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Energy Costs In Production Planning And Control: A Categorical Literature Review And Comparative Analysis

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Abstract

Rising energy prices are an increasing financial burden for manufacturing companies. In addition to established logistical and cost-oriented targets such as short throughput times and low stock levels, energy costs assume an increasingly important role. Energy costs can be included as a further planning variable in production. The aim is to lower costs either directly by reducing consumption or to use price mechanisms to exert an influence, for example peak shaving. Methods and procedures for energy-oriented production planning and control have been studied in numerous research projects. However, it is difficult to determine which approaches are most suitable under given system conditions. Therefore, the aim of this paper is to provide a literature review and an analysis of the efficiency of energy-oriented production planning and control approaches. It will be highlighted under which logistical system properties the investigated approaches are found to be effective and a comparison will be drawn. The results show that current research focuses mainly on scheduling procedures. Targets and suitable system conditions are potentially conflicting, so that a broader debate about the classification and applicability of methods is recommended.

Keywords

Energy-oriented production planning and control; logistical objectives; production systems

1. Introduction

Due to globalization and growing ecological demands, manufacturing companies are challenged with numerous economic, political and social changes [1]. As the industrial sector takes the worldwide largest share of energy demand, an important object of consideration is the constantly growing cost pressure of energy consumption associated with transforming costs and functional requirements for energy sourcing [2,3]. In addition to personnel expenses, there is a growing focus on rising energy costs (in this paper, energy costs are primarily defined as costs for electricity), which particularly affect production companies with energy-intensive processes [4]. Especially in the concrete, chemical, paper, steel, aluminium, copper and textile industries the share of energy costs in total production-related costs is particularly high [5]. In order to counteract these high energy costs, there are several possibilities [6]. For example, one approach considers time-of-day-variable electricity prices. With the establishment of the European Energy Exchange (EEX), short-term power procurement through the European Power Exchange (EPEX Spot) using day-ahead and intraday contracts has been made possible. This enables companies to purchase quantities of electricity at prices that depend on the time of day and thus be able to profit from price fluctuations during the day. [7]

Production planning and control (PPC) has an important role, when it comes to dealing with rising energy costs [8]. Using PPC opens up opportunities for manufacturing companies to use volatile electricity prices to their advantage by timing production orders. In general, an energy-oriented PPC enables manufacturing companies to save energy costs through peak shaving, time-of-use (dynamic) pricing and reduction of energy

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consumption. [9] Implementing energy cost-oriented management, e.g. through a sequencing rules, not only has an impact on costs but also on other objectives such as schedule reliability [10].

Based on a categorical literature research and a comparative analysis, this paper discusses the most common approaches to minimize energy costs using the PPC. The aim is to provide an overview of which approaches are frequently investigated, which tasks of PPC are covered in particular and which target figures are pursued. In addition, it will be examined under which system conditions with regard to logistical properties the approaches promise great success. With a comparative analysis, we want to show that supporting structures differ depending on the target figure or method pursued. Currently, there is no comprehensive review that examines energy-oriented PPC approaches in the context of supporting, logistical system properties under consideration of varying targets. Yet, the trade-off related to logistical objectives is seen as one of the biggest challenges [11].

This paper serves as the basis for further work in the field of the energy-oriented PPC. However, no technical approaches are considered, but only organizational measures that can be implemented by the PPC. The paper is organized as follows: In section 2, we first present the basics of the PPC with reference to energy-oriented production. Next, in section 3 we describe the methodology of the literature review. In section 4, the results of the categorical literature review are analyzed and comparative analysis will be conducted. Finally, a conclusion is drawn in section 5.

2. Fundamentals of energy-oriented PPC

The internal supply chain of a company is largely controlled by the PPC. The flow of production orders must be planned and executed in procurement, production and distribution, according to logistical objectives such as a short delivery time and high utilization. [12] The main purpose of production planning is to schedule the production program (short and long term). Production control, on the other hand, is primarily responsible for the actual production processes and ensures that all production plans are implemented in a targeted manner, even in the event of disruptions. [13,14] Next to delivery time and production costs, energy costs can also be significantly influenced by PPC as target figures. An energy-oriented PPC provides manufacturing companies with several ways to effectively respond to rising energy costs by pursuing different targets. [11,15]

