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Energy-efficient scheduling in manufacturing companies: A review and research framework

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ABSTRACT

Because sustainable scheduling is attracting increasing amounts of attention from many manufacturing companies and energy is a central concern regarding sustainability, the purpose of this paper is to develop a research framework for “energy-efficient scheduling” (EES). EES approaches are scheduling approaches that have the objective of improving energy efficiency. Based on an iterative methodology, we review, analyze, and synthesize the current state of the literature and propose a completely new research framework to structure the research field. In doing so, the three dimensions “energetic coverage”, “energy supply”, and “energy demand” are introduced and used to classify the literature. Each of these dimensions contains categories and attributes to specify energy-related characteristics that are relevant for EES. We further provide an empirical analysis of the reviewed literature and emphasize the benefits that can be achieved by EES in practice.

Keywords:
Scheduling
Energy efficiency
Research framework
Review
Manufacturing

1. Introduction

The global demand for almost any type of goods is continuously growing as populations and overall living standards are increasing, especially in countries such as China, India, and Brazil. However, the resources necessary to fulfill these demands are inherently scarce. Thus, sustainable use of resources is essential, and “... meeting the needs of the present without compromising the ability of future generations to meet their own needs, should become a central guiding principle of [...] enterprises” (United Nations, 1987). Following this statement about the need for sustainability, a rethinking of business operations began and led to Elkington's (1998) triple bottom line concept. This fundamental concept of sustainability defines any operation as sustainable if three dimensions—economic, environmental, and social— are considered simultaneously. Because industry is acting to fulfill the growing demand for goods and consequently is one of the primary consumers of energy (in 2012, industry accounted for approximately 24.2 percent of energy consumption in the European Union; Eurostat, 2012), it is essential to establish sustainability in the manufacturing sector (see Haapala et al., 2013; Jovane et al., 2008). Reducing manufacturing companies' energy demand is indispensable for sustainable development because energy usage and supply cause negative environmental effects (e.g., greenhouse gas emissions, acidification, and extensive land use). However, energy is a non-substitutable production factor. This is why reduction in energy demand is limited to a certain extent and is subject to the desired production output. Therefore, improving the ratio between energy input into and the desired output of a production process —i.e., improving energy efficiency— is one of the central aspects of sustainable manufacturing (for a detailed discussion of energy efficiency see, e.g., Fysikopoulos, Pastras, Alexopoulos, & Chryssolouris, 2014; Patterson, 1996). Furthermore, the Intergovernmental Panel for Climate Change (IPCC) states that the short-term potential for energy efficiency improvements in major industrial nations' manufacturing sectors is approximately 25 percent (Watson, Zinyowera, & Moss, 1996).

However, none of the IPCC reports identify scheduling as either a method or an instrument to improve energy efficiency (Edenhofer et al., 2014; Metz, Davidson, Bosch, Dave, & Meyer, 2007; Pachauri, 2001;Watson et al., 1996). Although there are a number of conceptual articles on and reviews of the fields of sustainable supply chain management (e.g., Carter & Easton, 2011; Dekker, Bloemhof, & Mallidis, 2012; Linton, Klassen, & Jayaraman, 2007; Nikolopoulou & Ierapetritou, 2012; Piplani, Pujawan, & Ray, 2008), sustainable operations management (e.g., Kleindorfer, Singhal, & van Wassenhove, 2005; Liu, Leat, & Smith, 2011), sustainable manufacturing (e.g., Chun & Bidanda, 2013; Duflou et al., 2012; Garetti & Taisch, 2012; Haapala et al., 2013; Jovane et al., 2008; Mani, Madan, Lee, Lyons, & Gupta, 2014), and energy in industry (e.g., Abdelaziz, Saidur, & Mekhilef, 2011; Trianni, Cagno, Thollander, & Backlund, 2013), scheduling is rarely considered as a suitable instrument to improve sustainability either in general or with respect to energy efficiency in particular. To the best of our knowledge, only four papers address scheduling and energy efficiency at a conceptual level. Garetti and Taisch (2012) give

