A Petri-net Based Approach for Evaluating Energy Flexibility of Production Machines

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Abstract
Nowadays production systems are faced with new turbulences in energy-markets due to the increasing use of renewable energy sources. Therefore, production systems and their machines have to be energy flexible. This paper provides an approach for evaluating energy flexibility of production machines based on a Petri-net modelling of machine behaviour. Furthermore, an application of the evaluation on two different machines is given.

Keywords:
Three most representative keywords; energy; flexibility; Petri-net

1 INTRODUCTION

Production systems are working in an environment that is characterized by a distinctive complexity and uncertainty [1]. This complexity and uncertainty derive e. g. from the globalization of the economy, the rising speed of information transfer and the rapid emergence of new technologies [2; 3]. To cope with these market uncertainties, production systems have to be flexible [4]. Flexibility in this context is understood as the ability of a system to adapt itself with little penalty in time, effort, cost and performance to changes in market environment [5]. Nowadays, production systems are faced with new turbulences in energy-markets. Due to the increasing use of renewable energy sources – especially wind power – prices for electrical energy are not fixed during the day. They are changing every 15 minutes on energy-markets depending on the current energy demand and the energy generation as a consequence of weather conditions. Based on these uncertainties utilities are designing new energy-contracts that force production systems to adapt their energy consumption to the actual energy availability in the energy grid. Therefore, production systems and in particular its production machines have to be energy-flexible.

This paper gives an introduction to the topic energy flexibility and presents an approach for evaluating energy flexibility of single production machines. Thus a Petri-net based modelling of the machine behaviour is given.

2 ENERGY FLEXIBILITY

The power demand of a production system stays within a lower and an upper boarder. The lower boarder represents the baseload of the production system, i. e. the power demand of the production system when all machines are switched off or not in use. The upper boarder is given by the sum of the maximal power demands of the machines of the production system. Within these boarders the power demand can vary depending on the state of the production system and its machines. Hence, the energy demand of a production machine also depends on process parameters e. g. cutting forces of milling machines.

This leads to the opportunity for production systems to generate economical benefits out of volatile energy prices. As explained before, prices for electrical energy can change every 15 minutes. Fig. 1 shows an energy price curve as it appears on energy markets like EEX and the corresponding power demand of a production system.

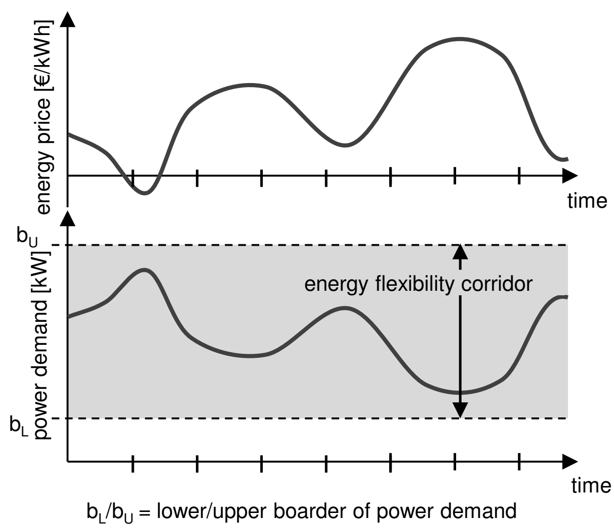

Figure 1: Volatile energy price and corresponding power demand.

An energy price tariff with varying components and an adapted behaviour of the production system can lead to significant energy cost savings [6]. An important requirement for that is, that production systems know their energy demand and know how to adapt the energy demand within the described boarders [7]. This capability is called energy flexibility [8]. Referring to classical flexibility definitions, energy flexibility in this context can be defined as the ability of a production system to adapt itself fast and without remarkable costs to changes in energy markets. The range of the power demand of the production system, within the lower and upper power demand boarder, can be defined as the energy flexibility corridor.