First and foremost, energy costs can be saved by reducing energy consumption, e.g. through the targeted avoidance of set-up processes [16]. A further option is to participate in the EEX (or equivalent in other markets) in order to be able to purchase electrical energy at prices that depend on the time of day. As the share of renewable energy generation increases, the volatility of the time-of-day-dependent electricity price also increases as well as the electricity costs in total, so that a distinction can be made between high-price and low-price periods. [7,17] For electricity in general, costs are mainly influenced by the variable costs for the purchase quantity (billed via the time-of-use price rates) and the maximum requested electrical power in the billing period (billed via the load-based price rates). The greater the amount of energy consumed, the higher the costs caused by the time-of-use price rates. [18] To be able to save energy costs at this point, variable electricity prices can be used by manufacturing companies to produce energy-intensive orders during periods of low electricity prices (see e.g. [15]). On the other hand, the greater the so-called “load peaks” in the load curve of a company are, the higher are the resulting costs for the company caused by the load-based price rates. To save electricity costs, the company should try to avoid extreme load peaks in the load profile [19].

These strategies can be implemented by load shifting [19]. The PPC can be a tool to integrate these strategies for energy-oriented production. Load shifting can be realized by job shop scheduling, production planning respectively control by setting up the production schedules respectively the production flow in a targeted way. This can be achieved, for example, by considering only one task (e.g. sequencing [10]), or by a combination of tasks (e.g. consideration of the entire production control [20]). Figure 1 shows the connection between the processes relevant for energy-oriented production and the main tasks and subtasks of the PPC. An information loop is created by adapting the outputs and evaluating the resulting data. The influence of the subtasks on energy-oriented production is evaluated and reported back to planning and control parts of the system [8].

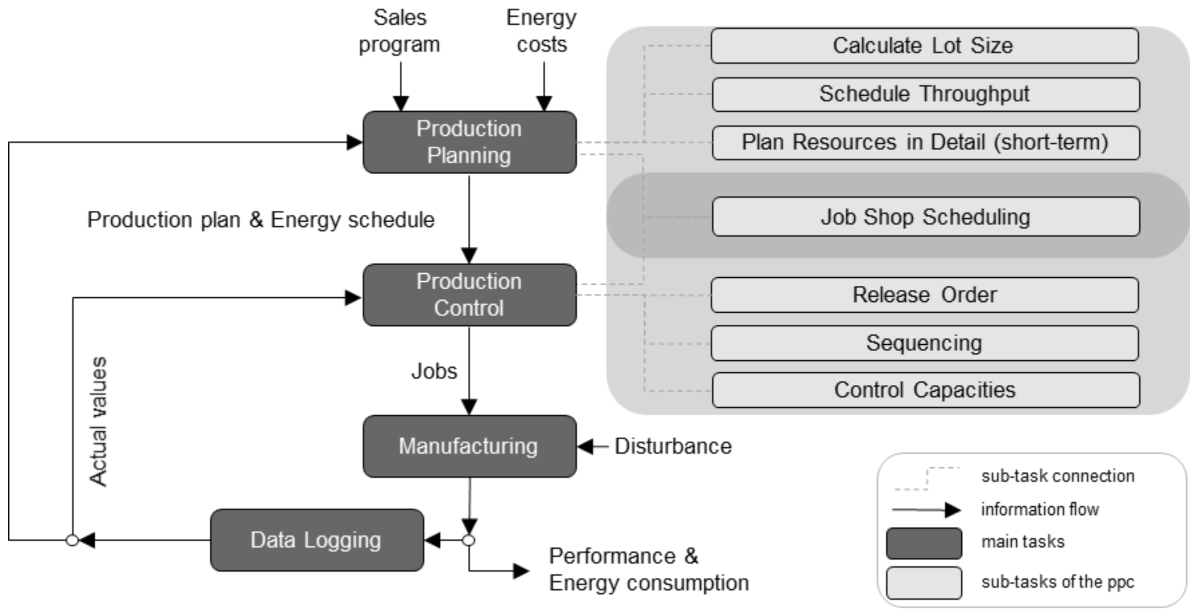

Figure 1. PPC as closed control loop in combination with the Hanoverian Supply Chain Model (HaSupMo) [21,8]

In this paper, supporting system conditions are investigated from a logistical perspective based on the objectives of production logistics according to Wiendahl [12]. Wiendahl describes four general logistics objectives and divides them into two groups. While short throughput time and high schedule reliability belong to logistics performance, high utilization and low work in process (WIP) are assigned to logistics costs. The simultaneous optimization of all objectives is not possible, as they are partly contradictory. Therefore, an active positioning is necessary. In order to achieve the set goals, the company processes can be organized with the help of PPC. [21]