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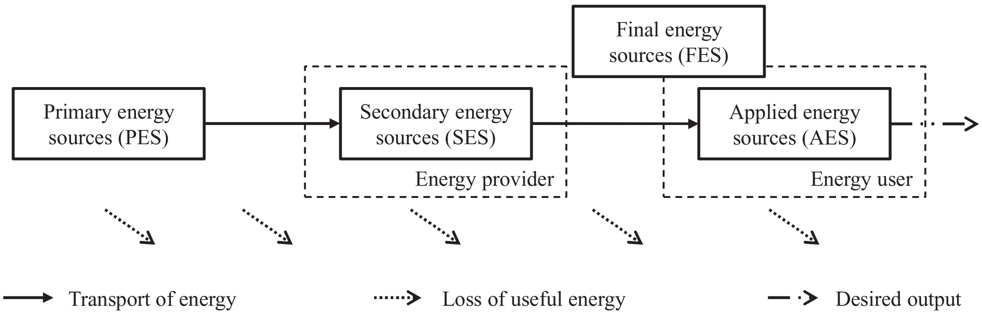

Fig. 1. Energy conversion chain (following Müller, 2009).

a broad overview of sustainable manufacturing and identify energy-aware production planning and control as a suitable instrument for energy-efficient manufacturing, but they give no further insights into this topic. Merkert et al. (2014) review and analyze several case studies, but their conclusions are rather general. Duflou et al. (2012) analyze methods to improve energy and resource efficiency in manufacturing companies. However, because of their broad scope, their analysis concerning scheduling approaches to increase energy efficiency is not very detailed. Nevertheless, their basic understanding of the relevant processes and systems is used in this paper. A similar scheme is applied by Haapala et al. (2013). In contrast to all other publications, they identify production planning and scheduling as key element of sustainable manufacturing and briefly describe selected articles.

Against this background, the purpose of this paper is to propose a research framework for "energy-efficient scheduling" (EES), which refers to scheduling with the objective to improve energy efficiency. Therefore, we conducted a structured literature review and analysis to identify and structure decision problems and their characteristics along with methods of operational production planning (scheduling) in manufacturing companies. Additionally, we intend to analyze whether scheduling is a suitable method of improving energy efficiency in manufacturing companies and thus can make a substantial contribution toward more sustainable production of goods.

To achieve this goal, we first specify the scope of our analysis and describe the research methodology used in this paper. In the following Section 3, we describe the proposed research framework for EES. This framework forms the basis for the literature classification presented in Section 4. Here, we not only classify the relevant literature but also perform an empirical analysis. Before closing with a comprehensive conclusion, we demonstrate the benefits of EES.

2. Scope and methodology

To assess the potential total impact of EES, we consider not only production processes and production systems but also energy supply processes and energy supply systems. Fig. 1 illustrates the energy conversion chain. Primary energy sources (PES: e.g., fossil fuels, mineral fuels, wind, or solar) are transported and converted into secondary energy sources (SES: e.g., electricity or refined fuels) by energy providers. When the ownership of SES is transferred to the final energy user (here, the manufacturing company), they are referred to as final energy sources (FES). Within the manufacturing company, applied energy sources (AES: e.g., electric current or natural gas) are used to perform the transformative (production) processes. We neglect any energy applications that are unrelated to production processes and cannot be influenced by scheduling (e.g., climate control, lighting, or information technologies). In some cases, an additional process to convert FES into AES (e.g., steam or compressed air) must be performed by the energy user (e.g., Agha, Théry, Hetreux, Haït, & Le Lann, 2010).

