

9.5 Performance adaptive manufacturing processes in an energy efficient car production

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Abstract

Energy efficiency is of increasing importance towards sustainable manufacturing in the automotive industry, in particular due to growing environment regulations and rising electricity costs. Approaches within the manufacturing planning phase are insufficient to address dynamic influences during run-time (e.g., electricity tariffs or workload). Additionally, conventional production monitoring and control systems consider the 'Overall Equipment Effectiveness' of manufacturing systems, but do not include related energy efficiency. This paper introduces a novel approach that combines these both aspects and provides more effectiveness based on so-called production variants. The latter are designed during the planning phase and used to adapt manufacturing behavior when facing dynamically changes during run-time. A simulation shows how dynamic adjustments of cycle times lead to a high reduction of energy costs while maintaining high throughputs.

Keywords:

Energy efficiency; performance adaptive production; production planning and control

1 INTRODUCTION

Sustainability has become increasingly important in the last years. The efficient management of resources is indispensable to globally address the ambitious environmental targets and economical growth. This is one of the key aspects of the European growth strategy 'Europe 2020' [1] as well as of the German 'Industrie 4.0' initiative focusing on next generation production systems. In the future 'Smart Factory', sustainability will be as important as productivity. A great contribution to the environmental goals is expected to come from the car manufacturing industry, both in terms of energy efficient cars as well as manufacturing processes. European car manufacturers have already started important initiatives. For example, Volkswagen AG launched the 'Think. Blue Factory.' project with the goal of improving ecologically friendliness of its factories by 25 % until 2018 [2].

This paper is addressing energy efficient car production by enabling performance adaptive manufacturing processes that support a wide range of alternative production modes with different energy consumption profiles. Enhancing manufacturing IT systems with such profiles allows dynamic adaptations of production processes based on run-time information such as electricity prices, resource availability, workload, and buffer utilization. In particular, the paper focuses on how complementary production variants can be designed, how they can be deployed to manufacturing IT, and how optimal variants can be selected by product control algorithms during run-time. The latter has to consider performance measures beyond traditional Overall Equipment Effectiveness (OEE) key performance indicators (KPIs) covering also energy-related aspects [4].

The remainder of the paper is structured as follows. In chapter 2 the main challenges to realize energy efficient production systems in the automotive industry are discussed. Existing work regarding solutions for these challenges is reviewed in chapter 3. Chapter 4 introduces the concept of performance adaptive manufacturing which is evaluated in

chapter 5 regarding its impact on production KPIs. Chapter 6 concludes the paper with a short outlook.

2 PROBLEM DESCRIPTION

A typical car factory consists of press shop, body shop, paint shop, powertrain and assembly. Especially the carbody shop has a large demand in electricity, because of its high degree of automation (see Figure 1).

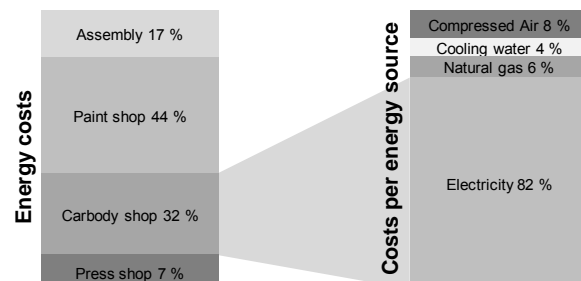


Figure 1: Energy costs per shop, based on [5].

Energy consumption is not just a static quantity; it has also a temporal progress. In order to reduce the total energy consumption in a long- and medium-term period, similarity patterns in the average consumption (uniform peaks in Figure 2) can be recognized and optimized in the planning systems of product lifecycle management (PLM). During run-time, however, this is typically done in enterprise resource planning (ERP) systems. Long- and medium-term planning has two major drawbacks. First, the volatile environment of energy consumption (irregularity of consumption in detailed view of Figure 2) caused by dynamic and complex influences, e.g., from the supply chain, can hardly be predicted, but have to be determined at run-time. Second, flexible electricity price tariffs, which will be introduced with the upcoming Smart Grid, will provide real-time price signals that cannot be used in the

long- and medium-term planning. For that reasons energy efficiency has to be considered in the short-time detailed production planning, which is usually done by manufacturing execution systems (MES). Today, detailed production planning approaches consider OEE, which only consists of availability, performance and quality, but not of energy consumption and prices [6].

