Promoting flexibility from prosumers through a generic characteristic flexibility model

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Abstract:

Energy systems require flexibility - an ability to respond to changes - to integrate higher shares of variable renewable energy. On the whole, flexibility potential from prosumers is significant and stems from various processes. As each flexibility option is unique, before utilization, its potential first must be assessed. This paper presents a universal flexibility model, so called generic characteristic flexibility model (GCM), as tool to characterize and assess most, if not all, flexibility options from prosumers. GCM establishes a generic flexible process with components representing physical parts, e.g. machine and storage, and various administrative decisions, e.g. changes in output delivery or operating hours. Each component is described with essential characteristics and constraints. As demonstrations, three flexible systems representing various sectors – a district heating system, a household appliance, and a production process - are characterized and modelled using GCM. Flexibility in these systems is utilized to minimize costs under time-varying electricity prices and subject to operational constraints. This in turn proves the concept of a universal flexibility model. GCM eases burdens of actors - flexibility providers and users - to develop assessment tools for each flexibility options. Its pre-defined structure and characteristics also support identification of flexible processes and communication between actors. Thus, it helps promoting the utilization of flexibility from prosumers.

Keywords: flexibility, model, optimization, demand side management

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1 Motivation and objective

This chapter gives an overview of flexibility in energy systems, examples of existing flexibility models and the objective of this paper.

1.1 Flexibility in energy systems

In contrast to controllable conventional power plants, variable renewable energy (VRE) is weather-dependent and consequently stochastic. As its share in energy systems increases, so does the fluctuation from the supply side [1]. Energy systems must become flexible to adjust its operating states in response to these fluctuations to maintain the energy balance, i.e. system stability, while keeping costs low and avoiding the utilization of fossil fuels [2]. [2] define flexibility as the ability of energy systems to respond to change in demand and supply, which is a characteristic of all energy systems. The lack of flexibility leads to difficulty in balancing energy and significant VRE curtailment, which is shown as increasing extremes and volatility of energy prices on wholesale markets. Energy systems can increase its flexibility via various options, shown in Figure 1, each of which has different benefits and operating constraints. Prosumer-side flexibility options stem from load (demand response or load shedding), flexible generation (curtailable renewable energy generation, controllable gas turbines or combined heat-and-power units), and storage (battery storage or thermal storage coupled with heat pumps) [3, 4].

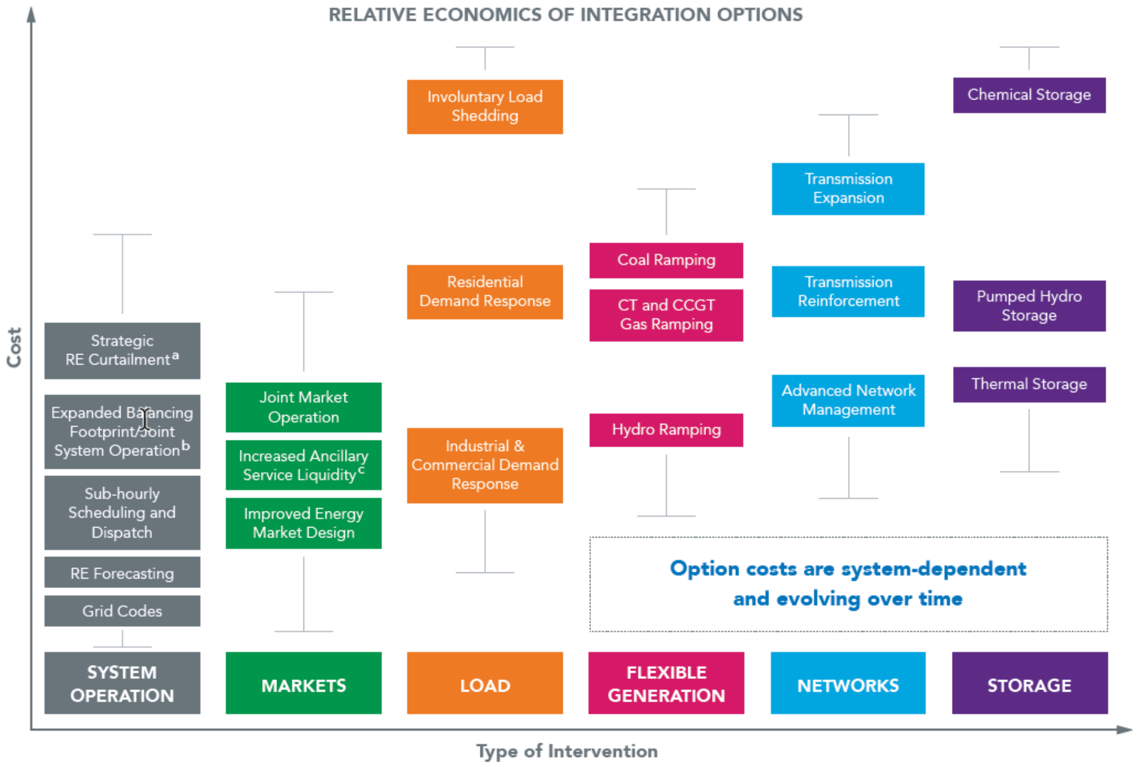

Figure 1 Flexibility options in energy systems and their relative costs [2]

The potential of prosumer-side flexibility is significant, e.g., [5] studies the theoretical demand response potential in Europe and finds that on average in Germany, demand can be decreased by 13.8 GW and increased by 32.2 GW; for comparison, maximum tendered volume of minute reserve in 2015 was 2.7 GW [6]. The utilization of flexibility serves diverse purposes, e.g. increasing market value of VRE, reducing or delaying network expansion, providing reserve energy on reserve markets or reducing electricity procurement costs [7–9], and may serve multiple users at the same time [10]. As the exploitation of any flexibility option is subject to individual investment, operational costs, and constraints [11], it involves first and foremost an assessment to understand how a particular process operates and how it can provide flexibility under different incentives. Often, the assessment is done using a model developed from relevant characteristics of the process in question.