With respect to this conversion chain, scheduling performed by the energy user (manufacturing company) addresses the end of the chain: the production system. Generally, scheduling can be defined as the allocation of production orders (jobs) to production units (machines) and the associated sequencing and timing on the machine. Processing intensity (e.g., speed) can also be part of the scheduling decision. Although a calculated schedule first determines the execution of a production process, it also determines that process's energy demand and thus can affect its energy efficiency (e.g., allocating energy-intensive jobs to more energy-efficient machines). This effect on energy efficiency is not only limited to AES demands but also can directly result in savings in terms of FES and SES demands (e.g., leveling of the peak AES demand leads to lower demand for SES). Therefore, the scope of our analysis is scheduling approaches that lead to increased energy efficiency somewhere in the conversion chain.

The methodology used in this paper is illustrated in Fig. 2. It is based on the general guidelines for literature reviews described in vom Brocke et al. (2009) (see also Cooper, 1988; Webster & Watson, 2002), and the framework development follows the methodology applied and described in Seuring and Müller (2008) (see also Meredith, 1993). The final proposed research framework (VI.) is derived

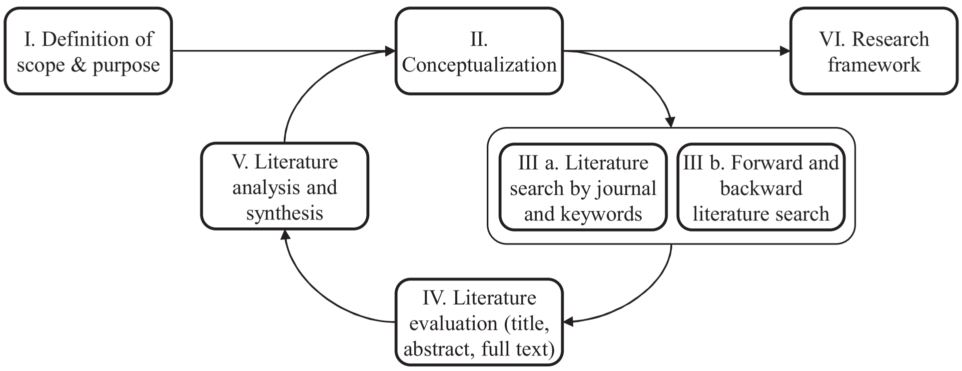

Fig. 2. Phases of the research process.

Table 1
Overview of keywords.

Keyword 1	Keyword 2
energy, environmental, ecological, sustainable, sustainability	scheduling, production planning, production

Table 2
Reviewed journals and relevant articles.

Name (initial hits)	Relevant articles after iteration one	Total number of relevant articles
Computers & Chemical Engineering (65)	7	13
Journal of Cleaner Production (852)	6	10
Industrial & Engineering Chemistry Research		6
International Journal of Production Economics (53)	4	8
International Journal of Production Research (418)	3	6
Applied Thermal Engineering		4
IEEE Transactions on Automation Science and Engineering		4
Computers & Operations Research (14)	3	3
Energy (224)	3	3
Annals of Operations Research (131)	1	2
Applied Energy (236)	1	2
Chemical Engineering Science		2
Computers & Industrial Engineering (15)	2	2
Energy Conversion and Management		2
International Journal of Sustainable Engineering (127)	2	2
AIChE Journal		1
Chinese Journal of Mechanical Engineering		1
CIRP Annals – Manufacturing Technology		2
Computer Aided Chemical Engineering		1
Computers in Industry		1
European Journal of Operational Research (43)	1	1
European Journal of Industrial Engineering		1
IEEE Transactions on Engineering Management (49)	1	1
IEEE Transactions on Power Systems		1
IIE Transactions (12)	1	1
International Journal of Energy Research		1
International Journal of Iron and Steel Research		1
International Journal of Sustainable Manufacturing		1
International Journal On Advances in Intelligent Systems		1
Journal of Manufacturing Systems		1
The International Journal of Advanced Manufacturing Technology		1
Robotics and Computer-Integrated Manufacturing		1
Ecological Economics (95), Energy Policy (203), INFORMS Journal on Computing (1), International Journal of Operations & Production Management (355), Management Science (46), Interfaces (77), Journal of Industrial Ecology (49), Journal of Heuristics (7), Journal of Operations Management (0), Journal of Optimization Theory & Applications (19), Journal of Scheduling (28), Journal of the Operational Research Society (236), Manufacturing and Service Operations Management (72), Omega (9), Operations Research (31), Operations Research Letters (1), OR Spectrum (41), Production and Operations Management (74)		
Total	35	87