For instance, if the company's objectives specifically require high capacity utilization due to high machine costs, it may be necessary to maintain high WIP in order to reduce WIP-related downtime. However, high WIP causes longer throughput times and, since these are more dispersed, this causes a lower adherence to delivery dates. [22] Energy costs as a further variable in the planning and control of production exacerbate this conflict, since, for example, a further decision must be made between schedule priority and a reduction in energy costs (see e.g. [10]). If energy-oriented methods can be selected in such a way that they correspond (partly) to the logistical objectives of companies (e.g. small lot sizes, focus on high capacity utilization, low WIP), this could reduce a potential negative impact on logistical performance. In this paper, supporting system properties/ structures are on the one hand the mentioned targets of logistic objectives, but also important control levers like lot sizing. Furthermore, the product portfolio with respect to the energy consumption and processing times needs to be considered.

3. Categorical Literature Review

Although there are already some review articles, there is no work yet that makes a categorical classification and, on this basis, performs a comparative analysis regarding the effectiveness of different system properties in terms of targeted WIP or lot sizes. [23] mainly investigates mathematical approaches to energy-optimized production, but without addressing logistic target figures or logistic system conditions. [24] investigates approaches to energy-efficient production planning with medium and short planning horizons and transfers it into a systematic classification. The aim of the study is to identify research gaps in the existing literature. However, logistic system conditions are not addressed in detail. [25] investigates energy-efficient scheduling approaches and creates a research framework. With an empirical analysis, they elaborate advantages that can be achieved with the different energy-efficient approaches. However, logistic structures are not considered in the analysis in this research either.

For our literature review, we used the search engines Google Scholar and ScienceDirect (conference papers as well as journal papers) to identify relevant publications using the search terms "energy costs", "electricity cost", "production planning" and "production control". The search was performed in English and analogously with the translated search terms in German. In order to limit the number of search results to relevant and topical articles, only papers published later than 2010 were analyzed. From the two search engines, considering the above search terms, a total of 6495 results could be found, most of which were written in English with 5462 hits. In an initial review, the papers found were filtered by the title and partly abstract according to relevant approaches. Pure mathematical (e.g. solving algorithms) and technical-oriented (e.g. storage technologies) approaches were sorted out, as well as papers with no visible profound reference to PPC. As a result, 142 papers were examined more closely. These papers were then categorized according to “concept”, “case studies” and “literature review”. As expected, few literature reviews could be found. The majority of the papers found contained a case study (83 papers). For a majority of the case studies considered, the focus is on the investigation of mathematical approaches and solution algorithms for solving energy-oriented approaches to PPC. By introducing two new categories ("application-oriented case study" and "methodical case study"), we were able to better distinguish these approaches and focus on the application.

Finally, 22 relevant papers (application-oriented case studies) could be selected and analyzed in detail. The papers found were categorized in different areas according to different perspectives. The focus was particularly on the PPC tasks based on the Hanoverian Supply Chain Model (HaSupMo), target figures, the applied methods and the supporting logistical system properties, as shown in figure 2. Either individual tasks of the PPC can be considered, such as lot sizing, or entire task areas, such as production planning. A special case is scheduling, where planning tasks are executed in parallel under given constraints. The target figures (logistical objectives, costs, etc.) were derived from the approaches and listed as well. In addition, each approach was assigned one or more of the three general methods to influence energy costs by the PPC (reduce consumption, peak shaving and dynamic pricing). Finally, all approaches were analyzed for supporting logistical system properties. The results of the analysis are presented in table 1.

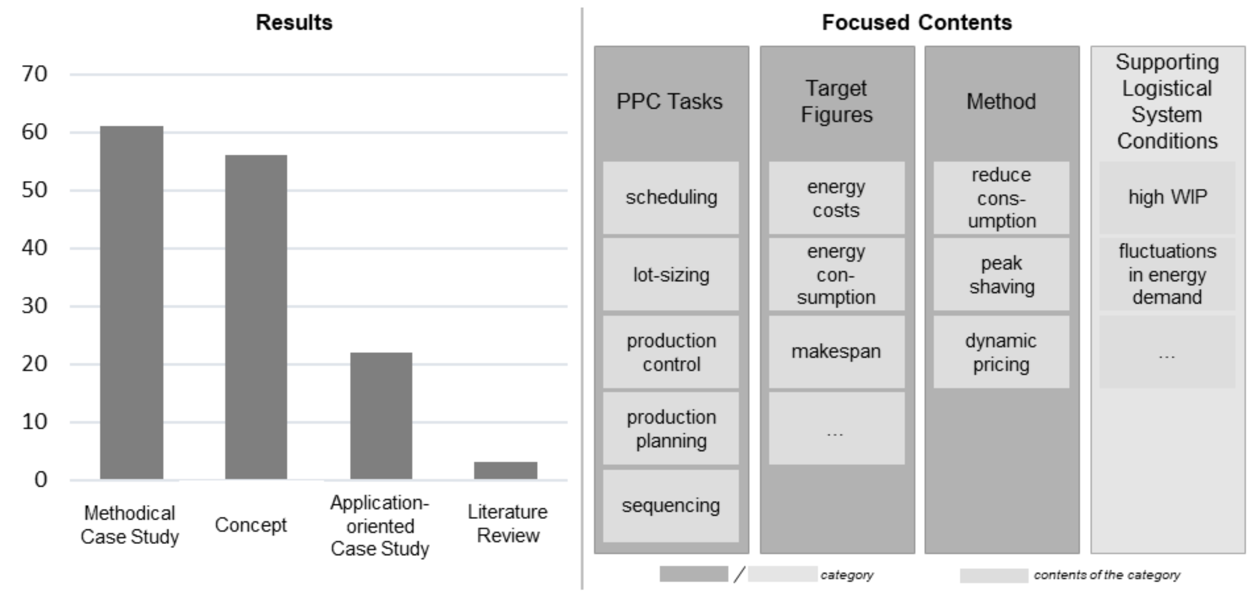

Figure 2. Publication-types: distribution of publication types (left) and categorization method (right)

Table 1. Categorical literature review

Author	Language	Mathematical approach	PPC tasks	Target figures	Method	Supporting logistical system conditions
Bettoni and Zanoni (2012) [26]	EN	simulation	production planning	energy costs; energy consumption	reduce consumption	-
Böning et al. (2017) [27]	EN	OR	scheduling	power peak; costs of unused capacity; waiting times of job's operations	peak shaving	-
Busse and Rieck (2019) [28]	EN	OR	scheduling	energy costs; completion time	dynamic pricing	-
Busse, Rüther and Rieck (2018) [29]	EN	OR	scheduling	energy costs; weighted sales revenues; total gross profit	dynamic pricing	heterogeneous product portfolio
Dellnitz et al. (2020) [30]	EN	OR	lot sizing; scheduling	special set-up process time; total energy costs; emissions of the production process with respect to the total energy consumption	dynamic pricing	-
Emec et al. (2013) [31]	EN	OR	scheduling	energy costs	dynamic pricing	high shifting flexibility
Ewering et al. (2014) [32]	EN	simulation	production control	energy costs	dynamic pricing	-
Gong et al. (2015) [33]	EN	OR	scheduling	energy costs	dynamic pricing	-
Johannes, Wichmann and Spengler (2019) [34]	EN	OR	lot sizing; scheduling	set-up costs; warehousing costs; stand-by costs; energy costs	dynamic pricing	-
Kawaguchi et al. (2017) [35]	EN	OR	scheduling	makespan, total energy costs	dynamic pricing	-
Renna et al. (2020) [36]	EN	simulation	production control	reducing the peak power needed to pursue a performance level	peak shaving	high utilization; potential uncertainty in processing time
Schuh, Brandenburg and Schulte (2014) [37]	DE	simulation	lot sizing	energy productivity	reduce consumption	high capacity availability; largest possible batch sizes without stand-by losses
Schultz et al. (2017) [38]	EN	simulation	production control	energy costs; schedule deviation	peak shaving; dynamic pricing	jobs with high fluctuations in energy demand
Schulz, Buscher and Shen (2020) [39]	EN	OR	scheduling	energy costs; total tarddiness	dynamic pricing; reduce consumption	-
Selmair et al. (2016) [40]	EN	OR	scheduling	time specific power demand; energy costs; makespan	dynamic pricing	-
Sharma, Zhao and Sutherland (2015) [41]	EN	OR	scheduling	energy costs per job; carbon footprint per job; number of jobs in a shift; electricity consumption	dynamic pricing	-
Tan, Duan and Su (2018) [42]	EN	OR	scheduling	energy costs; weighted makespan	dynamic pricing	-
Thornton et al. (2017) [43]	EN	OR	scheduling	energy costs while satisfying order due dates	dynamic pricing	-
Weinert, Rohrmus and Dudeck (2012) [44]	EN	simulation	production planning	energy costs; peak load limitation	peak shaving	-
Wichmann, Johannes and Spengler (2019) [45]	EN	OR	lot sizing; scheduling	set-up costs; warehousing costs; stand-by costs; energy costs	dynamic pricing	heterogeneous product portfolio; high capacity utilization; high WIP
Willeke, et al. (2018) [46]	EN	simulation	sequencing	energy costs; schedule deviation	dynamic pricing	high WIP; low mean processing times;-three-shift system is recommendable; jobs with high fluctuations in energy demand
Yusta, Torres and Khodr (2010) [47]	EN	OR	scheduling	production profit	dynamic pricing	small lot sizes