1.2 Existing flexibility models

This section aims to give examples of existing studies and flexibility models. It is worth mentioning that prosumer-side flexibility has been studied not only to support the integration of variable renewable energy. For example, in operation research, flexibility is an integral part of operation planning and is exploited to reduce production costs, to increase production efficiency or quality [12].

On one hand, studies, which focus on energy systems or markets, tend to develop simplified and generalized models. For example, [13] presents a framework to model demand shift using the analogue of an energy storage model. Flexibility is characterized by its planned demand (MW), peak operating demand (MW), and time frame of management (h) (i.e. shifting horizon). The latter together with planned demand define the capacity of virtual energy storage. [7] study the impact of residential demand response on the costs of fossil-free system reserve. Flexibility is characterized by a fixed ratio (-) indicating the share of flexible demand from an aggregated demand profile and a shifting horizon (h). They constrain demand shift to be recovered by day's end. [14] study effects of flexible demand on spot and balancing markets and model demand from various consumers as sine curves. Flexibility is quantified as phase shift of these curves.

On the other, studies, which focus on particular systems and utilization objectives, tend to develop detailed and specific models. For example, [4] study the provision of flexibility of an office building for grid services. They model technologies found in a typical office building (battery, boiler, heat pump, combined heat-and-power plants, and thermal storage) and building's heating model. [15] model a metal casting plant, which includes all processes and their interconnection. They study the optimal operating schedule to minimize costs of electricity on a day-ahead market and simultaneously to maximize revenue on a reserve market. [16] present a robust scheduling model for large electricity users with interconnected processes to capitalize their on-site flexibility (schedule shifting) on energy or reserve markets. The model is applied to a cement milling process. These studies largely focus on either energy intensive industries [15–17] or crossover technologies [4, 18, 19].

While these models serve their intended purposes, their applications beyond their scopes may be limited without further development or adjustment. For example, simplified models may neglect some operational aspects, which are crucial to flexibility providers while specific models may be proprietary or excessively complicated for flexibility users and their results may not be directly comparable to others. Here, a detailed and generalized flexibility model, which is usable by various actors and applicable to various processes, is lacking.

1.3 Objective

Prosumer-side flexibility has significant potential to support an increasing integration of variable renewable energy in energy systems. The utilization of each flexibility option is subject to costs and constraints and therefore requires detailed (often model-based) assessments. As prosumer-side flexibility stems from various processes, developing specific models as potential assessment tools for each process can be resource intensive and discouraging to new flexibility providers. In order to close this barrier, this paper presents a novel universal flexibility model, so called generic characteristic flexibility model (GCM), and demonstrates its application in characterizing and modelling prosumer-side flexibility. GCM reduces, if not eliminates, the task of model development and therefore eases the barrier for prosumers to assess and to utilize their flexibility potential.

2 Methodology

This chapter presents the developed flexibility model in section 2.1 and explains the context of flexibility utilization in section 2.2.

2.1 Generic characteristic flexibility model

Generic characteristic flexibility model (GCM) is based on the concept that: although flexibility options stem from different processes, they share generic characteristics. By defining these characteristics and underlying constraints, a model representing a generic flexible process can be developed as a model for most, if not all, flexibility options. Here, flexibility under the scope of GCM is defined as an ability of prosumers to alter realized energy use from plan via e.g. energy storage, demand response or controllable generation. In any process, characteristics are intrinsic properties and independent from their usage.

GCM structuralizes a flexible process in two interconnected levels: a physical level (*SYS*) representing real components and material- or energy flows in the system, and an administrative level (*ADM*) representing operation control and production-related decisions, corresponded to bottom and top parts of Figure 2. Referring to Customer Premises and Distributed Electrical Resources domains in the component layer of the framework of Smart Grid Architecture Model (SGAM) [20], *SYS* represents the Process zone and *ADM* represents the Operation zone. These levels are explained in the following subsections. Throughout this paper, texts written in italic refer to components in GCM.

In any process, a machine transforms inputs into outputs. Outputs can be physical products, services or energy. Electricity may be an input or an output depending on systems, e.g., input for electric motors or output for generators. However, GCM treats electricity as a separate entity to accommodate additional constraints. Processes may also include intermediates, outputs of a machine from certain states, which are used internally by other states. A flexible process is a process, whose planned operation can be determined in advance and realized operation may deviate from the plan in response to incentives. Its administrator, e.g. an operator, responds to trigger signals according to its operational purpose, e.g. cost minimization, peak shaving or grid services.