through an iterative literature analysis and synthesis process (II.–V.). An essential part of every literature review is the definition of its scope and purpose (I.; vom Brocke et al., 2009). This phase can be based on an established taxonomy that comprises six constituent characteristics (Cooper, 1988): focus, goal, organization, audience, perspective, and coverage. Our study's focus is to report on research outcomes, research methods, theories, and applications, with the goal of analyzing and synthesizing the central issues related to EES within a research framework (see the preceding paragraphs). This paper is organized conceptually and adopts a neutral perspective; its audience consists of specialized scholars. Its coverage is "exhaustive and selective"; that is, the entirety of the literature on EES (or at least most of it) is used to develop the conclusions, but only a selection of articles is described in detail.

The iterative process begins with an initial conceptualization phase (II.). We first investigate the topic of interest in general (Seuring & Müller, 2008) and initiate a deductive step, in which structural dimensions and analytic categories are specified. The central outcomes of this first conceptualization step are the keywords (see Table 1) and the list of journals (see Table 2) to be used in the literature search. The keywords are relatively generic to avoid missing any relevant articles.

In the first search phase (III a.), we limit our search to the major journals in the fields of operations research, applied mathematics, and production and operations management, along with the leading journals that address energy topics in general (see Table 2). All of the searched journals are published in the English language and peer reviewed, and their significance was evaluated based on their impact factors. We do not limit the time horizon. Because we assume that most high-quality research is published in the form of academic articles in the appropriate journals, we excluded books, theses, conference proceedings, and trade journals (Rubio, Chamorro, & Miranda, 2008).

In the evaluation phase (IV.), we preselect the found articles ("initial hits") by reviewing the title, keywords, and abstract. All of the promising articles are then analyzed using a full text review. To consider an article as relevant, several criteria must be met. The first

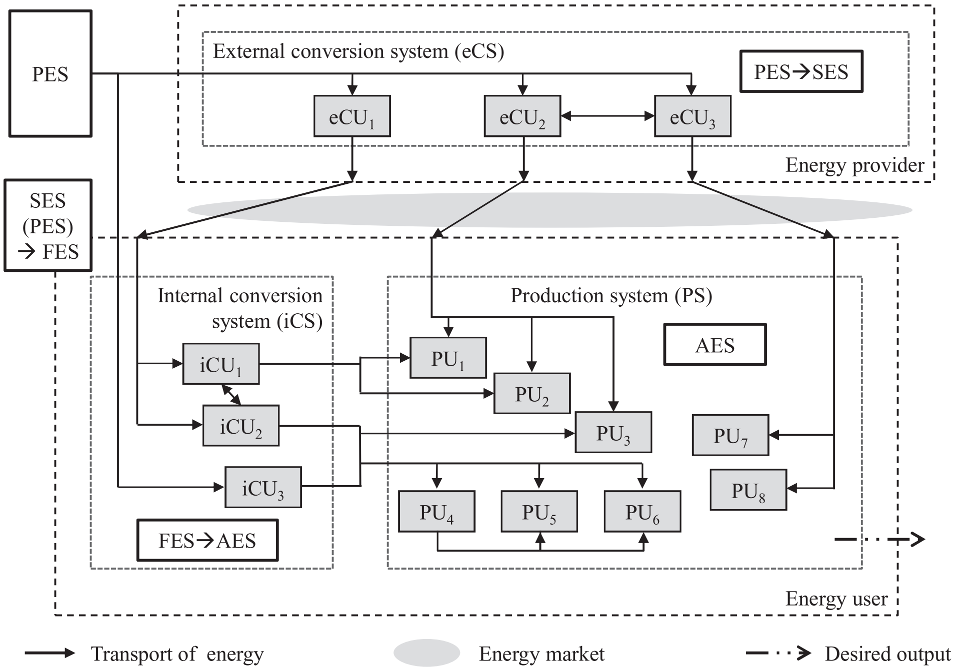

Fig. 3. Decision-relevant systems and entities.