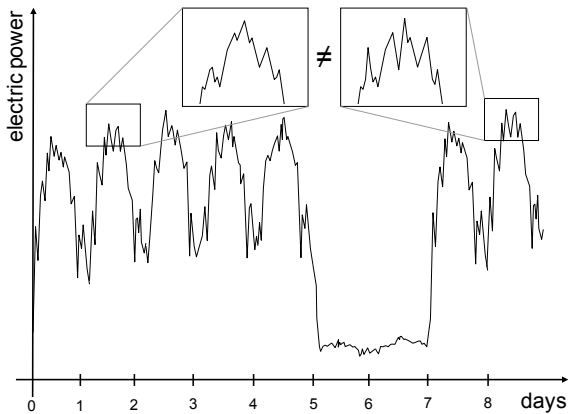


Figure 2: Characteristic energy consumption of a car production over one week.

In addition, a MES requires a high degree of flexibility to react on the volatile environment. Today, the flexibility is restricted by the fixed production process that is specified by PLM systems at design time and cannot be changed during run-time. In order to increase flexibility during run-time, different variants of production processes have to be designed in the PLM tools and made available to the MES. However, designing the most relevant production process alternatives is a complex task. For example, the large number of installed robots in a body shop enables a high flexibility, but requires also taking care of complex relationships along the process. A high number and diversity of possible variants, just-in-time and just-in-sequence logistics combined with lean management are additionally complicating the production process design.

Existing approaches to address these challenges are discussed in the following chapter.

3 RELATED WORK

Energy efficiency has to be addressed on all production levels from the machine level [17] to the multi-facility and supply chain level [7]. For a general overview of approaches see [18]. Today energy efficiency in terms of decreasing the total power consumption of manufacturing processes with unchanged output nearly is a exclusive topic of the 'factory design' phase of the PLM and especially of the so-called digital factory. The German innovation alliance 'Green Carbody Technologies' [3] researches the forecasting and optimization of the energy consumption by PLM tools, e.g., by the use of simulation of systems in materials handling including energy efficiency. On the one hand there are 15 % possible savings in energy consumption by the optimization of complete facilities. On the other hand optimizations on machine level leads to a statically energetic optimized operating like energy efficient robot movements with up to 30% possible savings in energy consumption.

Energy efficient control during run-time is a quite new area of application and is always based on measurement and monitoring of energy consumption on machine level. Suitable sensors or other measurement instruments can permanently record energy consumption over time. Other possibilities are single representative measurements or forecasting by simulation. These methods allow energy monitoring for single processes and control programs. Energy monitoring needs KPIs, which are currently standardized [7]. They are also required for applications on control level in order to identify weak points or correlations between operating modes and consumptions [8].

There are holistic approaches for energy efficiency during run-time [9], but most researches are based on conventional planning tools. Especially tools of the digital factory provide innovative solutions like combined simulations of material and energy flow [10, 11]. Another possibility is the development of an energy efficiency based production control [8] and superior energy control systems. Possible application scenarios are found in avoiding peak loads, reducing no-load losses or shift secondary processes into low-rate periods. Shutdown concepts should also be mentioned [12] which focus on energy saving in non-productive phases of a factory.

This paper in contrast deals with energy efficiency during the operating phase by performance adaptive manufacturing processes supported by tools of the digital factory.