While the energy demand and therefore the energy flexibility of a production system depends on the behaviour of the production

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system's machines, an approach for evaluating the energy flexibility of single production machines is presented in the following section.

3 EVALUATION OF ENERGY FLEXIBILITY

3.1 Petri Net Based Modelling of Machine Behaviour

In this work, a model is required that enables both a sensible modulation of machine behaviour and provides the necessary inputs for the investigation of energy flexibility. First of all, flexibility can be regarded as a function of variability, cost and time [1]. Therefore, a suitable model has to enable the consideration of these three variables. From a machine point of view, variability is regarded as the number of states that the machine can adopt. Time and cost can be thought upon as the penalty for changing states, so the definition of machine states is of key essence. [9] recommend the use of Petri-nets for the modelling of machine states, since it enables manageability of complex systems with several states. The possibility to assign each state with upper and lower time boundaries as well as power demands to each state make Petri-nets suitable for the task of this work. Other authors also use Petri-nets for modelling machine states in their works regarding the described topic [10]. Petri-nets are widespread in literature coping with flexible manufacturing systems [11-14]. For this reasons, Petri-nets are suitable for this work. By adding time to the Petri-nets, the flexibility of a machine can be regarded as a function of the time needed to reach a certain state [12]. Hence, using Petri-nets as modelling tool requires unambiguous an understanding of machine state and transition. Following definitions for this work are given.

Definition of Machine State

A machine state is defined through its average power demand P, its non-zero time duration (existence of a minimal and maximal time stay t_{min} and t_{max}) and its triggering and terminating events. The terminating event of one state is the triggering event of a succeeding state. The triggering event also defines the task of the following machine state. Machine states performing similar tasks can be grouped together into one state, if their average power demand does not deviate from one another with more than a defined tolerance of the maximum power demand of the machine. A machine can only adopt one state at any given moment.

Definition of Transition and Event

Transitions illustrate the direct connections between machine states. The transitions are executed by events e. g. turning on the machine. Neither the transitions nor the events can be assigned any power demand or time duration in the Petri-net model. A transition from one state to another is always triggered by an event. However, whether a transition can occur, depends on whether the requirements for leaving the previous state have been fulfilled. The requirement for leaving a state is remaining there for at least the time corresponding to its lower time boundary.

Below follows an example of a Petri-net modelling of a simple grinding machine with three machine states: "Off", "production state 1" and "production state 2". First the power demand of the grinding machine is measured. A picture of the investigated machine and results of the measuring can be seen in fig. 2.

The measuring of the machine starts in state "Off", where power demand is 0 W. A change of state from "Off" to "Production state 2" is executed at t ≈ 40 s. Power demand then rises and stabilizes at 1.89 kW. At t ≈ 135 s a new change of state slowly is carried out, from "Production state 2" over "Off" to "Production state 1". Power demand then stabilizes at 1.52 kW. None of the grinding machine's three states have any lower or upper time boundaries, which enables very fast state changes. Transferring the data gained in the power demand measure to the Petri-net, gives the model shown in fig. 3.

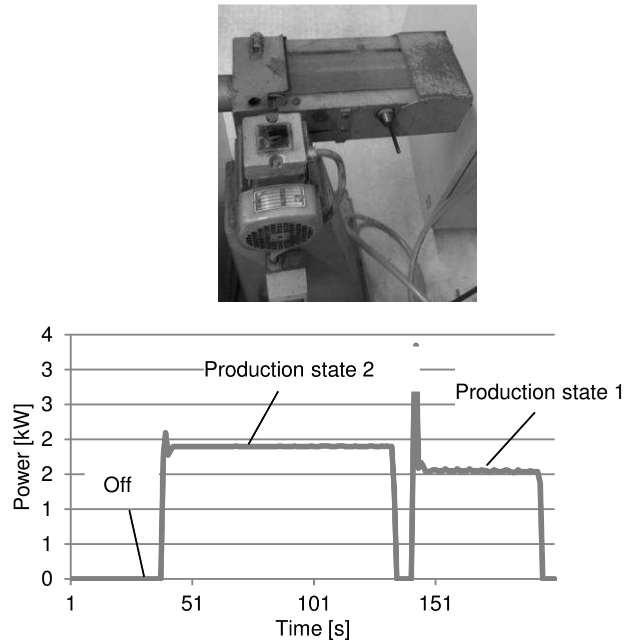

Figure 2: Grinding machine and its power demand.