criterion is a focus on energy — the purpose and objectives must explicitly address energy concerns. Second, we only include papers that address planning problems within a manufacturing context, that is, a tangible output is produced by a physical transformation of inputs. Thus, we do not consider any articles that address the scheduling of energy production (e.g., Zhang, Kusiak, & Song, 2013b) or energy conversion (e.g., Zhu et al., 2014), the scheduling of processors in the field of computer science (e.g., Albers, 2010; Różycki & Węglarz, 2012), or scheduling in any type of computer network (e.g., Türkoğulları, Aras, Altınel, & Ersoy, 2010). Third, we only account for scheduling approaches, which means that we exclude production program decisions (e.g., Radulescu, Rădulescu, & Radulescu, 2009) and process design approaches (e.g., Rajaram & Corbett, 2002) that are not directly coupled with operational scheduling decisions. Product design approaches and (supply) network or production facility design approaches are also neglected.

Next, we analyze and synthesize the remaining articles to search for common terms, analogies concerning the decision problem, and similarities in energy usage and energy supply (V.). Furthermore, general scheduling characteristics, such as objectives, constraints, parameters, variables, modeling approaches, and solution methods, are investigated. The outcomes of the analysis enable us to structure and concretize the initially determined dimensions and categories into a first version of the research framework (II.).

To broaden the base and to validate the first version of the framework, we conduct a one-level forward search and a one-level backward search (III b.) based on the relevant articles of the first iteration. We use the same criteria to evaluate the literature as specified above (IV.) and then apply the first version of the framework to analyze the additionally relevant articles (V.). The validation is based on an attempt to assign the "new" articles into the currently specified dimensions and categories. When necessary, these dimensions and categories are revised and/or enhanced.

The result of this final iteration is the proposed research framework for EES presented in the following section. In total, to develop the research framework, 35 articles are reviewed in detail for the first version and 52 articles are used for improvement and validation (see Table 2).

3. The research framework

As outlined in the previous sections, EES in manufacturing companies is a suitable instrument to reduce the total demand for PES. With the research framework proposed here, we aim to structure and conceptualize the field of EES. On the one hand, this is performed as a first step toward theory building (Wacker, 1998) and on the other hand, the goal is to "increase the external validity of OM research conclusions and thus their corresponding relevance to managers" (Meredith, 1993).

The analysis of the relevant literature indicates that two actors with individual objectives and three interacting systems determine the decision situation of EES (see Fig. 3, which is based on Agha et al., 2010; Duflou et al., 2012; Rager, Gahm, & Denz, 2014; Zhu et al., 2014).

The primary actor is the manufacturing company (the energy user) that uses AES to produce tangible goods. The secondary actors are energy providers, who offer one or more SES on the market. The three relevant systems are the following: the production system (PS) and the internal conversion system (iCS, also called utility system), both of which are operated by the energy user, and the external conversion system (eCS), which is operated by the energy provider. A basic assumption within the framework proposed here is that PES cannot be used directly as AES by the production units (PUs). Instead, PES must be converted by conversion units (CUs). These conversion units can be operated either internally by the energy user (iCU) or externally by the energy provider (eCU).

Based on these definitions, we propose three dimensions to classify EES approaches:

- Energetic coverage — specifies the systems (PS, iCS, eCS) addressed to improve energy efficiency, i.e., to reduce the actual energy demand
- Energy supply — describes the characteristics of FES and AES provisioning
- Energy demand — describes the characteristics of the AES application

Within each of the dimensions, we further specify attributes and categories (groups of attributes) to characterize EES approaches and to provide representative examples.

3.1. Energetic coverage

The dimension "energetic coverage" specifies the positions within the conversion chain at which the effects of EES lead to an actual increase in energy efficiency. To specify this energetic coverage, we use three non-exclusive attributes that are identical to the three systems defined above: PS, iCS, and eCS.