4 PERFORMANCE ADAPTIVE MANUFACTURING PROCESSES

Electric energy consumption depends for a big part on the specific movement of a machine. For the same path and different operation speeds there is always a characteristic graph of the required electric power as a function of the operating speed. For example, the energy consumption of a robot movement describes a bathtub curve (see Figure 3).

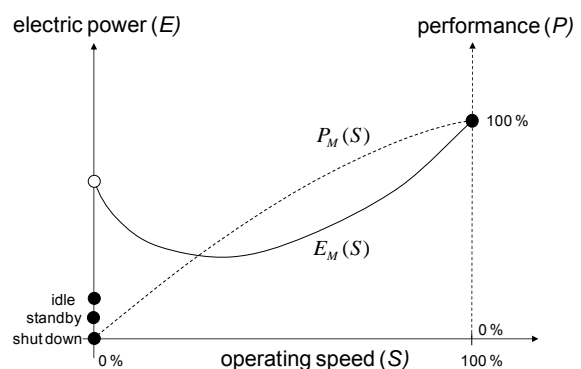


Figure 3: Power consumption and machine performance of a machine M , based on [13].

Until now robots are using only the four marked operation modes shutdown, standby, idle and full speed. The full flexibility of operating speed and performance is not used during the movement. In general a robot has low energy consumption in idle mode, which is equal to the part of energy, which is independent of movements. At slow speed it disproportionately needs much energy. The energy consumption is decreasing until a local energetic minimum,

because of the utilization of inertia. With higher speed the energy consumption is progressively increasing, because a double operating speed needs a four times higher kinetic energy. The performance (output) behaves nearly linear, but doubling speed does not mean doubling performance, because of unchangeable fix time slices like set-up times or runback times of sensors and actuators. In conclusion slower manufacturing processes are reducing performance, but need overall less energy.

Because not all machines are able to adapt their speed/performance, this paper focuses on highly automated manufacturing processes in subsections like body shop, power train or paint shop, where motion typically is a part of manufacturing (e.g., material handling systems, robots, CNC milling). Slower, less productive processes can be utilized in certain situations, when full speed is not always the best option, e.g., internal influences like the unavailability of material at previous production steps or foreseeable bottlenecks at following stations. Machines which are not in the critical path also do not necessarily need to run at full speed. External influences like an adaptation to volatile price of electricity or already in chapter 3 mentioned scenarios, like avoiding peak loads, are also reasons for performance adaptive processes. The traditional ineffective answer on such problems was to shut down the entire line and deal with high restart times or rework single products.

In the following, performance adaptive manufacturing processes are presented to handle dynamic influences. Figure 4 shows the major components of the approach. After production design and engineering (PLM) and virtual commissioning, the alternative production variants supported by the control programs are evaluated (chapter 4.1). A suitable subset of these variants is then stored in a library which is accessible by the run-time manufacturing IT (chapter 4.2). For utilizing these variants during operation the short-term production planning algorithms have to be extended (chapter 4.3) in order to enable them to select the most appropriate variant by an MES for a given production situation (e.g., production program, electricity price, machine utilization). The plant automation in the shop floor then is executed and monitored by a hierarchic structure of programmable logic controllers (PLCs), robot controls (RCs) and computer numeric controls (CNCs).

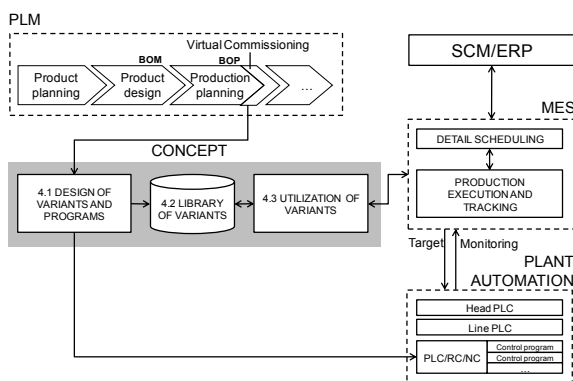


Figure 4: Concept of performance adaptive manufacturing processes.

