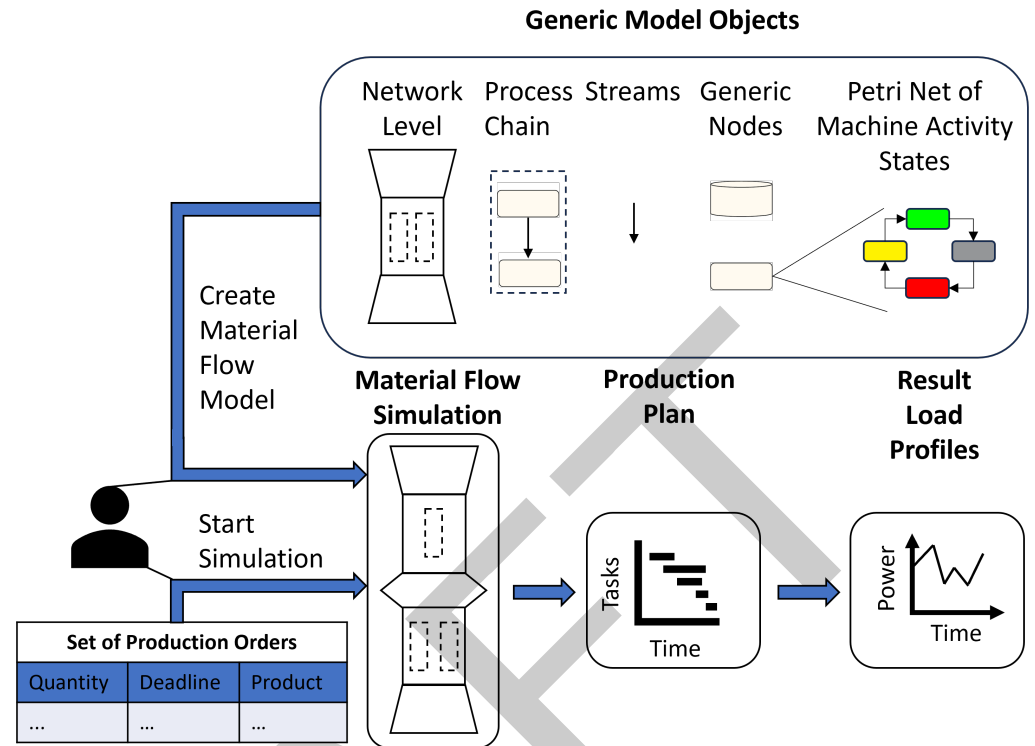


Figure 1: The main components of ETHOS.PeNALPS are the generic models objects, material flow simulation, production plan and load profiles.

Statement of Need

Load profiles are of particular interest for assessing energy demand fluctuations in energy system modeling and design. For industrial processes, load profiles are often not available for open research due to:

- Efforts by enterprises to protect commercial secrets;
- Missing measurements;
- Unstructured energy data collection in enterprises;
- Novelty of the industrial processes and their currently missing implementation.

ETHOS.PeNALPS can provide these missing load profiles via simulation.

Method

ETHOS.PeNALPS is capable of modeling noncyclical industrial production networks. The simulation is created from generic objects, which are shown in Figure 1. The most important components are the generic nodes that handle and create the material requests as agents. The generic node types are:

- Source
- Sink
- Process step
- Storage

These nodes are connected by streams that determine the direction of the material flow in the simulation. Sequentially-dependent nodes and streams are combined in so-called process chains. Multiple or single process chains are integrated into a network level. Multiple chains

46 in a single network level model the parallel operation of similar equipment. Multiple network
47 levels can be used to model network features of the industrial process.

48 A single network level starts with a source and ends with a sink, which determines the start
49 and end points of the material within that level. To connect two network levels, the source of
50 one network level and the sink of another are replaced by a shared storage.

51 Each of the nodes acts as an agent that handles material requests.

- 52 ▪ Sources only provide materials and sinks only request them.
- 53 ▪ Process steps and storages provide and request materials.

54 To initiate the simulation, the first request is created in the sink from the production order.
55 These requests are then passed to the upstream until they reach the source of the network.
56 Within a chain, a request can be adapted if it can be fulfilled in time. The adaptation shifts
57 the request to an earlier time, so that the deadline is always met.

58 The behavior of a process step during the fulfillment of a request is determined by a sequence
59 of states that are stored in a petri net. A petri net is a state transition system which consists
60 of places, transitions, and arcs (Peterson, 1977). The states can be as simple as on or off
61 switches or constitute a complex network of states during production. The combination of a
62 petri net and process step agent is the main novelty of the tool and thus provides its name.

63 **Example: Toffee Production**

64 The ETHOS.PeNALPS workflow is demonstrated based on the example of a simplified toffee
65 production process, which is described by Korolessi and Linninger (2005, pp. 31–32). During
66 the process, the raw toffee materials are mixed, cooked, and cooled in a toffee machine. The
67 cooled toffee is then cut and packaged in two-subsequential machines. The corresponding
68 model is depicted in Figure 2. The energy values are taken from similar machines from
69 (Wojdalski et al., 2015) and should be interpreted as a non validated showcase example. The
70 nodes in the material flow simulation are (a) first named by their generic name and its specific
71 name in the example in brackets. It is assumed that the process consists of two toffee machines
72 that operate in parallel. The toffee produced is cut and packaged by two sequentially-ordered
73 machines. The activity of the machines and streams is tracked in the production plan (b),
74 which is partially shown in the figure. Based on the states of the process steps and streams,
75 load profiles (c) are calculated using specific energy demands.