Scheduling approaches classified with the attribute PS directly reduce AES demand. This reduction is achieved, e.g., by turning idle machines off (Mouzon, Yildirim, & Twomey, 2007), by sequencing production orders to avoid energy-intensive setups (Yildirim & Mouzon, 2012), by allocating jobs to machines taking account of their energy requirements (Ji, Wang, & Lee, 2013), by adjusting a machines' processing speed (Fang & Lin, 2013), or by exploiting energy recovery potential (Halim & Srinivasan, 2011). Consequently, energy efficiency improvements are achieved by reducing the total AES demand of the PS.

In contrast to the PS attribute, the attributes iCS and eCS refer to approaches for which the scheduling decision does not influence the total amount of AES demand but instead influences the temporal course of the (cumulated) AES demand (Rager et al., 2014) or the temporal course of the FES demand (Luo, Du, Huang, Chen, & Li, 2013), respectively. Thus, energy efficiency improvements are achieved either in the iCS or eCS. Here, interdependencies and coordination mechanisms between these systems on one side and the PS on the other side have to be considered when using the scheduling approach. With respect to this matter, there is a fundamental difference between iCS and eCS. Because an iCS belongs to a manufacturing company, all decisions about the structural design and operation of the conversion system (CS) are its responsibility. Therefore, more direct, and thus often more suitable, coordination of the scheduling decision is possible (Agha et al., 2010). Several mechanisms to coordinate a PS's temporal course of FES demand with the eCS exist. Most of these mechanisms are price driven (see Ashok, 2006; Castro, Harjunkoski, & Grossmann, 2011), but there are also event-driven approaches (Sun & Li, 2014). The mechanism itself is categorized within the energy supply dimension. If reduction of the energy demand is achieved in more than one system, EES approaches can be classified by a combination of the three attributes PS, iCS, and eCS. To achieve such an energy reduction, not only the energy supply characteristics specified in the following section but also the specific characteristics of the PS concerning the energy demand are of central importance (see Section 3.3).

3.2. Energy supply

By means of this dimension, the scheduling relevant characteristics of the energy supply, i.e., the provisioning of the PS with FES and AES, are specified. For this purpose, two basic categories are used: "internal infrastructure" and "coordination mechanism". The internal infrastructure category describes the (technical) infrastructure of the primary actor and thus the interdependencies between the PS and the iCS. Therefore, this category is strongly correlated with EES approaches that address iCSs. In contrast, the category coordination mechanism is mainly correlated with eCS-related approaches. Because EES approaches that are classified exclusively with PS are generally independent of the technical infrastructure, the energy supply dimension is typically not relevant. Exceptions are approaches that are based on energy recovery systems.

With respect to coordination mechanisms, we distinguish between price-driven and event-driven demand response mechanisms. In the context of demand-side management (e.g., Merkert et al., 2014), demand response is defined as "changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (Kathan, 2012). Here, we use demand response and related concepts in a broader sense and address not only electricity but also energy in general. Because the terms and definitions used in the demand-side management and demand-response literature are not always consistent, we do not use all of them but instead only adopt the relevant ones as necessary. Event-driven demand response mechanisms aim to reward energy users for adjusting their energy demand in response to certain events, such as extreme weather conditions or generation-equipment failures (e.g., Sun & Li, 2014). Because this mechanism is rarely used in the industrial context, no further differentiation is made here. In price-driven demand response approaches, FES rates (which are defined by the energy provider) vary over time to encourage energy users to change the temporal course of their FES demands. For this type of approach, four combinable mechanisms and corresponding attributes are defined: time of use, critical peak pricing, real-time pricing, and load curve penalties. The first three have time based rate prices and the latter one has a power based rate price. In a time-of-use environment, energy prices are defined in advance for periods of a day, week, month, or year (e.g., Shrouf, Ordieres-Meré, García-Sánchez, & Ortega-Mier, 2014). In real-time pricing environments, energy rates change at least every hour. In critical peak pricing environments, basically energy demand peaks are penalized by higher rates (e.g., Ashok, 2006). Critical peak pricing environments could be further differentiated: fixed-period critical peak pricing, variable-period critical peak pricing, variable peak pricing, and critical peak rebate. Because none of the analyzed scheduling approaches uses one of these variants explicitly, they are subsumed by critical peak pricing. A more direct mechanism to coordinate several FES demand courses is load curve penalties. In this setting, energy demand courses are negotiated between energy providers and users (e.g., Nolde & Morari, 2010). Therefore, the energy demand courses of several energy users can be (directly) coordinated by an energy provider to improve energy efficiency at the eCS. These coordination mechanisms can also be used to coordinate iCSs and PSs.

As stated above, more direct coordination of PS and iCS is possible. This coordination is enabled by direct consideration of the internal infrastructure and its technical characteristics through the EES approach. Because these technical characteristics are very application specific, we only specify general types of CUs and basic components of the energy supply system. Therefore, we distinguish among "heat" (e.g., Rager et al., 2014), "cold" (e.g., Halim & Srinivasan, 2011), "power" (e.g., Moon & Park, 2014), and "combined heat and power" (e.g., Agha et al., 2010) conversion units. Special structures include iCSs with an energy storage system (e.g., Moon & Park, 2014), iCSs that use multiple energy sources (e.g., Küster, Lützenberger, Freund, & Albayrak, 2013), and energy recovery systems (e.g., Halim & Srinivasan, 2011). Such an energy recovery system is often combined with an energy storage system (e.g., Seid & Majozi, 2014a). With respect to scheduling, the absence of an energy storage system in a recovery system (direct integration) requires stricter scheduling conditions than does indirect integration based on an energy storage system (Fernández, Renedo, Pérez, Ortiz, & Mañana, 2012).

3.3. Energy demand

This dimension describes the energy demand characteristics that are utilized by an EES approach to increase the energy efficiency. Concerning these characteristics, two categories are defined: "non-processing energy demand" and "processing energy demand". This division into two categories and the corresponding attributes are based on the reviewed literature (in particular see Liu, Dong, Lohse, Petrovic, & Gindy, 2014c) and on several preceding works regarding energy consumption in manufacturing environments (Dahmus & Gutowski, 2004; Dietmair & Verl, 2009; Fysikopoulos et al., 2014; Li, He, Wang, Yan, & Liu, 2014; Peng & Xu, 2013; Seow & Rahimifard, 2011; Vijayaraghavan & Dornfeld, 2010).

Non-processing energy demand arises whenever energy is used within the production process but no value is added to the product during that period of energy usage. The attributes in this category are "machine turn on" (e.g., Shrouf et al., 2014), "machine idle" (e.g., Luo et al., 2013), "machine setup" (e.g., Eren & Gautam, 2011), "machine turn off" (e.g., Liu et al., 2014b), and "material storage" (e.g., Halim & Srinivasan, 2009). The first four attributes represent certain states of machines (PUs), each of which is associated with an individual demand for energy. A more general concept to represent different states of PUs is used by Sun and Li (2014), who define a set of hibernation states. Because this concept is less meaningful for describing EES approaches, it is not used here. The last attribute, material storage, represents the effect of energy losses of a product (e.g., heated steel) during its storage in a buffer or warehouse (e.g., Solding, Petku, & Mardan, 2009).

Processing energy demand arises when energy is used to immediately transform inputs to a desired output. These processing energy demands can depend on several non-exclusive characteristics. First, they can be "machine related" (e.g., Castro et al., 2011), i.e., a certain amount of energy is required by the machine for processing, independent of the current product (job) to be processed. Second, they can be "job related" (e.g., Agha et al., 2010), i.e., the AES demand is defined by the jobs' data. A special type of job-related energy demand is "varying job-related" energy demands. Here, the energy demand of a job (e.g., in a parallel machine environment; Rager et al., 2014) or its operations (e.g., in a job shop environment; He, Li, Wu, & Sutherland, 2014) varies in a predefined way during its processing. The AES demand per period can also be subject to scheduling decisions. In this case, in contrast to a defined AES demand per period, a total AES demand is determined by the machines' or jobs' data, and the scheduling approach decides the intensity (e.g., speed) at which the job is processed (e.g., Fang, Uhan, Zhao, & Sutherland, 2013). This type of demand is called a "flexible" energy demand. All of the attributes that describe processing energy demand can be combined to classify a scheduling approach. For example, Fang, Uhan, Zhao, and Sutherland (2011) consider job-related and machine-related energy demands. Artigues, Lopez, and Haït (2013) consider varying job-related energy demands and decide the energy given to the PU; thus, they consider a flexible energy demand.

3.4. *The framework at a glance*

The three dimensions, their categories, and the attributes of the proposed research framework for EES are summarized in Fig. 4.

The abbreviations in Fig. 4 can be used to classify an EES approach in terms of the three dimensions C|S|D (in a manner similar to the traditional $\alpha|\beta|\gamma$ classification scheme for deterministic scheduling problems; Błażewicz, Ecker, Pesch, Schmidt, & Węglarz, 2007).

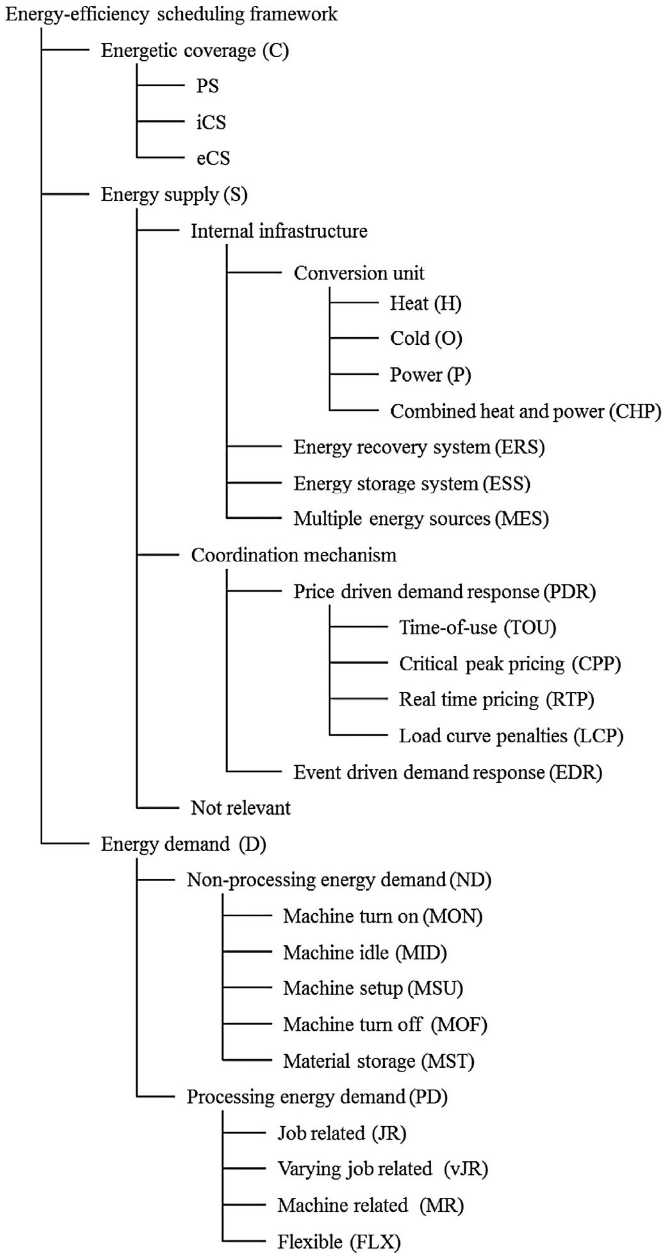

Fig. 4. EES framework.

4. