Synthetic Load Profile Generation for Production Chains in Energy Intensive Industrial Subsectors

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Kurzfassung/Abstract: The generation of synthetic load profiles offers the possibility to easily and efficiently depict the dynamic energy consumption and generation of single consumers. Therefore, it is vital for evaluating future challenges for the physical energy system, support the forecast models of grid operators and energy suppliers and improve deriving demand side management measures for consumers. In this paper, we present *Ganymed* as a suitable software for assessing energy consumption and generation behaviour of production chains in energy intensive industrial subsectors. A dynamic user interface allows a swift and easy application and adaption of processes and production routes. The underlying methodology is based upon discrete-event simulation as a case study is applied to prove the functionality of *Ganymed*. Within this case study, we modelled a part of a production chain of an existing cement plant and compared the generated load profiles to measured ones. The results show good approximations to the measured load profile with an average deviation of 4.1%.

Keywords: Industry, Load Profile, Software, Energy Model

1 Introduction

The industrial sector is accountable for 37% of the overall primary energy demand in Austria [1]. Therefore, the industry undoubtedly has to take part in the energy transition [2]. The development of comprehensive energy system models may help therewith and align the industrial sector with the European net zero greenhouse gas (GHG) emission goals. Energy system simulations allow to get hold of fast changing trends and technologies, evaluate their impacts on the physical energy system and support the strategic decision making for the energy transition. Due to increasing volatility within the energy system, various models incorporate analysis of future grid demands and for energy suppliers [3]. Hence, the calculation of timely resolved behaviour of energy consumption and generation of industrial consumers in terms of load profiles (LP) play a key factor.

1.1 State of Research and Scope of the Work

The goal of most energy system models is to efficiently depict long-term GHG emission pathways, the impact of increased energy efficiencies or the implementation of future technologies and renewable energy sources [4]. A number of these models investigate the mentioned factors in a coarsely time-resolved way. The impact of these factors on the finely resolved energy consumption patterns (e.g. hourly resolved values) of consumers is often disregarded because of the extensive and detailed scope of this task. However, the development of such models is crucial for grid operators and energy suppliers to adequately improve their forecast models or for industrial sites themselves to support their demand side management.

Throughout an extensive literature research, we found that such models were developed for the mobility and residential sector. Vopava et al. [5] examined approaches in the mobility sector simulating the energy consumption of electric vehicles at charging stations. These models are either based on modelling of the driver's behaviour [6] or measured data [7]. In the private sector, behavioural characteristics of residents were also investigated by Pflugradt and Muntwyler [8] to synthesize corresponding load profiles (LP) of the single households.

Models for LP generation for the industrial sector were not developed in a such far reaching scope yet [9]. We reasoned this because the industrial sector holds a more heterogeneous nature in terms of energy consuming or generating factors than compared to mobility and residential. Some studies like Starke et al. [10] or Thiede et al. [11] investigate the industrial sector nevertheless. However, their models require a deep base of data before being applied.

Therefore, our overall goal is to develop a methodology for generating synthetic LPs for various energy carriers like electricity, direct fuel or steam of production chains of all industrial subsectors and provide an extensive database within the user-friendly software environment *Ganymed* [12]. The default data can be applied to instantly depict the consumption and generation behaviour of real or fictitious industrial sites and can be extended with new data anytime. The software can be downloaded via *ganymed.ga*.

2 Methodology of *Ganymed*

We divided this chapter into two parts covering the overall model and simulation paradigm first. Afterwards we describe the application of the base model for industrial processes which was developed throughout our studies.

In a first step, we applied the classification of the International Energy Agency (IEA) to divide the industrial sector into energy intensive and non-energy intensive subsectors [13]. We integrated the energy intensive subsectors Iron & Steel, Pulp & Paper, Chemical and Non-Metallic Minerals into *Ganymed* first, since we concluded that these sectors only exhibit a limited range of different and energy demanding production processes and principles. The product variety is smaller compared to other non-energy intensive subsectors [9]. Therefore, a bottom-up approach can be applied to depict those subsectors.

Throughout a standardised research approach, we investigated all four subsectors and their underlying processes and production chains extensively. We characterised the processes in regard to their runtime, operating type (e.g. continuous or discontinuous), specific energy demand or time series etc. The other non-energy intensive subsectors will also be introduced into the system.

2.1 Overall Model Paradigm

After building up a sound database of the included industrial subsectors, we developed a calculation approach based upon discrete-event simulation. Via this paradigm, a sequence of interactions of i active components (e.g. tonnes of steel) with m resources (e.g. industrial processes like blast furnace etc.) can be depicted [14]. Therefore, a logical production route can be designed and its timely resolved energy demand evaluated. We enhanced the simulation paradigm extensively to meet the necessary requirements for depicting industrial process routes of the mentioned energy intensive industrial subsectors.

Figure 1 shows the overall functionality and the adaption of discrete-event simulation in *Ganymed*. We defined the backend of *Ganymed* as the simulation environment (a), while its graphical user interface (GUI) (b) takes the role of the frontend. The user defines or sets the desired production chain with its containing processes and the amount of components, which shall be processed, within the GUI (c). The classes of all included processes (f) in the default database (e) create *m* specific object resources (e.g. three pulp digesters in one production route). Via drag and drop the user can then dynamically design the desired route and interlink all processes with each other (h).

When this setup is finished, the user initiates the simulation (d). All included processes operate within the defined production route and sequence via timely events (i). The energy consuming (or generating) behaviour of the processes is added up to depict a general LP (j).