4. Comparative Analysis

In general, it can be seen that there is a large number of different approaches to energy-oriented production, each using different methods and pursuing different target figures. As with the search results in general, the detailed review examined predominantly English-language papers. Furthermore, the topic appears to be present throughout the investigation period, as the papers analyzed were evenly distributed over this time. Since the selection was conducted with a particular focus on logistic system properties, the mathematical approaches were not considered in detail. However, it can be stated that the distribution between simulation approaches and Operations Research (OR) approaches is balanced. Furthermore, it can be seen that most papers only consider one method. Exceptions are [38,39], where two methods are combined respectively are equally possible. All three methods are not combined in any approach investigated. The consideration of dynamic pricing is by far the most used among the methods (70%). About 17% of the papers examined use peak shaving as a method for minimizing or considering energy costs. Reducing the amount of energy consumed via PPC is only considered in about 13% of the approaches. However, it is noticeable in the analysis that hardly any information is given on how exactly the energy demand was modeled. With regard to the target figures, it can be seen that almost all papers consider a reduction in energy costs directly. In addition, other targets related to energy are considered, for example costs for unused capacities [27,34,45] and targets related to CO2 emissions [30,41]. A combination with logistic target figures appears in only a few approaches. Target figures with regard to schedules, completion time or makespan are considered in [28,38, 39,42,46]. Looking at the focused PPC tasks in figure 3, it can be seen that scheduling is by far the most frequently considered approached in the reviewed literature. Furthermore, it is noticeable that the PPC tasks lot sizing and scheduling are considered in combination in the papers [30], [34] and [45].

	peak shaving	dynamic pricing	reduce consumption	
lot-sizing	0.00%	0.00%	4.35%	**4.35%**
lot-sizing + scheduling	0.00%	13.04%	0.00%	**13.04%**
production control	8.70%	4.35%	0.00%	**13.04%**
production planning	4.35%	0.00%	4.35%	**8.70%**
scheduling	4.35%	47.83%	4.35%	**56.52%**
sequencing	0.00%	4.35%	0.00%	**4.35%**
	17.39%	**69.57%**	**13.04%**	

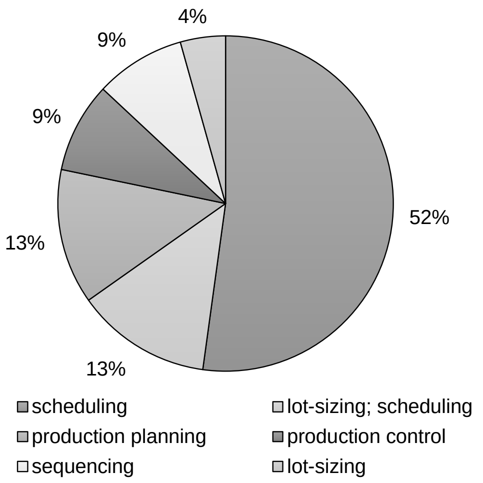

Figure. 3. Level of integration and methods matrix and focused PPC tasks

In the analyzed papers, the logistic structure of the production system is only sporadically discussed in the context of energy-oriented production. However, eight papers could be identified which include statements with respect to supporting logistic properties to some extent. With respect to peak shaving, two approaches can be found which contains statements on the logistic structure [36,38]. In [38], the main targets are to minimize schedule deviations as well as reduce energy costs. Here, peak shaving is not directly controlled, but the deviation of a given load curve. Other methods such as dynamic pricing are also conceivable. However, it is noted that high differences in energy demand support the approach developed. [38] In [36], another peak shaving approach is presented which concludes that a high or medium utilization as well as potentially uncertain processing time benefit the method.