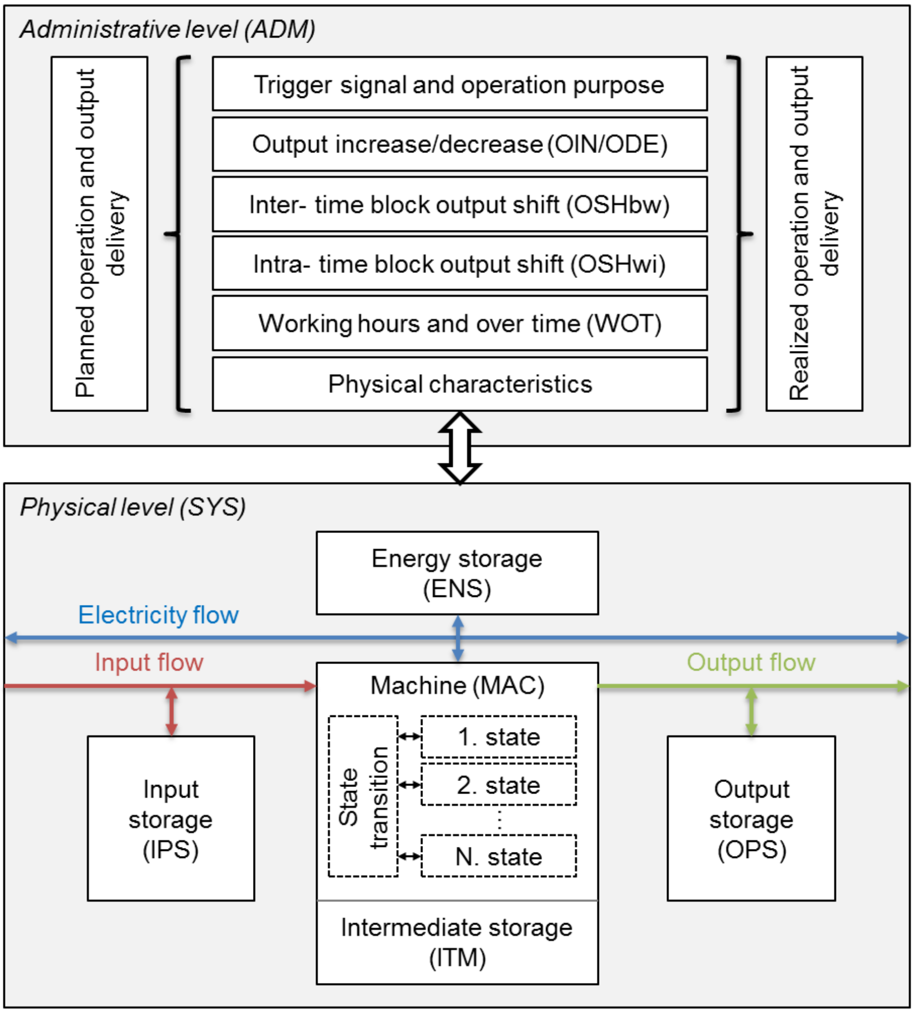

Figure 2 A depiction of a generic flexible process according to GCM.

GCM is developed as a deterministic, mixed-integer linear programming (MILP) model. Time is discretized and represented by two indices, namely time steps and time blocks (groups of adjoining time steps). For example, in a week-long evaluation, one time step represents a 15-minutes interval and one time block represents one day. Time blocks are introduced as subdivisions of an evaluation period. Through it, GCM can capture constraints, such as daily allowable output change or temporal boundary of output shift.

2.1.1 Physical level

In a physical level (*SYS*), a machine (*MAC*) performs a transformation among electricity, inputs, outputs, and intermediates. Electricity exchange is bidirectional (into and out of *SYS*); whereas inputs and outputs are unidirectional and there is no exchange of intermediates outside *SYS*. Each quantity - inputs, outputs, electricity, and intermediates - is accompanied by storage, respectively *IPS*, *OPS*, *ENS*, and *ITM*. Although real components may physically locate apart from one another, GCM treats them as one node and assumes no flow constraint between internal components.

The machine (*MAC)*, the key component to any process, is modelled as state-differentiated linear machine. For example, eq.1 governs machine’s operation and power flow. Variables (written in bold) for power flow, operation level, and binary indicating an operating state are respectively $\boldsymbol{power}_t^{MAC}$,$\boldsymbol{operation}_{s,t}^{MAC}$, and $\boldsymbol{state\_bin}_{s,t}^{MAC}$. *MAC* characteristics for operation-dependent power use and fixed power use (e.g. for auxiliary services) are respectively $eff\_power_s^{MAC}$ and $aux\_power_s^{MAC}$. Subscripts s and t indicate state and time step indices. Superscript MAC indicates an affiliation of variables or parameters to the machine. Analogous equations are also applied to inputs, outputs and intermediates.

$$\boldsymbol{power_t^{MAC}} = \sum_s \left(\boldsymbol{operation_{s,t}^{MAC}}.eff\_power_s^{MAC} + \boldsymbol{state\_bin_{s,t}^{MAC}}.aux\_power_s^{MAC}\right) \ldots eq.1$$

Furthermore, *MAC* may only occupy one state at a time and transitions between certain states can be restricted. An operation level in each state is constrained by upper and lower state boundary limits. This *MAC* formulation allows GCM to capture different process types, e.g. continuous-, discrete-, sequential- or non-linear processes.

Characteristics in the physical level (*SYS)* are:

- Related to the external interactions: upper limits of input, output and electricity flows; lower limit of electricity flow; price of input, output and electricity; CO_2-Emission intensity of input and electricity
- Related to the machine (*MAC)*: maximum ramp rate; state boundaries (upper and lower limits of operation level); operating and auxiliary efficiencies; maximum and minimum run time; price of activating (entering a state); price of operating (staying in a state); allowable state transitions
- Related to each storage unit[2]: flow limit; stock limit; fixed stock level (stock level at the first and last time steps of an evaluation period); transferring and storing efficiencies

These characteristics are implemented in equations, such as: flow balance equations, applied at connecting points of internal components; storage equations modelling relationships of flow, stock and efficiencies; machine equations modelling operation (e.g. eq.1), state detection, and run time limits.

2.1.2 Administrative level

An administrative level (*ADM*) makes adjustments to planned operation and output delivery (output of the physical level). Any adjustments are subject to *SYS* characteristics (i.e. physical constraints), input and output delivery time, possible alteration to output delivery or working hours (so called *ADM* flexibility), trigger signals and operation objectives. *ADM* flexibility includes adjustments to output delivery and working time.

Output increase (*OIN*) or decrease (*ODE*)

This option refers to the ability to change output delivery within time blocks, which does not impose any operation adjustment in other time periods. It includes, for example, renewable energy curtailment or unplanned ramp up/down generator and is characterized by: flow limit; volume limit; and costs of activation, peak of output change and volume of output change.

Output shift within time block (*OSHwi*)

This option refers to the ability to shift output delivery within a time block, i.e., any alterations must be recovered in the same block. It represents namely shiftable demand within a short time horizon (e.g. <4 h) similar to flexibility described in [7, 13] and is characterized by: flow

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[2] In GCM, four storage units – *ENS*, *IPS*, *OPS* and *ITM* – are modelled in the same way.

limit; volume limit; shiftable time horizon (in hours); shift direction (forward or backward); and costs of activation, peak- and volume of output change.

Output shift between time block (*OSHbw*)

This option refers to the ability to shift output delivery between two time blocks, i.e., output delivery is decreased in one time block, which is recovered by an increase in another. It represents a deviation margin of product or service delivery. It is characterized by: flow limit; volume limit; shiftable time horizon (in number of time blocks); shift direction (forward or backward); and costs of activation, peak- and volume of output change.

Changes from aforementioned *ADM* flexibility are applied to planned output delivery ($planned\_output_t^{SYS}$) in eq. 2, which results in realized output delivery ($\boldsymbol{output_t^{SYS}}$). The latter term is applied to the output balance in the physical level *SYS*; therefore, it links *ADM* flexibility to *SYS* flexibility.

$$\boldsymbol{output_t^{SYS}} = planned\_output_t^{SYS} + (\boldsymbol{ADM\ output\ changes}); \ldots eq. 2$$

Working overtime (WOT)

This option refers to the ability of a system to operate outside normal working time. It is characterized by: set of normal working time; set of allowable overtime; costs of working overtime. The system may operate only during normal working time or allowed overtime. It is detected as in-operation when storage is used or a machine is not in a shutdown state.

2.2 Trigger signals and operation purposes

Prosumers need incentives to utilize their flexibility potential, as any deviations from plans may incur additional costs or simply be inconvenient to prosumers [21]. Here, flexibility utilization is described by trigger signals and operation purposes. For example, a prosumer with PV-panels would like to adjust his/her demand to reduce CO_2-Emission (purpose) according to an on-site generation profile and an emission profile of electricity from the grid (signals). These incentives are subjective to prosumers and outside the scope of this paper.

GCM models intrinsic flexibility characteristics. This ensures that GCM-based flexibility characterization is always applicable regardless of assumptions on its utilization and allows flexibility providers or users to test different objectives or market conditions based on the same characterization. This feature is essential to flexibility assessments as their results are susceptible to market conditions and tariff structures, which vary on a regular basis [18, 22].

To demonstrate flexibility utilization in the following chapter, it is assumed that prosumers first plan their weekly operation and output delivery without consideration for time-varying electricity prices, i.e. a flat price is perceived. Their plans and GCM characteristics of their systems are sent to their electricity suppliers, who optimizes new operation plans to minimize costs based on a prognosis of time-varying electricity price[3]. These plans are proposed back to prosumers, who can either realize them or maintain original plans.

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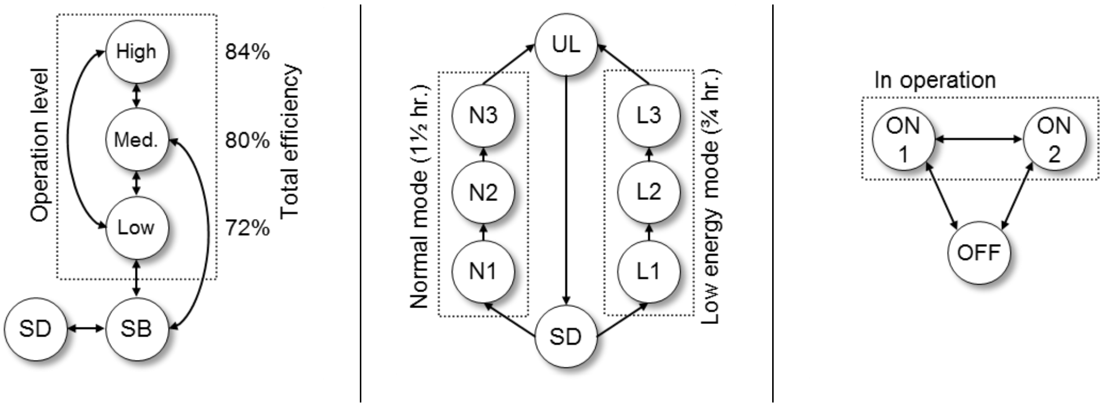
[3] A weekly EEX price from year 2015 is calculated and scaled up so that the average is 30 ct€/kWh, an approximated average of electricity prices for household consumers.

3 Results

In this chapter, an application of generic characteristic flexibility model (GCM) in characterizing and assessing flexibility potential is demonstrated for three exemplary systems, sections 3.1 - 3.3. Section 3.4 discusses further application of GCM. As their parameters are estimated, resulting operation and cost reduction potential should not be taken as representative. Figure 3 presents state diagrams of machines in each system and will be elaborated in following demonstrations.



(a) combined heat-and-power unit (b) washing machine (c) production processes

Figure 3 State transition diagrams of machines in exemplary systems. Each circle represents one state. Arrows indicate allowable transition between states.

3.1 System 1: flexibility from a district heating system

A 1-MW_{el} gas-fired combined heat-and-power unit (CHP) and a 1.5 MWh thermal storage generate heat for a communal district. Its electricity generation is sold back to the grid. Heat supply from the system must match heat demand at all time. Gas is purchased at a fixed price of 7 ct€/kWh. In the planned operation, CHP operates in heat-driven mode and charges storage only prior to periods of low heat demand (<250 kWth), in which CHP cannot operate.

Implementation in GCM

This system is mapped into GCM framework in that gas is *input*, heat is *output*, CHP is *MAC*, and thermal storage is *OPS*. *MAC* has five states (see Figure 3-a): shut down (SD), with 5€ penalty for each entry into SD; stand-by (SB), with auxiliary input of 12 kW to keep *MAC* heated; low- (output level 25-50%); medium- (50-75%); and high operation level (75-100%). Efficiencies in three in-operation states are linear approximation of a real non-linear nature that *MAC* is more efficient when it operates near the rated capacity. The *OPS* has a stock limit of 1.5 –MWh, transferring (charging) efficiency of 95%, and storing efficiency of 85%. As output delivery (heat supply) cannot deviate from plan (heat demand) and the system operates around the clock, administrative flexibility options and working-time constraint are disabled.

In some heating systems, the availability of input may place additional constraints, e.g. flow limit of natural gas, storage capacity and delivery time of wood pellets. Curtailment or a shift of heat-consumption can also be modelled via *ODE* or *OSHwi*. Furthermore, heat produced at different temperature levels can be modelled via multiple outputs. If MAC supports multiple fuels, they can be modelled as multiple inputs.

Optimized operation

Table 1 and Figure 4 show results and operation profiles of system 1 over one week evaluation period. As a result of electricity-prices-oriented operation and increased electricity generation, total revenue (revenue from electricity sold minus costs of input) increases by 7%. In realized operation, *OPS* utilization increases, which leads to higher *OPS* losses (*OPS* losses correspond to discrepancy between *MAC*/*SYS* Output). Furthermore, input consumption increases by 8%. Thus, the system is less efficient. Realized *MAC* operation increases during periods with high prices (grey area in Figure 4-a) and decreases during periods with low prices (red area). Whereas, planned *MAC* operation (dashed line in Figure 4-b) follows output delivery (blue area) and *MAC* overproduces only before periods with low demand. Figure 4-c shows *OPS* stock (state-of-charge of thermal storage), which corresponds to the discrepancy between *MAC* output and output delivery and *OPS* efficiencies.

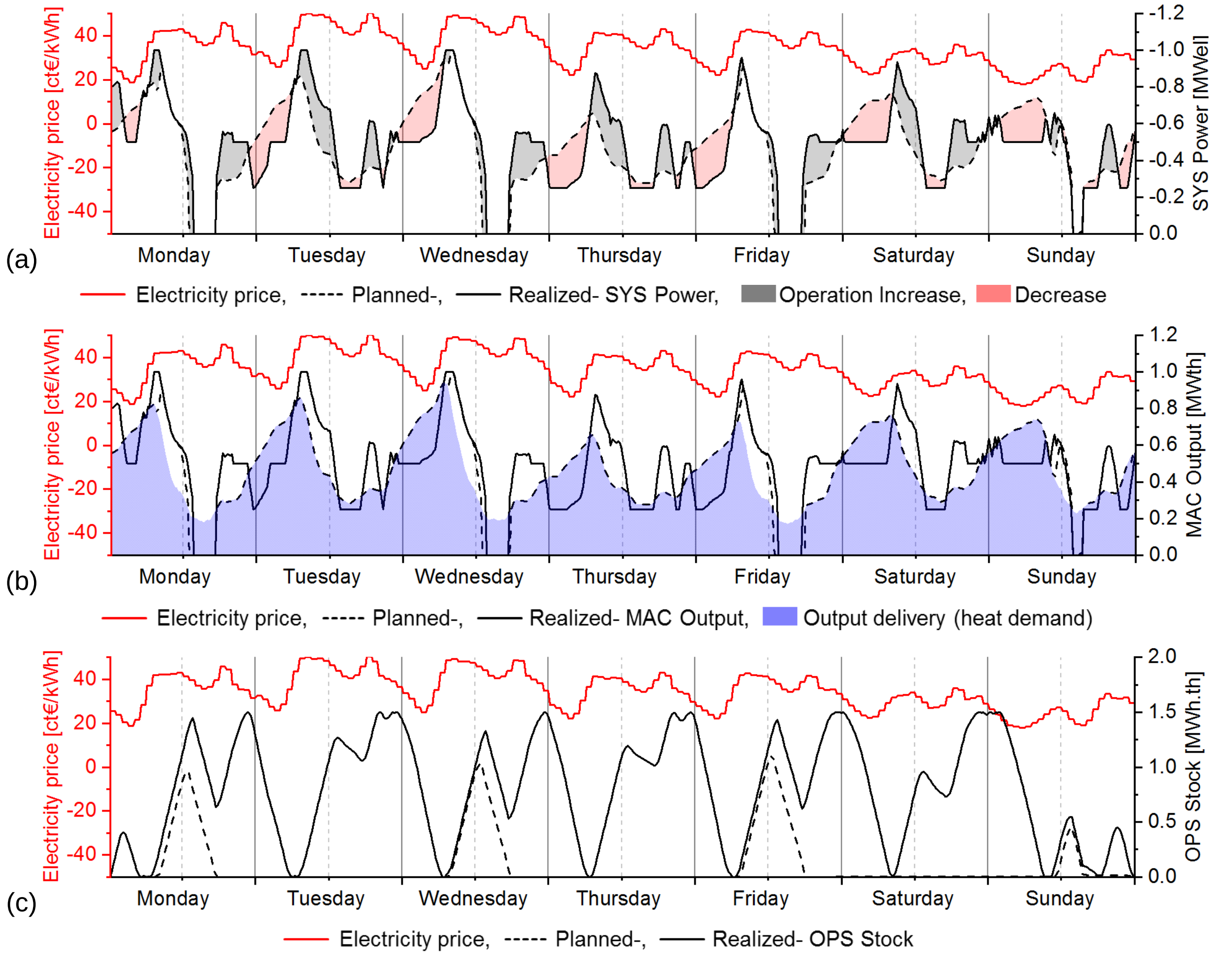


Figure 4 Operation profiles of system 1; (a) SYS power (b) MAC output (heat) (c) OPS stock level

	Total costs [k€]	**Electricity** [MWh]	**Input** [MWh]	**MAC/SYS Output** [MWh]	**OPS Utilization** [%]/[Cycle][4]
Planned Operation	-13.5	-79.1	188.5	79.1/78.6	7 % / 2.6
Realized Operation	-14.4	-80.9	203.2	80.9/78.6	54 % / 9.9

Table 1 Results of system 1. Total costs are costs of input (gas) minus revenue from electricity sold.

3.2 System 2: flexibility from a household appliance

A washing machine in a household is used four times a week. Its schedule is set based on the presence and needs of occupants. Each usage is shiftable within ± 2 hours or to the next day. Occupants are present during 13:00 – 22:00 weekdays and 09:00 – 23:00 weekend.

Implementation in GCM

This system is mapped into GCM framework in that the washing machine is *MAC* and one finished washing cycle is *output*. It is assumed that *MAC* can be operated in a preferred normal mode (NM) or a low energy mode (LM), see Figure 3-b. Each mode consists of three successive states with fixed run times and energy consumption. NM lasts for 90 minutes and consumes ≈ 1 kWh and LM lasts for 45 minutes and consumes ≈ 0.6 kWh. For each LM operation, users are compensated with 0.17€ via costs of entering state L1. Upon completion of N3 or L3 states, an output is delivered in a unload state (UL), after which, *MAC* enters shut down (SD). Here, the sequence of *MAC* operation is enforced by allowable state transitions. Furthermore, output shift is represented as administrative flexibility by *OSHwi* and *OSHbw*; their shifting horizons are two hours and one day respectively. Lastly, the presence of occupants is characterized by 'normal working time' in *WOT*.

While a modern washing machine has several modes, only those, which users are willing to use, are considered. Working time can also be extended beyond the presence of occupants when for example the starting time of *MAC* can be pre-set or remotely controlled.

Optimized operation

Table 2 and Figure 5 show results and operation profiles of system 2 over one week evaluation period. As a result of demand shift to periods with lower electricity prices and demand reduction by 23% due to activations of LM mode, total costs (costs of electricity and compensation to users) reduce by 17%. Operation during weekdays, where electricity prices are high, is switched to LM mode (#1) or where possible postponed to weekend (#3, *OSHbw*). Furthermore, time of use is shifted to adjacent periods with lower prices (#2, *OSHwi*). After states N3 or L3, an output is delivered, which is represented by a discrete impulse function in Figure 5-b. Each operation is subject to the presence of occupants.

	Total costs [€]	**Electricity** [kWh]	**Output** [# finished cycle]
Planned Operation	1.63	4.25	4 (NM)
Realized Operation	1.35	3.25	2 (LM) and 2 (NM)

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[4] *OPS* Utilization is indicated by two values: average stock level to stock capacity and total flow into *OPS* to *OPS* stock capacity. The latter is analogous to charging cycle in battery.

Table 2 Results of system 2. Total costs include costs of electricity and costs of entering low energy mode (compensation to the user)

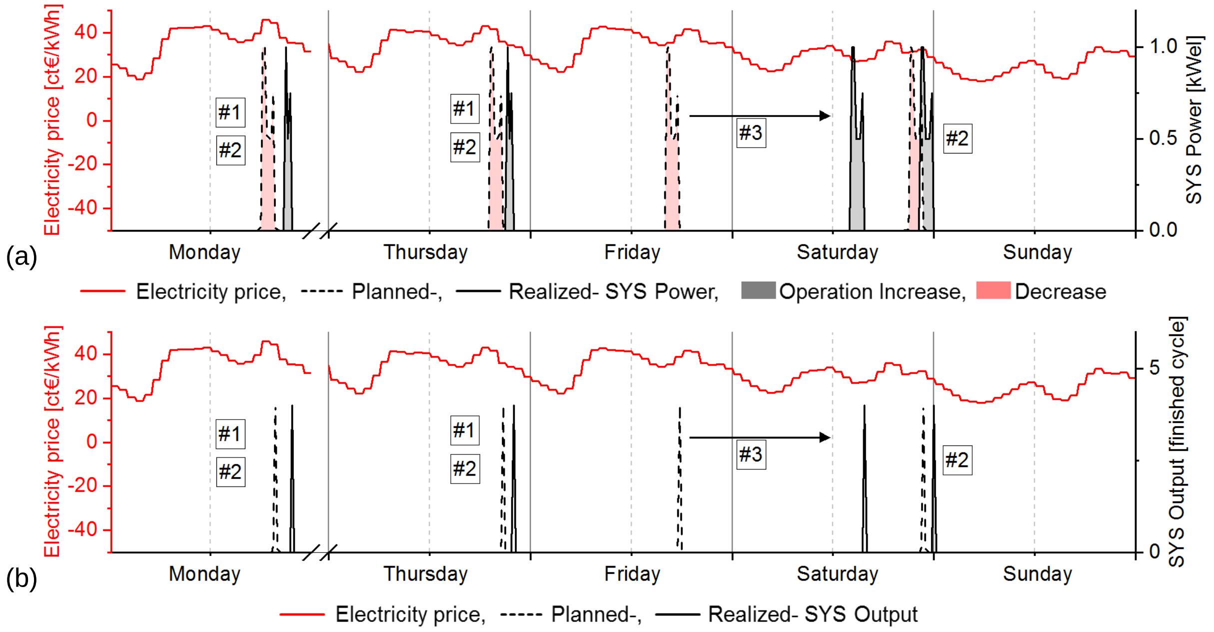

Figure 5 Operation profiles of system 2; (a) SYS power (b) SYS output (finished washing cycle)

3.3 System 3: flexibility from a production process

A factory has two identical, independent on/off production lines and a storehouse with capacity of 150 units. Its production capacity is 20 units per hour while consuming 100 kWh. One hundred units are produced daily and to be delivered at 17:00. Per contract, daily delivery can deviate up to 10 units; but it must be balanced out in the next day. The factory operates on weekdays from 08:00 – 17:00 with breaks during 12:00 – 13:00 and sufficiently stocks its inputs. A midday break of one operator may be rescheduled with compensation of 20€ which allows operation during midday. The planned operation is to produce just enough for daily delivery by operating one machine in the morning and two in the afternoon.

Implementation in GCM

This system is mapped into GCM framework in that the production lines are *MAC*, the storehouse is *OPS*, and products are *output*. As inputs are sufficiently stocked and therefore do not constrain the operation, they are excluded from flexibility characterization. The *MAC* has three states: OFF, no production; ON1, producing with one line; and ON2, producing at full capacity, see Figure 3-c. Here, the discreteness of MAC is enforced by a fixed state boundary, i.e. upper and lower limits are equal. The *OPS* has a stock limit of 150 units and efficiency of 100% (no loss in storing a physical product). Furthermore, output deviation is represented as *OSHbw* with a time horizon of one day and a volume limit of 10 units. The option to work during midday breaks is characterized by set of overtime and costs in *WOT*.

Optimized operation

Table 3 and Figure 6 show results and operation profiles of system 3 over one week evaluation period. As a result of electricity-prices-oriented production plan, total costs (costs of electricity) reduce by 3%. Referring to *OPS* utilization in Table 3, an average stock level increases; however, utilization cycle remains the same. This means *OPS* time-of-use changes; whereas total flow remains the same, see Figure 6-b. As electricity prices during

Tuesday and Wednesday are higher than others, production during this period is avoided by following actions: operation capacity on Monday is maximized and excess outputs are stored in *OPS* and delivered on following days (#4); output delivery on Wednesday is decreased by 10 units, which is compensated by an increase on Thursday (*OSHbw*). The option to work during breaks (*WOT*) is not utilized.

	Total costs [€]	**Electricity** [MWh]	**Output delivery** [#unit per day]	**OPS Utilization** [%]/[Cycle]
Planed Operation	1012	2.5	100, 100, 100, 100, 100	10 % / 3
Realized Operation	977	2.5	100, 100, 90, 110, 100	23 % / 3

Table 3 Results of system 3. Total costs are costs of electricity.

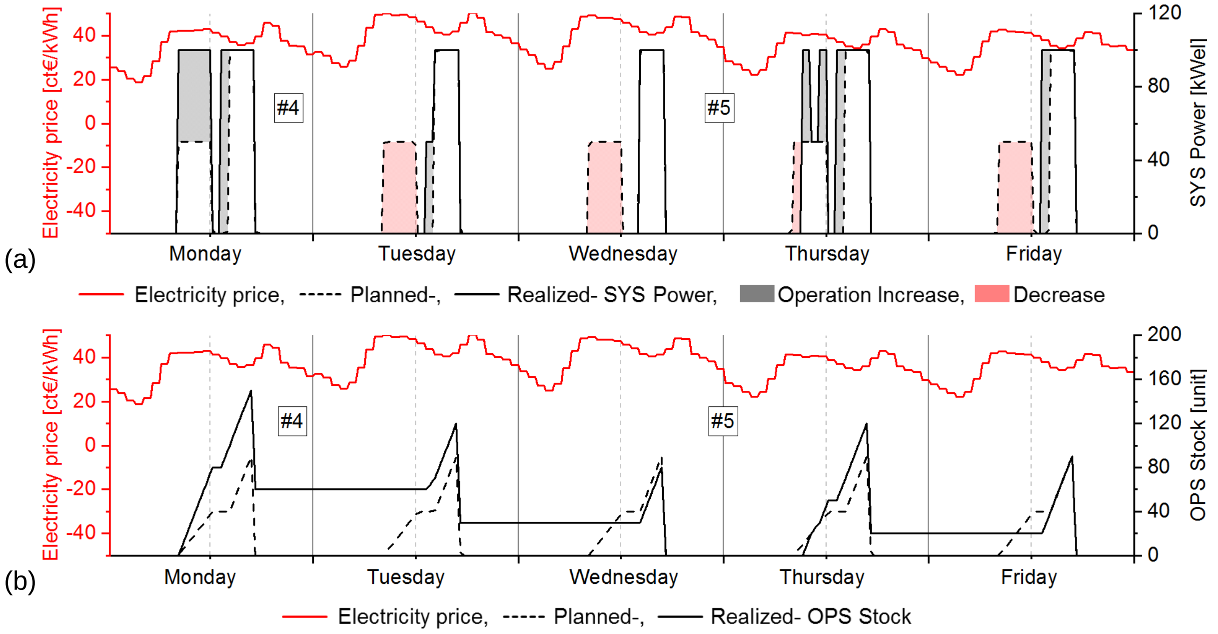

Figure 6 Operation profiles of system 3; (a) SYS power (b) OPS Stock level

3.4 Discussion

In previous sections, the developed generic characteristic flexibility model (GCM) is applied to various flexible processes and results are analyzed. This validates the concept of a universal flexibility model before further applications on real cases. It is shown that GCM can model various process types, namely non-linear continuous, sequential or discrete processes, and that it can capture various flexibility options, which exist in the same process. In short, GCM includes detailed physical and operational constraints under a generic framework. In this section, the scope and potential application of GCM are discussed further.