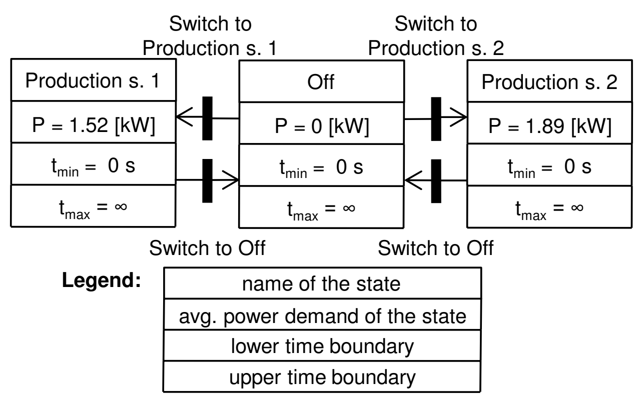

Figure 3: Petri-net of the grinding machine.

More complex machine states showing non constant power demand can be modelled as a sequence of different machine states when required.

3.2 Axioms of Energy Flexibility

In order to improve the understanding of energy flexibility of machines some basic properties of energy flexibility need to be discussed first. Fig. 4 visualizes the numbers of states Z and the distribution of these states in relation to their power demands P of three different machines.

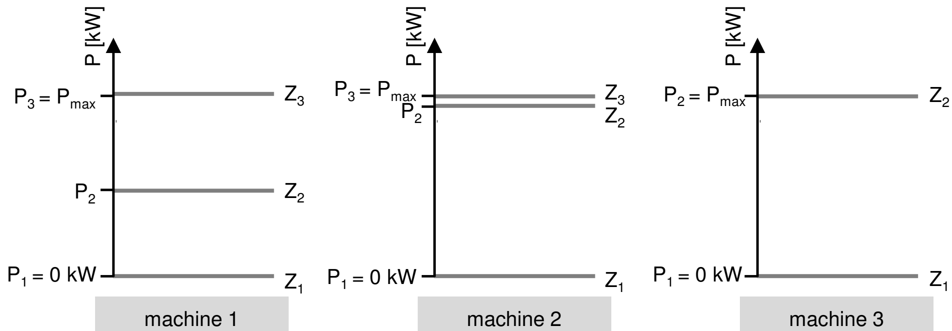

Figure 4: Machines with different adoptable states.

Since flexibility is a function of variability, a machine displaying more adoptable states should be more energy flexible than a machine with fewer adoptable states. Therefore, machine 1 in fig. 4 has to be more energy flexible than machine 3. Machine 2 has – as machine 1 – three adoptable states and therefore has to be more energy flexible than machine 3, which has only two adoptable states. Yet the difference between the power demands of the states Z_2 and Z_3 of machine 2 is so small that the adoptable states of machine 2 are almost like the ones of machine 3. This leads to the conclusion that a more even distribution of the machine states should increase energy flexibility since it increases variability. Therefore machine 1 is more energy flexible than machine 2 which again is more energy flexible than machine 3.