4.1 Design of variants and programs

Performance adaptive manufacturing starts already during the production planning. In this context, various IT systems and tools are used for the design and engineering of run-time components. These systems have to be extended at various points to support performance adaptive processes. The conventional design of a production starts with initial product and process information like bills of material, manufacturing technologies and production quantities. Amongst others the tasks of production planning are the creation of a bill of process (BOP), the selection of machines and the planning of capacity, material flow and factory layout. Virtual commissioning is the last step of production planning, which also serves automatic program generation for PLCs, RCs or CNC. Information about machines (e.g., attrition) and processes (e.g., maximum speed) as well as about complex dependencies between the different components of the machine are considered for the program design. Such information is typically not available in the later stages of the product or production lifecycle and in particular not in the run-time systems. Therefore, the upfront design of alternative operating variants that provide flexibility to the later manufacturing IT is important.

For defining the operating variants for a performance adaptive production process we first have to take a closer look at the specific presupposed energy consumption curve of each machine (cf. Figure 3). Under the assumption that the energy consumption of a machine $E_M(S)$ depends solely on its own configuration and not on the configuration of the other machines in the line, the energy consumption of the line L can be calculated by $E_L(S) = \sum_{i=1}^n E_{M_i}(S)$. In the field of automotive industry, there are fixed cycle times for every line, which are independent from product variants. Slower process execution S means higher cycle times C . Different machines along a line have to be configured for the same cycle times as long as no buffers are available between machines (or lines). If a buffer is available cycle times of two lines can be different, i.e., $C_{L_1} \neq C_{L_2}$ for the two lines L_1 and L_2 connected with a buffer, but $C_{M_1} = C_{M_2}$ for two machines without buffer. This concept is exemplified in Figure 5.

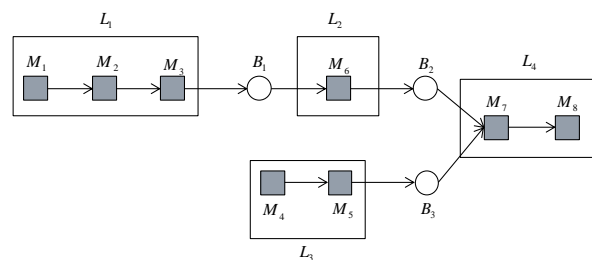


Figure 5: Structure of a production system.

As different lines can be operated independently with different operating speed, operating variants have to be defined for each line separately. Therefore the line-specific function for the energy consumption $E_L(S)$ is calculated using the consumption profiles of each machine in the line. Figure 6 shows a simplified example for the body shop where electricity demand is mostly generated by robots. It is supposed that the curve is continuous and has only one minimum.

In many cases the number of possible variants that can be configured is extremely large (e.g., due to continuous parameters in the control program). However, the number of the variants has to be restricted in order to reduce the programming effort and allow an efficient selection of the most suitable variant during run-time. Therefore, a pre-selection of the most important variants has to be done in the design phase. A variant is important if there could be a situation during run-time, where the performance (KPIs including energy demand) can be improved by selecting it. Thus, system performance as combination of e.g., energy efficiency and throughput (*BPI*) [4] can be improved by adding this variant. In the first place this statement holds for all variants that are located at minimum or maximum points regarding energy consumption or cycle time. During run-time the fastest and slowest possible variants as well as the variants with the lowest and the highest consumption are required (variants v_1 , v_3 and v_5 in Figure 6). A high consumption variant could be necessary even if it is not the fastest variant in case of negative electricity prices which can be possible in demand response scenarios.

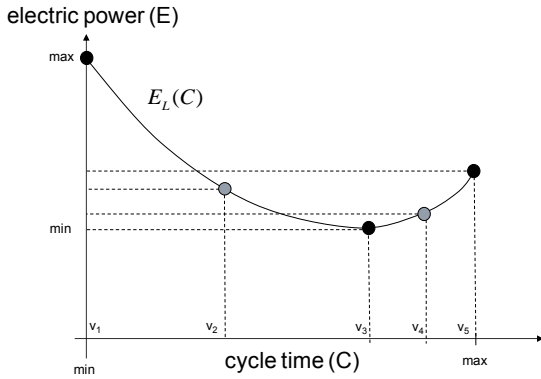


Figure 6: Selection of line operating variants with different discrete cycle times.

In addition, to these basic variants additional operating variants can be designed to enable a more fine-grained optimization approach during run-time (variants v_2 and v_4). However, too many variants lead to an explosion of the solution space (e.g., 4 lines with 5 variants each support already 3125 different production processes). Therefore, the number of variants is a trade-off between the additional computational complexity and the benefit. The additional benefit depends on the degree of difference in terms of energy consumption of the new variant v_{new} compared to the existing variants V . As a guideline for assessing the number of required variants the following formula can be used:

$$v_{new} := E_L^{-1} \left(\frac{E_L(v_i) - E_L(v_{i+1})}{2} \right) \text{ if } |E_L(v_i) - E_L(v_{i+1})| > SF,$$

with $v_i \in V$, the inverse function E_L^{-1} and the parameter SF representing the minimum energy saving factor. The smaller the parameter SF is chosen the more variants will be generated making sure that variants are chosen for areas with strong differences in energy consumption (i.e., first derivative $|E_L'(C)| \gg 0$). Note that this approach might lead to variants with similar energy consumption but different cycle time. This is required to address situations where cycle times are very restricted and still options regarding energy consumption are required.

This approach does only consider productive phases. Therefore, standby modes or the complete shutdown of machines are not considered as variants in this concept. The topic of energy efficient control of production lines in non-productive phases is discussed in [12].

In the next step the control programs for the required variants have to be realized and manually transferred to the respective controllers (PLC, RC or CNC). For example a robot gets five speed adaptive programs, planned with PLM tools in a movement simulator and transferred to its RC controller. In conclusion the robot does not longer have only two options of full speed or idle. It is now able to choose between five programs or variants with different operating speeds and idle, standby or shut down mode.

4.2 Library of variants

The library of variants is a database containing a description of the specified variants and serves as an interface between the PLM planning systems and run-time manufacturing IT. The library is completely filled at design time and can be constantly accessed during run-time. As shown in Table 1, variants are assigned to each line, process and the line's machine control programs. Furthermore they specify the expected energy consumption as well as cycle times, and define the product for which a variant can be used. Transports between process steps can also be included. The total factory performance can now be calculated by the cumulated cycle times during the run-time. The electric power will be declared instead of energy consumption for idle modes.

Table 1: Library of variants

Variant	Line	Process	(Machine / Control Program)	Product	Energy consumption	Cycle time
V1	L1	Welding	(M1, CP2), (M2, CP5)	P1	51 kWh	30 s
V2	L1	Welding	(M1, CP3), (M2, CP4)	P1	30 kWh	40 s
V12	L6	Bonding	(M32, CP3)	P2	32 kWh	40 s
V63	L12	Transport	(M44, CP5)	P1	1 kW	Idle
...						

4.3 Utilization of variants

The library of variants provides additional flexibility to the detailed production scheduling done by the MES. Detailed production scheduling has to be extended beyond production order sequencing in order to additionally select the most suitable process variant for each line given in a certain production situation. The production situation is defined by a set of variables that can be observed or measured during runtime. These variables include:

- the current and future production program
- the current electricity tariff
- unexpected events such as machine breakdowns or JIS/JIT failures
- current capacity of buffers

Generally, long-term changes of variables are addressed by the ERP system and medium-term changes can be handled by a dynamic, event-driven order sequencing approach as

outlined in [14]. In the following, we focus on short-term adaption of line-specific cycle times through selection of the most appropriate variant from the library considering not only throughput but also energy-efficiency. The goal is in that context to select one of the Pareto-optimal variants.

Optimal selection of the variants requires a robust prediction of variable values above (e.g., future electricity prices). Given such predictions, a dynamic programming approach could be used to calculate the optimal production processes. However, as correct predictions are not possible, optimization approaches will lead to suboptimal results. In addition, optimization approaches are sometimes not intuitive for the line operators because understanding the solution can be highly complex. Therefore, in the following a rule-based approach is proposed that is based on fuzzy logic [15, 16]. On the one hand, fuzzy rules have the advantage that their evaluation is extremely fast and can be easily done during run-time (even for large solution spaces). On the other hand, they are quite intuitive for operators due to the usage of linguistic variables (e.g., expensive, cheap) and more robust to imprecise predications of traditional rule-based systems.

The application of fuzzy rules requires defining membership functions that map continuous variables to fuzzy sets which are described by linguistic variables. Figure 7 exemplifies this ‘fuzzification’ for the variable electricity price. In a similar way, also the variables that reflect the available capacity of the buffers and delay of input material can be mapped to fuzzy sets. Discrete variables with a low number of values (such as the variants) can be used in the rules without fuzzification.

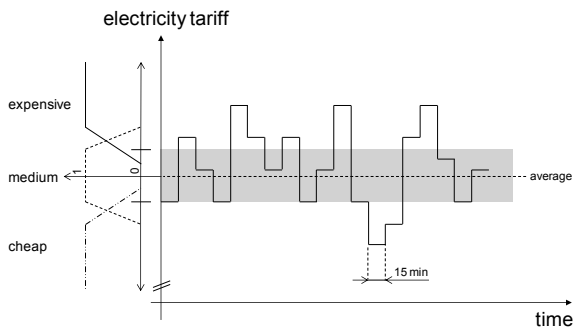


Figure 7: Fuzzification of electricity price.

Based on the fuzzy sets rules, it can be defined by the operators how the system should react on changes in variable values. E.g., the operators can define that variant v_4 should be used for line L_1 if electricity prices are ‘expensive’, buffer capacity B_j is not ‘scarce’ and utilization is ‘low’. If in the same case utilization is ‘high’, variant v_2 would be more appropriate. The degree of fulfillment of a rule and defuzzification are calculated as proposed by [16]. Usually it is sufficient to define one rule for each production line and variant, but of course also more detailed reactions can be configured via such rules. Obviously, the approach is a heuristic and typically will not lead to an optimal solution. However, a complete optimization would also lead to a suboptimal solution (due to uncertain predictions).

In the next section the concept is evaluated regarding the performance of an automotive production line.

5 EVALUATION

To evaluate the concept of performance adaptive production lines, a simulation model was built in Plant Simulation 9.0 based on the production system in Figure 5. Table 2 lists the parameters with their respective categories that were implemented into the model in a morphological box. Most importantly, we define four variants that vary the operation speed of each production line from its maximum value to its half. Similar to the preceding outlines, the highest speed is associated with the highest energy consumption while the lowest speed requires the least energy. Also, in accordance with Figure 3, a small decrease in speed from a high performance level is accompanied by a disproportionately large drop in energy consumption. Conversely, a large decrease in speed at low levels results only in a small drop in consumption.

To evaluate the performance of utilizing multiple variants, line performance (i.e., speed) is subjected to considerations regarding external energy prices and internal in-process inventory levels. First, the energy price for the simulation was derived from hourly price data over half a year from the spot market of the European Energy Exchange. Using the maximum likelihood method, the values were fitted to a normal distribution with a mean of 41.82 €/MWh and standard deviation of 12.92 €/MWh. In accordance with Figure 7, Table 2 shows the division of the price range into four categories from cheap through expensive. The energy price in conjunction with adaptable speeds allows the deceleration of production when prices are high. Second, the three buffers of the production system in Figure 5 allow for the measuring of the work in process (WIP) inventory. Again, Table 2 shows that the WIP level for each buffer was also divided into four categories. The WIP level of subsequent buffers in conjunction with adaptable speeds of preceding lines allows to slow production when the buffer is full, implying that the following lines do not cope with the current workload.

Table 2: Categorization of parameters

Parameter	Categories			
Operation speed	Slow (50%)	Medium (70%)	Fast (90%)	Maximum (100%)
Energy price	Cheap (<30 €/MWh)	Low-end (30-40 €/MWh)	High-end (40-50 €/MWh)	Expensive (>50 €/MWh)
WIP level	Empty buffer (<5 units)	Low buffer (5 - 9 units)	High buffer (10-14 units)	Full buffer (>14 units)

The simulation ran for 100 days and was implemented with three strategies – WIP, energy price and a hybrid strategy. The latter balances the other two factors. The results are displayed in Figure 8. The strategies are compared against the full productivity scenario where all production lines of the system run at maximum speed to achieve the highest throughput performance. Considering the energy costs per unit, all strategies are superior to the baseline scenario. Intuitively, the strategy that focuses solely on the energy price outperforms all others, cutting energy costs per unit almost by half. The same is true for the energy costs that accumulated over the 100 days. However, considering the actual system output, the price-based strategy performs poorly with only 70% of the output of the baseline strategy. It slows production whenever prices are high and thus, is completely subjected to the random fluctuations of the energy price. Although it is not applicable to real-life scenarios, the price-based strategy

illustrates the scope for energy efficient production lines. The WIP-oriented strategy neglecting energy prices results in the highest energy and unit costs but achieves a significantly higher output than the price-based strategy.

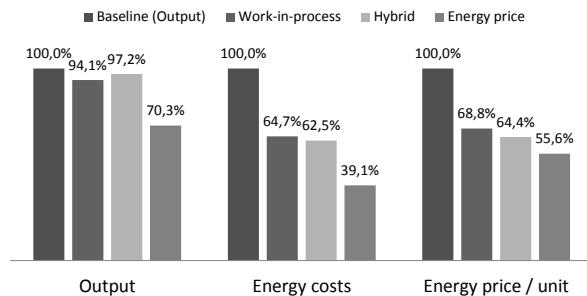


Figure 8: Comparison of results.

The best performance is recorded for the hybrid strategy. It combines the constraints of the other strategies by producing at full speed whenever energy prices are low or the subsequent buffer is starved. Conversely, it produces at slow speeds whenever the price is high or the subsequent buffer is close to full. Figure 9 illustrates this connection: Whenever the energy price is low, the system produces at full speed, which subsequently increases the total WIP level of the system. Conversely, when the price peaks, the system slows down and the WIP-level is reduced. Figure 8 shows that the hybrid strategy achieves a higher output than all other strategies at lower energy costs than the WIP-based strategy. Furthermore, it comes close to the 'optimum' of the full productivity scenario while reducing energy costs considerably.

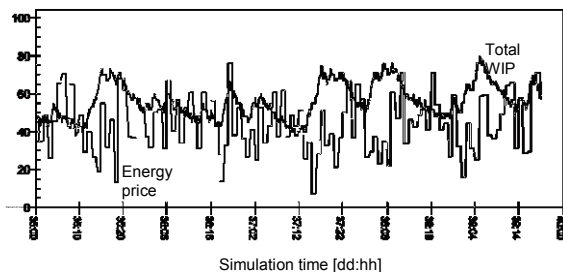


Figure 9: Price versus total WIP level.

6 SUMMARY AND OUTLOOK

It has been shown that performance or speed adaptive manufacturing processes increase energy efficiency and sustainability. The approach was realized during run-time and supported by PLM planning tools. A library of variants works as an interface and provides different energy consumptions for several production variants and cycle times. The variants can be dynamically requested during run-time.

Prospective researches will deal with a higher diversity of variants and complexity. The temporal progress of energy consumption will be provided more detailed and simultaneous simulations will be used during run-time.

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