Scope of GCM

GCM is primarily developed as an operation model for independent flexible processes, whose operation within described flexibility characteristics does not influence other processes, or vice versa. To model a complex system with interconnected processes, GCM may describe each single process with additional variables linking processes to one another (cascading or paralleling). Furthermore, GCM focuses on the operation and does not endogenously consider expansion or investments of any characteristics.

GCM provides a flexible framework; in which users are free to decide how each system or process is modelled. While a precision in modelling a real process can be enhanced by increasing a number of machine's states or by reducing a length of time steps, this comes with increases in complexity and necessary resources to solve a problem, e.g. to find an optimized operation plan. The decision of modelling precision should consider the principle of parsimony and conditions of intended flexibility utilization (e.g. market requirements).

Potential applications of GCM

The main application of GCM is to characterize prosumer processes, which is the basis for a model-based assessment of potential. Through its pre-defined structure and characteristics of a flexible process, GCM supports various steps in the development of flexibility potential, as illustrated in Figure 7. Its functions are as follows:

- Identification and characterization: Thus far, flexibility is a vague concept and often has different, technology-specific interpretation. GCM serves as a template, which prosumers (flexibility owners) can identify and characterize processes with flexibility potential within their systems.
- Assessment: GCM provides a mathematical description of flexibility, which actors (flexibility owners or users) can use to assess different flexibility options under various triggers (e.g. from different markets). Under the same assessment framework, results are comparable and actors can choose the most suitable option.
- Communication: GCM characteristics contain information of all potential operation plans and their constraints. Owners can communicate their planned operation and flexibility to potential users (e.g. network operators or energy providers), who select new operation plans and submit them back to the owners.

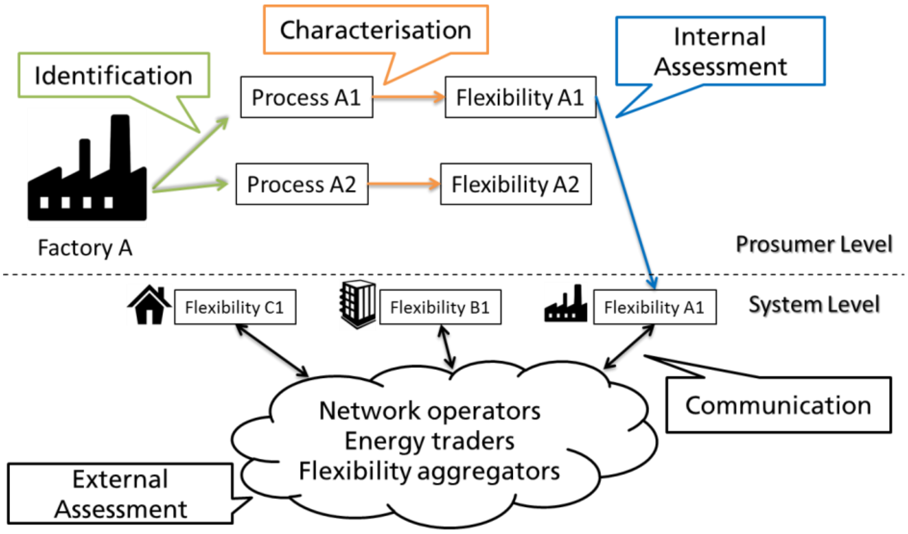

Figure 7 Example of a process to develop flexibility potentials from prosumers

For future works, GCM shall include characteristics of communication and control (e.g. response time) and uncertainties in planned operation. GCM will be applied to a case study representing a regional energy system with various flexible processes. Upon completion, a full model paper will be published.

4 Conclusion

In this paper, a generic characteristic flexibility model (GCM) as a universal flexibility model, is presented. GCM models a generic flexible process and therefore can be applied to most, if not all, flexible processes from prosumers. A process is structuralized into a physical level representing real components and flows of material or energy and an administrative level representing operation-related decisions. Each component is described by characteristics of its operation constraints. The formulation of a machine, a transformation component in the physical level, also allows modellings of various process types (continuous, non-linear, discrete or sequential). As demonstrations, three flexible processes (a district heating system, a household appliance, and a production process) are characterized and assessed using GCM. In each process, its flexibility is utilized to minimize total costs under time-varying electricity prices. It is shown that a process may possess multiple flexibility options, which do not necessarily arise from energy storage, and that GCM can model different processes and capture their internal interactions.

GCM provides a framework to identify, characterize, and assess flexibility options from prosumers. Actors (flexibility owners and users) can map relevant parameters of any processes into GCM characteristics, which are then assessed with different trigger signals and operation purposes to find fitting usages for their flexibility without needing to develop a model for each process. Furthermore, its pre-defined structure and characteristics reduce communication barriers between actors. Thus, GCM helps promoting the utilization of flexibility from prosumers. Further challenges in an effective utilization would include: creation of common market place, an extensive upgrade of information-and-communication technology (ICT) infrastructure, development of business models, and introduction of incentives for prosumers to adjust their planned operation.

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