Five approaches, considering the dynamic pricing mechanism, include statements of supporting logistic structures. [29] presents an OR approach that uses scheduling in order to increase total gross profit with the help of reduced energy costs. As supporting logistical system properties, they propose a heterogeneous product portfolio in terms of energy demand and processing time. [31] concludes that a high shifting flexibility benefits the method. The flexibility is affected by the capacity and constraints of the production system. [45] presents a simulation approach in which a combination of simultaneous scheduling and lot sizing is used to exploit daytime electricity prices in order to reduce energy costs. They state that a heterogeneous product portfolio, a high capacity utilization and a high WIP have a favorable effect on energy-oriented production. [46] presents a simulation approach, which is intended to reduce energy costs with the help of energy-oriented sequencing. It states, that a high WIP-level, jobs with high fluctuations in energy demand and short mean processing times are advantageous. Furthermore, they recommend a three-shift system for optimal exploitation of time-of-day electricity prices. [47] presents an OR approach that also performs scheduling using dynamic pricing. The aim is to reduce energy costs and thus maximize production profit. They state that especially small lot sizes have a positive effect on energy-optimized production.

Regarding the reduction of energy consumption, only one approach can be determined which considers logistical structures. [37] presents a simulation approach in which lot sizing is used to reduce the amount of energy consumed. The goal of the simulation is to generate a high energy productivity. They state that the ideal lot size should be as large as possible without stand-by losses due to idle time. Since only one approach could be found, a comparison of the logistic system properties within this method cannot be made.

It can be noted that no major statements on logistic system properties can be identified within the methods peak shaving and dynamic pricing that are strongly contradictory. A comparison of the different methods reveals differences with regard to capacity utilization and lot sizes. [37] considers high capacity availability as a supporting property for energy reduction whereas [36,45] consider a high capacity utilization as a supporting feature for exploiting variable energy prices. [45,46] state that a high WIP benefits the application of procedures for dynamic pricing, which typically leads to a high utilization. Furthermore, [37] state that large lot sizes benefit the procedure. This represents a clear contrast to [47], which states that small lot sizes are beneficial. [46] states low processing times as beneficial, which in turn can also be achieved by small lot sizes. Thus, an indication of a conflict of objectives between the different methods (reduction of consumption and dynamic pricing) can be identified. Further trade-offs in terms of logistic objectives are discussed in [39] and [46]. A negative influence on the schedule reliability is confirmed in both of them. Other logistic objectives are not considered in detail, although some of them are considered important prerequisites. It can be derived that a high capacity utilization offers a higher cost reduction potential for energy-oriented PPC pursuing dynamic pricing [45]. A high WIP provides more space for sequencing decisions as the order backlog available for sequencing (e.g. orders with different energy requirements) is larger (e.g. [45,46]). Consequently, a high WIP ensures a higher flexibility to shift orders with different energy demands, and also minimizes WIP-related downtimes that increases utilization. The negative impact of high WIP, consequently high throughput times on schedule reliability has already been made clear.

In conclusion, adopting different energy-oriented management methods simultaneously appears ineffective due to partly conflicting objectives, as shown for the reduction of consumption (via large lot size) and dynamic pricing (via small lot sizes / short processing times). The evidence that hardly any approach investigated use more than one method at the same time supports this finding. It can be stated that a pre-selection of potentially suitable and effective methods could be made based on individual logistic system properties. However, this requires a more detailed investigation on the impact of lot sizes, WIP-levels and utilization rates. An evaluation of the extent to which the logistical structures provide an advantage for energy-oriented production is rarely given in the approaches investigated.

5. Conclusion and Findings

This paper presents a literature review and comparative analysis of current approaches that incorporate energy costs into the PPC with regard to supporting logistic system properties. First, an overview of energy-oriented PPC is given. This is followed by a presentation of the design of the literature review. Finally, in section 4, the results are presented and analyzed.

Logistical system properties such as small lot sizes and small processing times support a control that aims to exploit dynamic prices. To reduce energy consumption by e.g. setup-optimal lot sizing, large lot sizes should be chosen. A heterogeneous product portfolio in terms of energy demand of individual orders seems to be a prerequisite for energy-oriented control respectively planning. Pursuing different approaches to energy-oriented management simultaneously seems ineffective due to partly conflicting targets.

Mutual dependencies of logistical objectives need to be addressed and active positioning is required, weighing up the possible effects. An analysis of the current logistic system properties seems useful to make a rough estimate about the efficiency of an energy-oriented method. Objectives and suitable system conditions are potentially contradictory, and different methods are differently applicable from a logistic point of view. However, in order to estimate this validly, further work has to be done, e.g. modelling the dependencies of different methods such as dynamic pricing or peak shaving depending on PPC-procedures to be used, WIP levels, energy demand of individual orders or distribution of processing times.

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