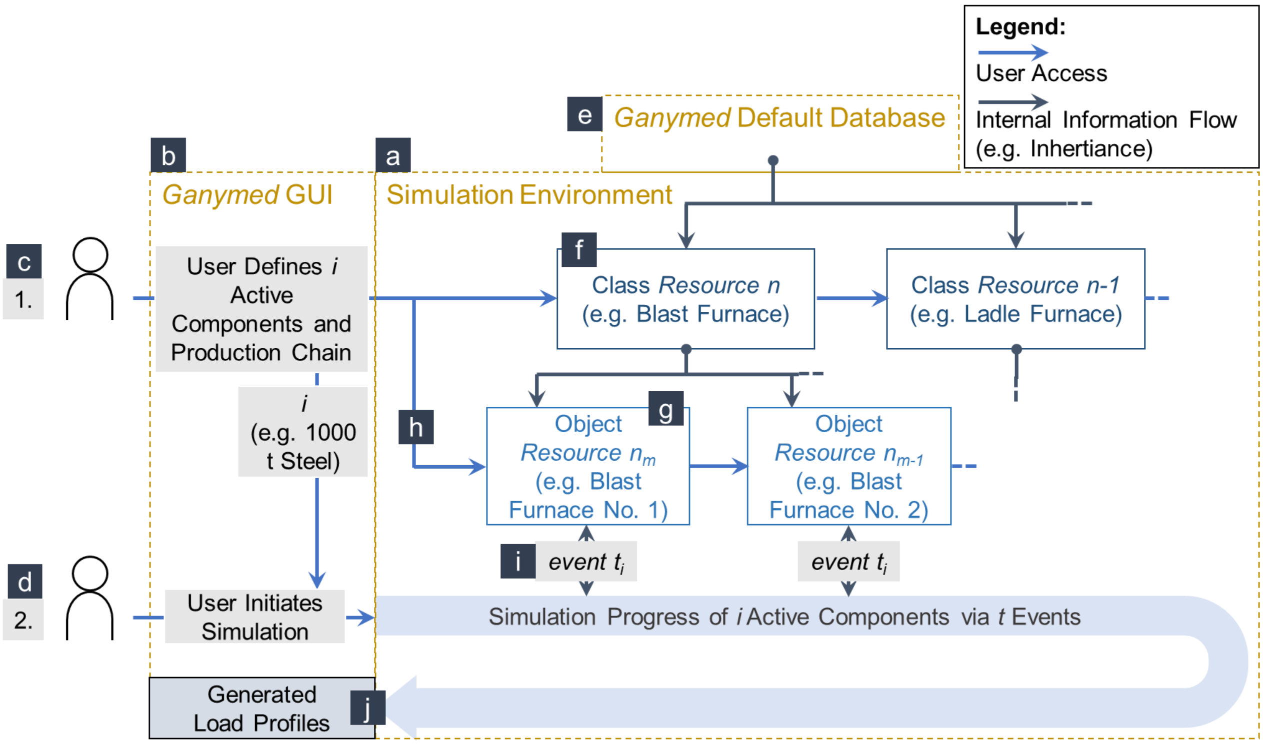

Figure 1: Functionality and simulation operation of Ganymed

2.2 *Ganymed*'s Application on Industrial Processes and Production Routes

As we described above, the paradigm of discrete-event simulation is applied to adequately depict industrial processes and their operational behaviour.

For one, all depicted processes are divided into discontinuous (batch) and continuous processes. Continuous processes are characterised by throughput (e.g. in t/h), batch-wise ones by unit size (e.g. in t) and operating times including charging and discharging durations.

The alignment of these processes to a production route can be performed freely and dynamically by the user as mentioned above. To successful communicate this structure from the GUI to the simulation environment, a coordination matrix is applied. Figure 2 (a) shows a possible production route in *Ganymed*, whose start and end point is defined accordingly. The coordination matrix (b) of the main product route (indicated by black directional arrows) contains the address of each dispatching and receiving process. Furthermore, subproduction chains can be aligned in serial or parallel.

Figure 2 also shows the application of different materials streams besides the main product in *Ganymed*. For example, the main product can be defined as pulp (in Figure 2 (a) indicated by black arrows). A possible auxiliary material could be recycled paper as indicated by green arrows. A by-product of chemical pulp production is black liquor [15] (see blue arrows in Figure 2 (a)), which can also be depicted in *Ganymed*. The coordination matrix for recycled paper and black liquor model implementation is extended accordingly (Figure 2 (c) and (d)).