The next property under investigation is the influence of time on changes of states and how this affects the energy flexibility of a machine. As established in section 3.1, only machine states can be assigned time duration. However, the presence of lower time boundaries brings inertia in to the system and can make momentary state changes due to energy price changes impossible. In fig. 5 there are two similar systems illustrated. They have the same number of machine states and the distribution of the machine states is equal. The only difference is the lower time boundary of the machine state Z_2. Flexibility is considered as a function of the penalty of changing state. Regarding machine 1, the time penalty of changing from Z_1 to Z_3 and back is lower than the penalty of the corresponding change of machine 2. Hence, machine 1 is more energy flexible than machine 2.

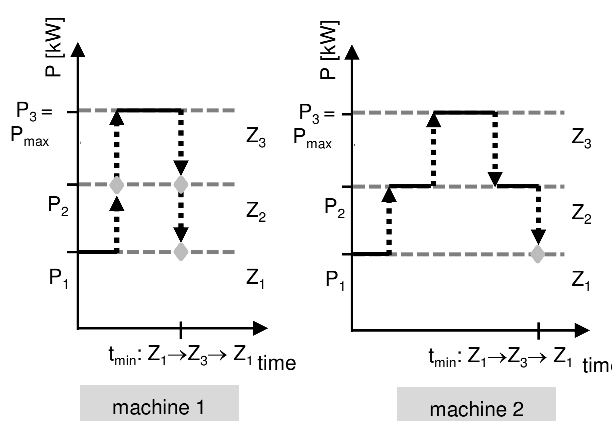

Figure 5: Systems with the same machine states but different lower time boundaries.

The influence of lower and upper time boundaries in machine states on the energy flexibility of a machine is displayed in fig. 6. A low positioned lower time boundary t_{min}, ensures fast machine state changes, and is therefore positive for the energy flexibility of a machine. A high positioned upper time boundary t_{max} also has a positive influence on the energy flexibility, since it allows long stays in machine states. Therefore, machine 1 is more energy flexible than machine 2.

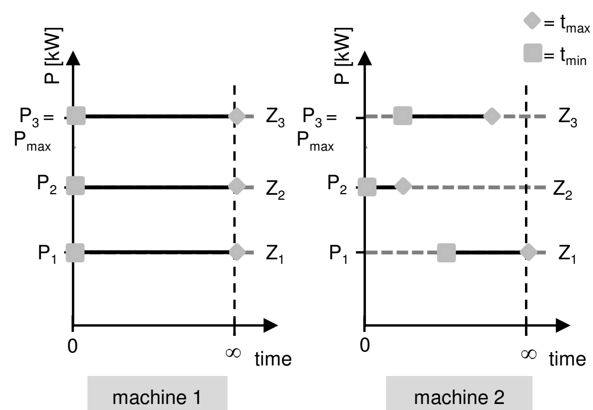

Figure 6: Machines with different lower und upper time boundaries.

Referring to the conclusions made in this section, five essential axioms to enable evaluation of energy flexibility of an arbitrary machine are made:

1. The energy flexibility of a machine increases/decreases with an increase/decrease of adoptable machine states Z_i.
2. The energy flexibility of a machine increases when the distribution of the power demand of the adoptable machine states is more even.
3. The energy flexibility of a machine increases/decreases when the required time t_{ij} for a change of state decreases/increases.
4. The energy flexibility of a machine decreases when there exists a lower time boundary t_{min} in one or more of the adoptable machine states. A decrease of the lower time boundary increases the energy flexibility.
5. The energy flexibility of a machine decreases when there exists an upper time boundary t_{max} in one or more of the adoptable machine states. An increase of the upper time boundary increases the energy flexibility.

3.3 Evaluation of Energy Flexibility

Based upon the 5 axioms defined in section 3.2 an equation for evaluating energy flexibility of an arbitrary production machine has been developed. The resulting equation given from this work is:

$$E_{machine} = \frac{1}{2P_{max}^2}\Big(\sum_{i=1}^{n^+-1}\alpha_i\Big(\sum_{j=1}^{i}\Delta P_j - \sum_{j=1}^{i-1}\Delta P'_j\Big)\Big(P_{max} - \alpha_i\Big(\sum_{j=1}^{i}\Delta P_j - \sum_{j=1}^{i-1}\Delta P'_j\Big)\Big) + \alpha_{n^+}P_{max}\sum_{i=1}^{n^+}\Delta P_i$$
$$+\Big(\sum_{i=1}^{n^--1}\alpha_i\Big(\sum_{j=1}^{i}\Delta P_j - \sum_{j=1}^{i-1}\Delta P'_j\Big)\Big(P_{max} - \alpha_i\Big(\sum_{j=1}^{i}\Delta P_j - \sum_{j=1}^{i-1}\Delta P'_j\Big)\Big) + \alpha_{n^-}P_{max}\sum_{i=1}^{n^-}\Delta P_i \quad (1)$$

with

$$\Delta P'_j = \alpha_j\left(\sum_{k=1}^{j}\Delta P_k - \sum_{k=1}^{j-1}\Delta P'_k\right) \quad (2)$$

Parameters

$E_{machine}$= Energy flexibility of the machine

P_{max} = Maximal power demand of the machine

α_i = Weighting factor of state i

ΔP_i = Power demand difference between the states Z_i and Z_{i-1}

$\Delta P'_i$ = Weighted power demand difference between the states Z_i and Z_{i-1}

n^+ = Number of machine states with a higher power demand than the base state

n^- = Number of machine states with a lower power demand than the base state

The equation is applicable to all machines with at least two machine states and it returns dimensionless values between 0 and 1, where 0 means that the machine has no energy flexibility and 1 is the maximum possible energy flexibility. Referring to the axioms number 1 and 2 the more machine states the machine has and the more evenly distributed they are, the higher the value the formula returns.

First of all a base state Z_B has to be selected. The base state is the state, which usually is the origin for changes of state. It normally has no lower or upper time boundary. For the example with the grinding machine, the natural choice would be to set machine state “Off” as base state since the machine has neither a stand-by state nor any ramp-up time. Next, the differences between the power demands of two states ΔP_i and the weighted state differences $\Delta P'_i$ have to be calculated. Therefore, starting at the base state every state gets weighted step by step. It should also be noticed that the choice of base state affects the end result of the value of the energy flexibility $E_{machine}$.

The reason for weighing the machine states is to describe their importance for the energy flexibility of the machine more accurate in accordance to the axioms number 3-5. The weighting of each ΔP_i is done by the factor α_i and it is defined by equation 3.

$$\alpha_i = \frac{1}{1+\frac{t_{iZB}+t_{ZBi}}{t_{ref}}}\int_{t_{min,i}}^{t_{max,i}}\frac{1}{q} * e^{\frac{-t}{q}}\,dt \quad (3)$$

The times t_{iZB} and t_{ZBi} are the transition times from machine state Z_i to the base state Z_B and back. The time t_{ref} is a reference time that depends, as well as the fitting parameter q on the speed with which the energy prices changes. The integral part of α_i manages the influence of time boundaries in machine states. A lower time boundary, t_{min}, is of high significance since it means that a state can be adopted fast as a reaction to quickly changing energy prices. A high upper boundary, t_{max}, enables a long stay in a state. This is up to a certain limit important because energy prices usually stay for at least 15 minutes at the same price-level. However, regardless of the machine, the importance of being able to stay in a state declines when t_{max} moves against infinity since changing energy prices makes a longer stay of non interest. Fig. 7 gives a visualisation with a random example of the parameters used in the given equation.

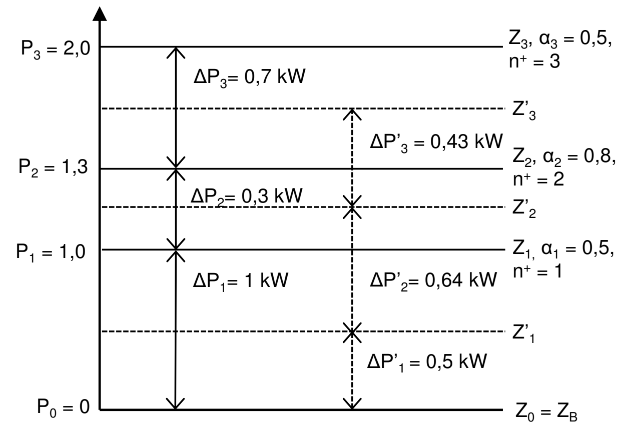

Figure 7: Visualisation of the given equation.

4 CASE STUDY

For the evaluation of the equation given in section 3.3 a case study was carried out. The case study was conducted on two different machines. The first machine is the grinding machine described in section 3.2 and the second machine is a Laser Sintering machine (MTT SLM 250). The laser sinter machine has eight main systems, a SPS, a computer (GUI), a heating system, an inert gas system providing the essential protecting atmosphere in the workspace, a metal powder delivering and filtering system, an automatically lowering construction table, a water based cooling system and a laser.

Turning on the main power switch starts the Laser Sintering machine. With main power on, the SPS automatically starts up and the GUI can manually be turned on. When GUI is accessible, the heating system of the construction table can be switched on. The use of the heating system is optional and the temperature is infinitely variable between room temperature and 200 °C. To reach the maximal construction table temperature from room temperature takes 20 minutes and is the most time consuming preparation. Before the production of a defined part can start, the inert gas system has to be turned on. The inert gas system sucks the air out of the workspace and replaces it with Argon. This system has a ramp-up time of 3 to 5 minutes and simultaneously as this is being done, the water-cooling system is turned on, without any ramp-up time. After these operations the machine is ready for production. The ramp-up of the laser takes only a few seconds and is therefore regarded as a part of the production state in this work. Lower and upper time boundaries of the machine state “Production” can hardly be sharply defined. The lower time boundary is set to one hour because process times less than one hour lead to parts with only a few millimetres thickness, which normally is not achievable. Upper time boundary is in practice defined by the size of the workspace of the machine. When the machine is done with its part it automatically turns off every system except the SPS and the GUI.

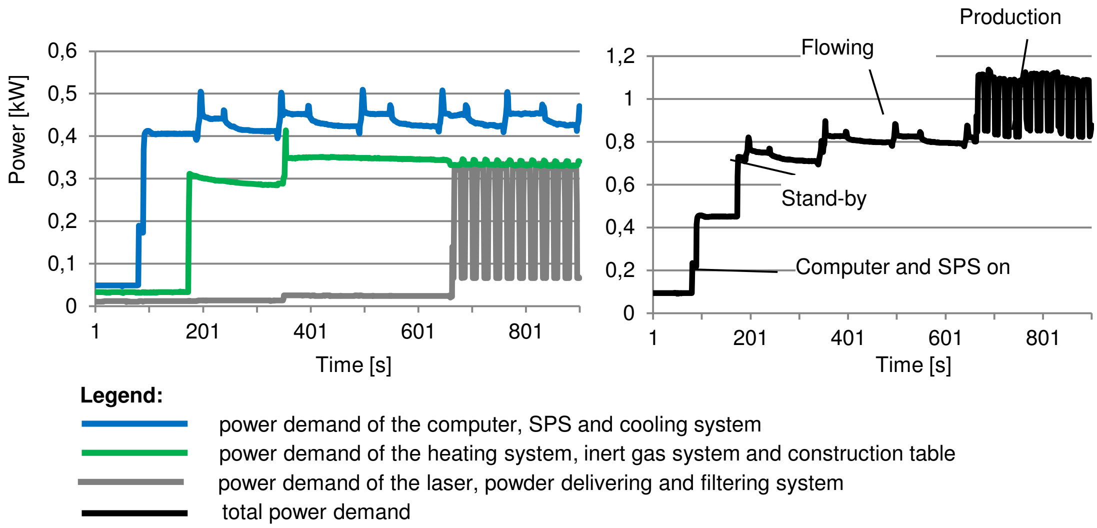

Figure 8: Left: Power demand measured in the three conductors in order to determine the individual power demand of the machine sub-systems. Right: Total power demand of the machine.

To be able to create a Petri-net for the laser sinter machine, power demand of the machine was measured. The results are displayed in the two graphs in fig. 8.

In fig. 8 on the left, the power demand of the three conductors can be seen and combining this information with the time for the switch on of the different systems enables the determination of their individual power demand. In fig. 8 on the right, the total power demand of the machine can be determined. Using the data from fig. 8 the Petri-net of the laser sinter machine is constructed. Notably is the power demand appearing as range in the machine states “Stand-by”, “Flowing” and “Production”. The reason for this is the heating system, which depending on setup uses between 0 and 260 W and the laser which also depending on setup has a power demand between 0 and 380 W. Fig. 9 shows the Petri-net of the described machine.

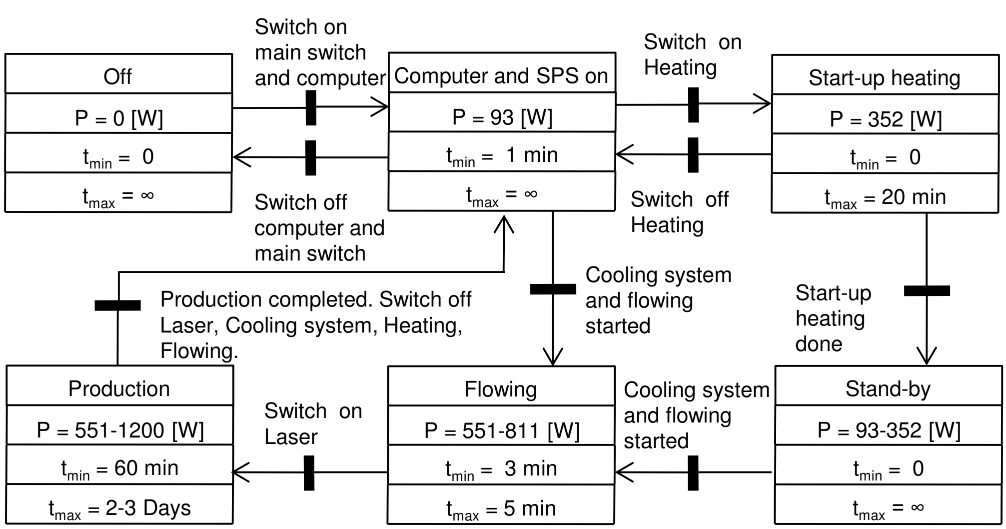

Figure 9: Petri-net of the laser sinter machine.

Evaluation of Energy Flexibility

Equation 1 has been implemented in MATLAB®. Calculating the energy flexibility of the grinding machine and the laser sinter machine using equation 1 gives the results represented in table 1.

Machine	Basic machine state	Energy flexibility
Grinding machine	"Off"	0,5786
Laser sinter machine	"Computer and SPS on"	0,5778

Table 1: Energy flexibility of the grinding machine and the Laser sinter machine.

The values of t_{ref} and have been set to t_{ref} = 15 min and q = 60 min. The machines exhibit energy flexibility values very close to each other although these are two very different machines. The grinding machine has a disadvantage in few adoptable machine states and an advantage in very wide time boundaries in its states. The laser sinter machine has a big variability and also in general low lower time boundaries in its states. According to the definition of a machine state given in section 3.1, a machine state has to have a power demand that differs from an already defined state with at least 5 % of the maximum power demand of the machine to be defined as a new state. Using this definition, a total of 11 different production states can be defined. The laser has a stepless power demand between 0 and 380 W. A lower laser power reduces production speed and vice versa. This ability offers great benefits for the energy flexibility of the machine, if the production program enables its utilization. The same applies on the machine state "Stand-by", where by setting a lower temperature than 200 °C for the table heating and hence, not constantly using 260 W, at least 5 different stand-by states can be defined. This provides a very high variability of the Laser Sinter machine. The combination of inability to interrupt production, a lower time boundary of the machine state "Production" of 1 hour and long lead times for big parts highly restricts its energy flexibility at times. However, the time boundaries set here for the production state are primarily defined by the product the machine produces and not by itself. With a lower time boundary of 3 minutes in machine state "Production", the energy flexibility formula returns the value $E_{machine}$ = 0,8514. This highlights the problem with defining the border between energy flexibility of a machine and its production program. One way to handle this issue could be ignoring the restrictive influences that products have on the machine and regarding the energy flexibility value that is received as the theoretical highest possible value.

5 CONCLUSION AND OUTLOOK

This paper gives an introduction to energy flexibility. While the energy demand and also the energy flexibility of a production system depends on the behaviour of the production system's machines, an approach for evaluating energy flexibility of production machines is presented. Based on a Petri-net modelling of machine behaviour an equation is given that meets the requirements of five axioms of energy flexibility. An application of the equation to two different machines shows how the number of machine states, its distribution and time constrain affect energy flexibility. Based on the presented equation, future work has to take in concept actions that can lead to changes of the states of the production machines to adapt the energy demand and the corresponding costs of these actions.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Slack N (1983) Flexibility as a Manufacturing Objective. International Journal of Operations and Production Management 3/3:4–13

[2] Abele E, Reinhart G (2011) Zukunft der Produktion. Hanser, Munich

[3] Westkämper E, Zahn E, Balve P, Tilebein M (2000) Ansätze zur Wandlungs-fähigkeit von Produktionsunternehmen. wt Werkstattstechnik online 90(1-2):22–26

[4] Wiendahl1 HP, ElMaraghy HA, Nyhuis P, Zäh MF, Wiendahl HH, Duffie N, Brieke M (2007) Changeable Manufacturing - Classification, Design and Operation. Annals of the CIRP 56/2:783-809

[5] Sethi AK, Sethi SP (1990) Flexibilty in Manufacturing. The International Journal of Flexible Manufacturing Systems 2/4:289–328

[6] Yusat JM, Torres F, Khodr HM (2010) Optimal mythodology for a machining process scheduling in spot electricity marketsEnergy Conversion and Management 51:2647-2654

[7] Pechmann A, Schöler I (2011) Optimizing Energy Costs by Intelligent Production Scheduling. In: Hesselbach J, Herrmann C. Clocalized Solutions for Sustainability in Manufacturing: Proceedings of 18th CIRP International Conference of Life Cycle Engineering. Braunschweig, 2.-4. May 2011. Berlin

[8] Reinhart G, Reinhardt S, Graßl M (2012) Bewertung der Energieflexibilität von Produktionssystemen. wt Werkstattstechnik online 102 (9):622–628

[9] Dietmair A, Verl A, Wosnik M (2008) Zustandsbasierte Energieverbrauchsprofile. wt Werkstattstechnik online 98 (7/8):640–645

[10] Mitraa S, Grossmanna I, Pintob J, Arorac N (2012) Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes. Computers and Chemical Engineering 38:171-184

[11] Chryssolouris G (1996) Flexibility and Its Measurement. Annals of the CIRP 45/2:581-587

[12] de Toni A, Tonchia S (1998) Manufacturing flexibility. International Journal of Production Research 36/6:1587–1617

[13] Gupta YP, Goyal S (1989) Flexibility of manufacturing systems. European Journal of Operational Research 43/2:119–135

[14] Barad M, Sipper D (1988) Flexibility in manufacturing systems: Definitions and petri net modeling. International Journal of Production Research 26/2