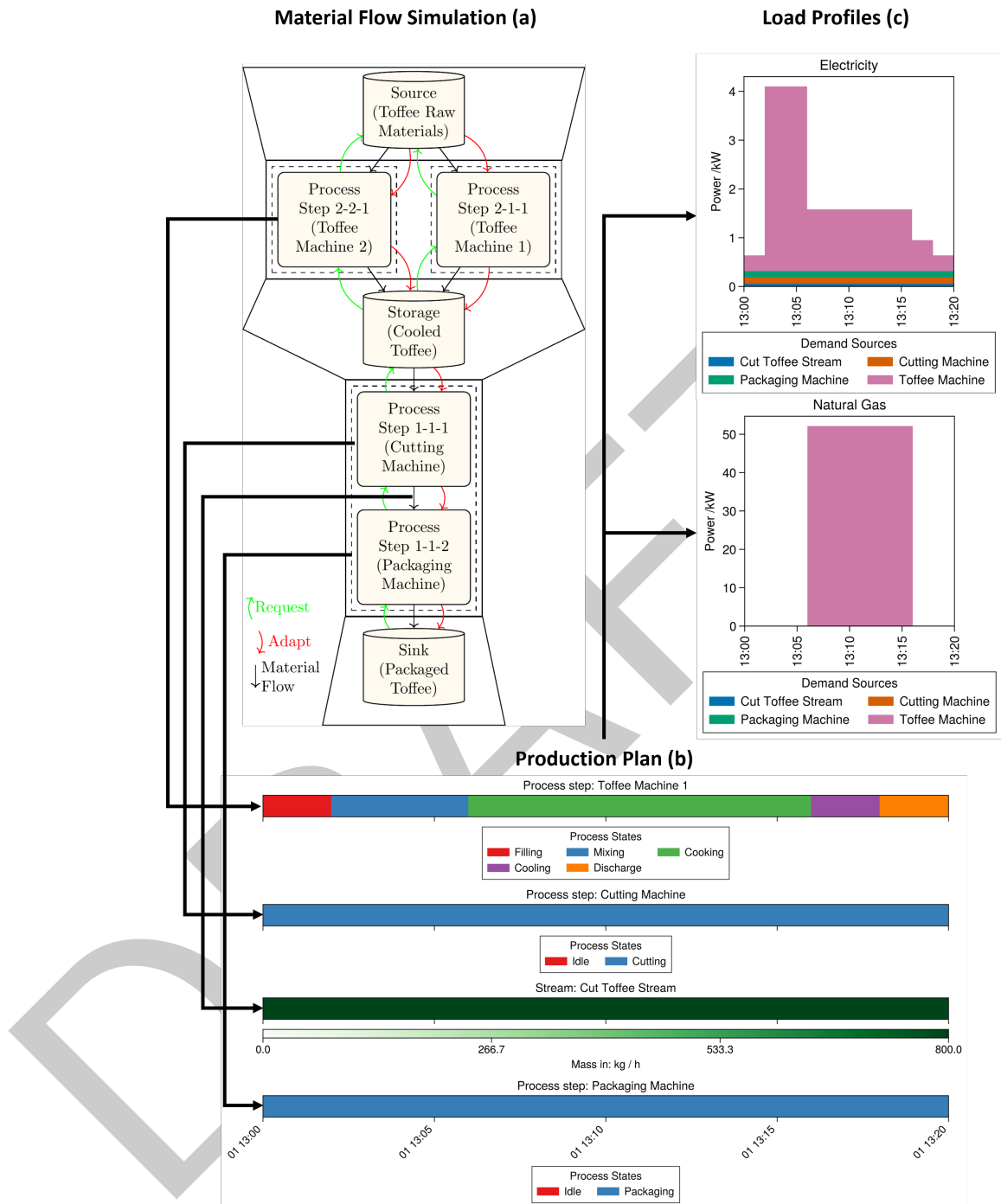


Figure 2: Demonstration of the functional principle of ETHOS.PeNALPS using the example of toffee production. It contains the main components (a) material flow simulation the production plan (b) and the load profiles (c)

76 The simulation is begun by passing a set of orders for packed toffee to the packaged toffee
77 sink. It then generates requests for the upstream node, which is the packaging machine. This
78 in turn triggers a chain of upstream requests until it reaches the source.
79 While fulfilling the request, a process node switches a cycle through its petri net. Figure 3
80 displays an example petri net for the toffee machine. The places of the petri net are the

81 machine states of the modeled machine. There are four different kinds of states:

- 82 ▪ Idle state (yellow), which is the start and end point
- 83 ▪ Input state (green), determines the activity of the input stream
- 84 ▪ Output state (red), determines the activity of the output stream
- 85 ▪ Intermediate state (gray), resembles a specific task or phase of the production

86 They are ordered by temporal occurrence during production. To fulfill a request for an output
87 stream, the process step switches over a full cycle from idle state to idle state. Each active
88 state during the switch cycle is tracked in the production plan, which simulates the machine's
89 activity. Even though the states are stored in the correct forward temporal order, the internal
90 switches occur in the opposite temporal direction. This is useful because the output request
91 that is passed to the process step only provides the required time frame for the output state.

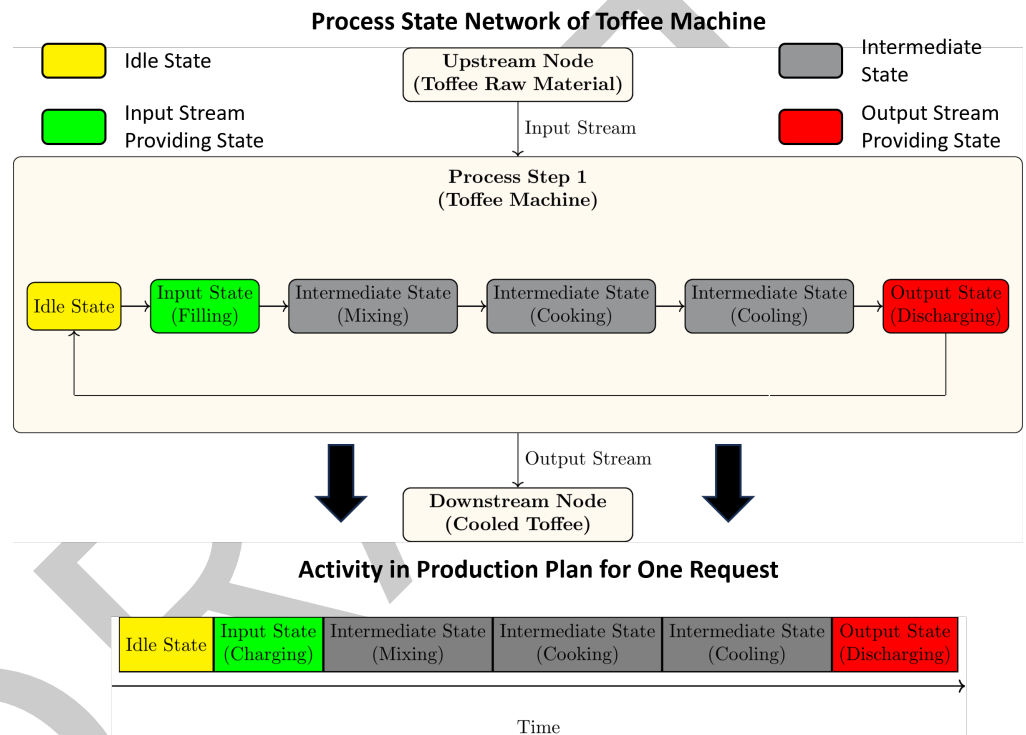


Figure 3: This figure shows the petri net of the example toffee machine and how it determines the activity of the machine in the production plan.

92 The packaging and cutting machine only have one state apart from their idle state, which are
93 termed “Cutting” and “Packaging”, respectively. Each state can be associated with a specific
94 energy demand that causes an energy demand during the activity of the respective state. Thus
95 the sequential activity of the states can be used to model the energy demand fluctuations in
96 the load profile. Furthermore, an energy demand can also be attributed to a stream to model
97 a conveyor belt or pump, for instance.

98 Other Tools and Methods

99 To overcome the lack of industrial load profiles, simulation tools and methods have been
100 developed. However, most of these are not open source or are a method rather than a reusable
101 tool.

102 Kohl et al. (2014) proposed using a material flow simulation created by the commercial tool

103 Plant Simulation to simulate the load profiles of the manufacturing processes. Measured load
104 profiles were then allocated to the internal machine states using the observer pattern.

105 Binderbauer et al. (2022) published a study on the “Ganymede” software, which also uses a
106 material flow simulation to simulate load profiles. The material flow simulation is based on a
107 discrete event simulation. Ganymede only distinguishes between continuous and batch process
108 steps. In order to implement more detailed load profiles of machines, external load profiles
109 are required for the respective machines. These are difficult to obtain for many machines,
110 especially as machine-readable data.

111 Li et al. (2022) implemented a petri net to forecast the energy demand of individual machines
112 in real time. This approach lacks a method to coordinate the activity of multiple machines
113 that are connected in a network.

114 Dock et al. (2021) created a discrete event based on a material flow simulation for an electric
115 arc furnace plant. It uses a parameterized Markov Chain load profile model to generate
116 load profiles for the electric arc furnace. Neither the Markov Chain parameters nor the load
117 profile used for parametrization have been published. Moreover, maintenance activity and
118 interdependent activity are implemented for some of the process steps. The applicability of the
119 model to other industrial processes cannot be verified, because the source code of the model
120 has not been published.

121 Sandhaas et al. (2022) use a different approach to generate load profiles which is not based
122 on a material flow simulation. Rather, their approach is based on the recombination of eight
123 standard load profiles of appliances, which are used to model the load profile of an industry. For
124 a specific industry the share of each appliance of the standard load profiles is determined. These
125 shares are then used as weights in the recombination of the standard load profiles. Furthermore,
126 some stochastic fluctuation is applied to the recombined load profile. This approach requires
127 less input data, but cannot model any features that are not contained in the standard load
128 profiles. It has been published as an open-source code.

129 The software eLOAD employs an approach similar to that from Sandhaas. Instead of applying
130 it to individual industries, Boßmann & Staffell (2015) applies it at a national level. They also
131 assume demand response flexibility for some appliances. The source code and appliance load
132 profiles used have also not been published.

133 Authors Contribution

134 **Julian Belina:** Software, Writing, Visualization, Methodology. **Noah Pflugardt:** Conceptualiza-
135 tion, Methodology, Supervision, Writing - Review & Editing. **Detlef Stoltzen:** Conceptualization,
136 Phd Supervision, Resources, Funding acquisition.

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