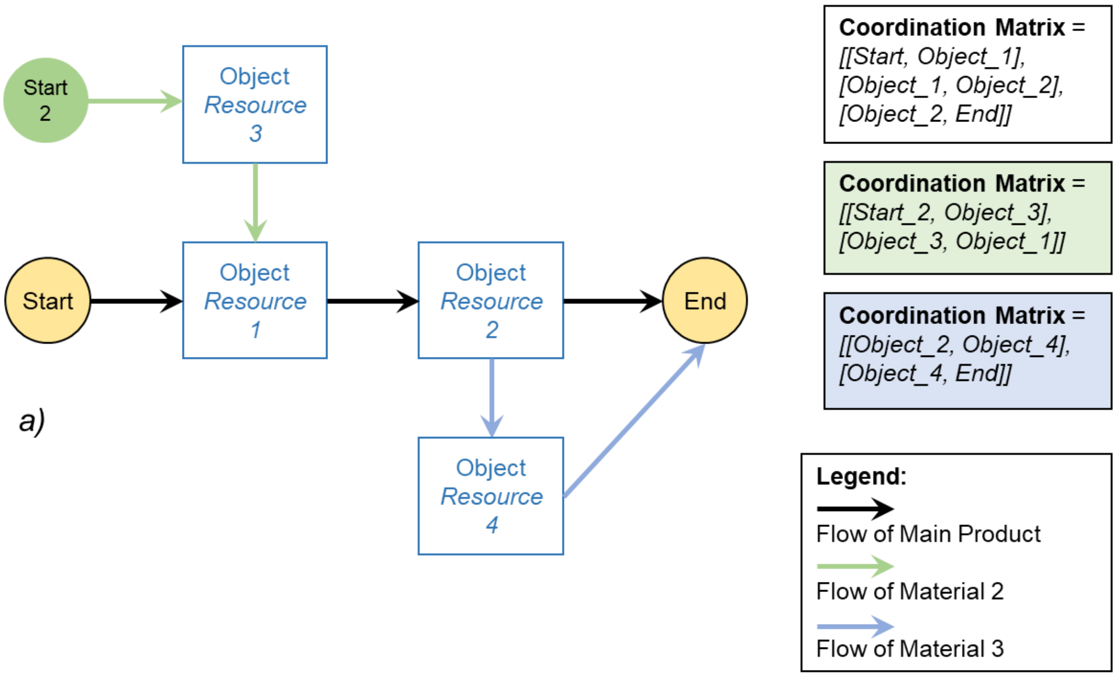

Figure 2: (a) Possible production route in Ganymed with a according coordination matrix for the main product in (b) and the auxiliary material streams in (c) and (d)

All calculations of energy flow balances can be performed for various system dimensions. Therefore, we introduced user-defined, variable system boundaries into *Ganymed*.

A production route typically contains several production related processes as shown in Figure 3 (a). These processes either take part in the production itself and consume final energy (e.g. electricity for pulp digester) or transform energy carriers within or outside the industrial site (e.g. CHP plants, electrolysers, blast furnaces…). The latter are defined as “autoproducers” by the UN Energy Statistics regime [16].

The bold arrows in Figure 3 indicate the energy streams/carriers. When defining the balance border as shown in (a), *Ganymed* will only generate synthetic direct fuel LPs due to the intersection of this energy carrier with the system boundary. Electricity and steam is generated and consumed within the border. However, the user can adapt the boundary to just depict the electricity LP of e.g. object resource 1 (b). Additionally, the energy consumption and generation behaviour of the included autoproducer can be assessed, when the boundary is defined accordingly in (c). The dynamic system boundaries are therefore capable of depicting the energy consumption and generation of single processes, parts of the manufacturing route or the overall industrial site.

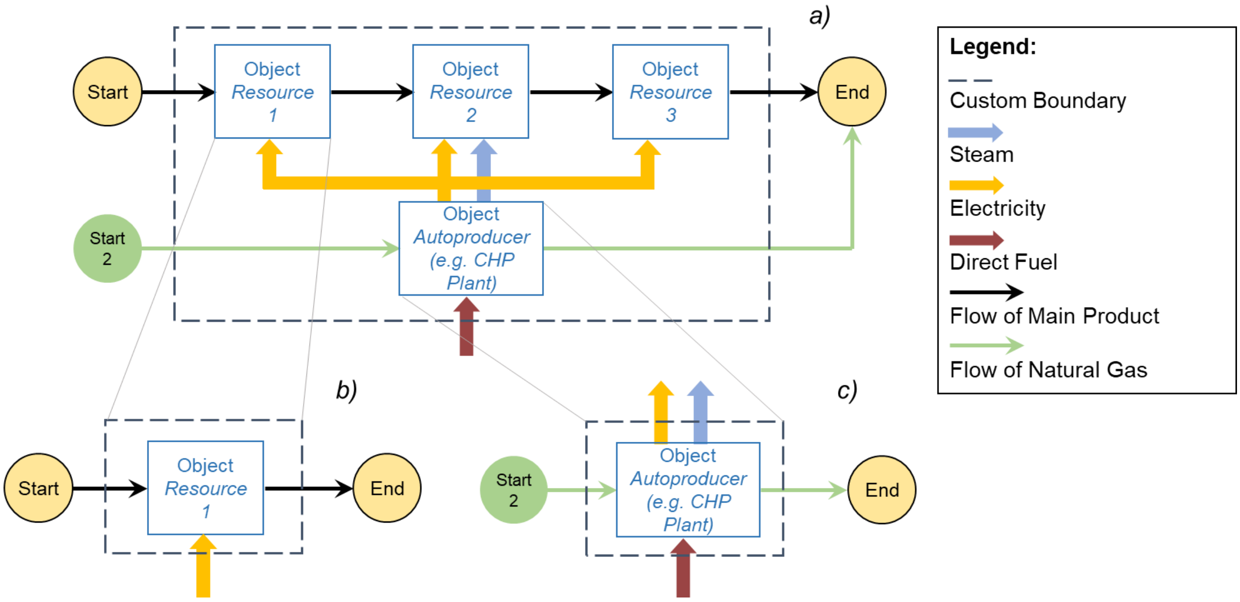

Figure 3: System boundaries in Ganymed: (a) Overall production plant boundary including (b) single production processes and (c) autoproducers

3 Case Study

We evaluated the functionality of *Ganymed* via various case studies modelling the consumption behaviour of real industrial sites. In a preceding study [9] we investigated an iron & steel mill in Austria and found good approximations of our results to the measured data.

For this paper, we'd like to present a case study modelling the electricity demand of an existing cement plant based upon the work and measurements of Lidbetter et al. [17]. In this study the most energy intensive part of the cement production route is described and its underlying real electricity demand is published. Lidbetter et al. derived DSM measures from their analysis and improved the energy efficiency at the real production site.

We implemented the given process layout of this study shown in Figure 4 in *Ganymed*. The main part of the process chain consists of two parallel sub-production routes, which are designed similarly. However, the starting crusher unit as implemented in all cement mills is not included in the route. Two roller mills process the raw meal to meet the specific grain size for the finished product and are operated batch-wise. After this step two raw meal silos act as a buffer for the incoming raw meal and its further processing. We calculated the mean time of storage based upon the mentioned study as 5 minutes per tonne main product. Two follow up rotary kilns burn the raw meal continuously. These units are excluded from the energy balance because they are responsible for just a small share of the overall electricity consumption. However, they are nevertheless part of the sequential simulation to depict the real production flow as accurate as possible. The following clinker silo stores excess material and therefore buffers any fluctuations of material flow. The two remaining ball mills (cement mills) refine the clinker to the finished product.

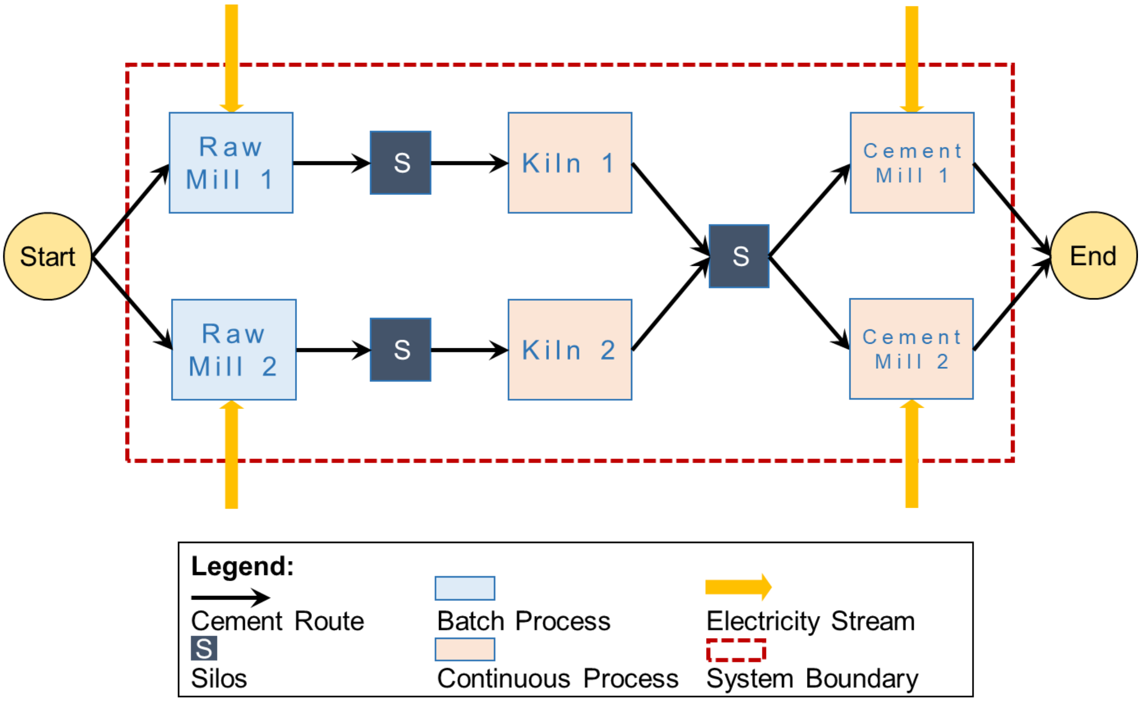

Figure 4: Process layout of Lidbetter et al. [17] as implemented in Ganymed

The electricity consuming behaviour of raw mill 1, raw mill 2, cement mill 1 and cement mill 2 will be assessed throughout this case study. Further information on the included process units are shown in Table 1 as they are classified as either batch (blue) or continuous (orange) processes in accordance to Figure 4. We implemented the corresponding throughput, unit sizes and durations from Lidbetter et al. in our model, while the corresponding electricity consumption origins from the *Ganymed* database. Furthermore, we altered the mean consumption slightly because the underlying literature data from our database lists these demands in ranges.

Table 1: Characterisation of processes in this case study

Name	Throughput [t/h]	Unit Size [t]	Duration [min]	Charging and Discharging Time [min]	Specific Electricity Consumption [kWh/t]
Raw Mill 1	-	240	60	10	15
Raw Mill 2	-	150	45	15	17
Kiln 1	120	-	-	-	-
Kiln 2	80	-	-	-	-
Cement Mill 1	130	-	-	-	29
Cement Mill 2	180	-	-	-	25

The simulation was conducted in 6.2 seconds with a production of around 200 tonnes cement per hour over a course of 5 days.

Figure 5 shows the comparison of the generated synthetic LP of the shown system in Figure 4 and the measured LP from Lidbetter et al. It is noted that we excluded downtimes due to repair, which mainly occurred at raw mill 1 during time of measurement and result in null lines in the measured LP, because these influences could not have been predicted. Additionally, due to the summation of just four process units these sudden downtimes of one unit would have caused an unrealistic impact on the overall LP.

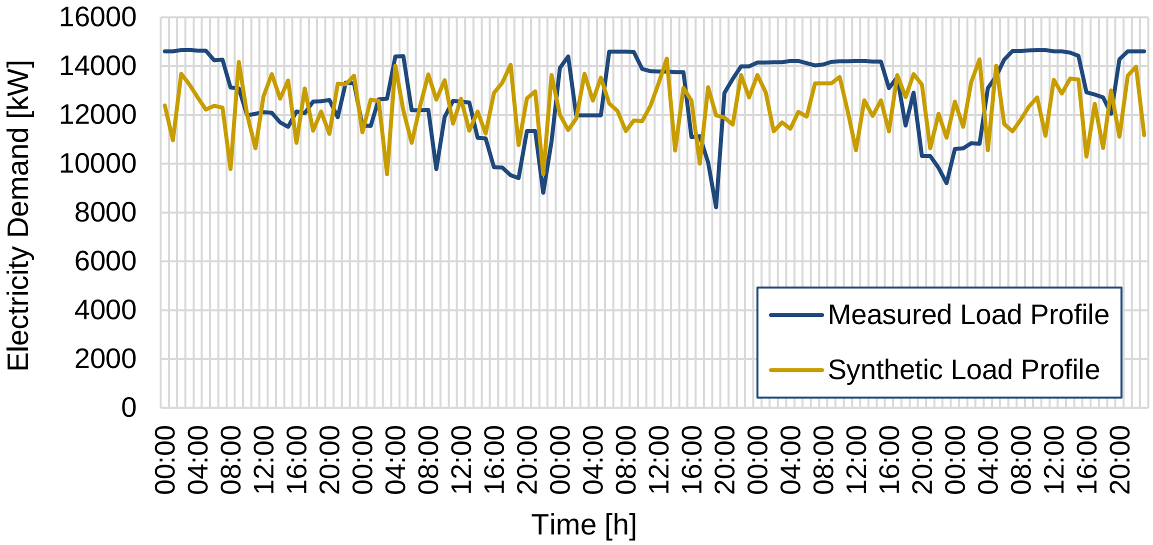

Figure 5: Comparison of synthetic LP in Ganymed to real measured LP

It can be observed that *Ganymed* provides a good approximation to the measured LP. The mean electricity demand of the synthetic LP lies at 12341.03 kW, of the measured LP at 12867.52 kW, which results in a deviation of around 4.1%. The overall fluctuation of the synthetic LP is more present because the range of the data points varies slightly as the histogram analysis in Figure 6 indicates. It can be observed that the electricity demand of the synthetic LP is influenced by normal distribution to a greater extent than the measured counterpart, which is more biased in the direction of higher demand values.

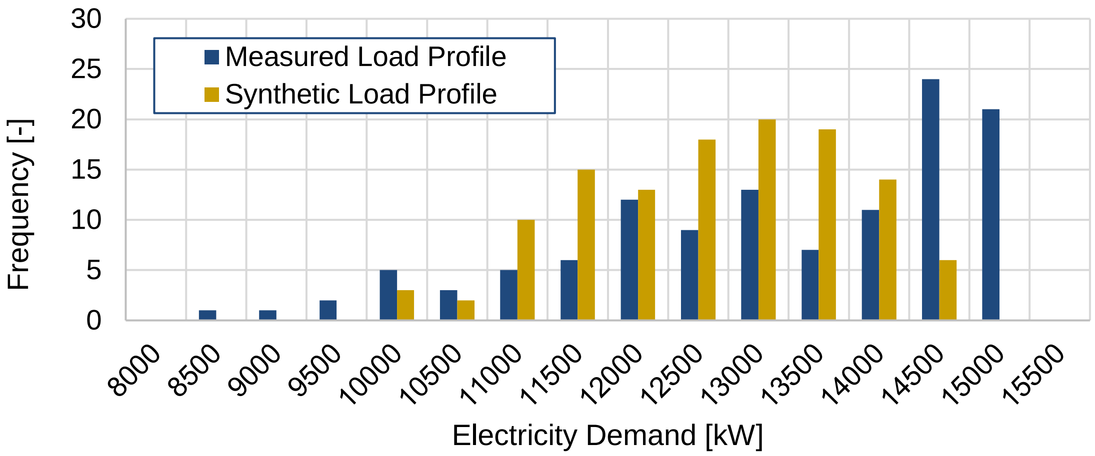

Figure 6: Histogram analysis of data points from both LPs

4 Discussion & Outlook

Energy system models with higher times resolutions (e.g. 15 min/1 h) provide the necessary means to evaluate future challenges of the physical energy system. This includes all partaking bodies from energy suppliers and grid operators to consumers. Generation of synthetic load profiles (LP) support this process by swiftly calculating demands on the energy grid and reveal areas where counteractions have to be taken.

In our study, we apply *Ganymed* as a user-friendly and highly adaptive solution for designing new or existing industrial production chains and evaluate their energy consumption and generation behaviour. The derived LPs can be generated for various energy carriers and system boundaries.

Within the applied case study, modelling an existing cement production plant we found good approximations to the overall electricity consumption and fluctuation range. The data density of the synthetic LP varies slightly compared to the measured LP. However, given the existing data from literature, we deem this case study as sufficient enough to prove the functionality of *Ganymed*.

Future work will introduce a more extensive application of data analysis to also depict other energy extensive industrial subsectors. Furthermore, shift models and economic sciences will be taken into account to enlarge the provided algorithms and database in *Ganymed*.

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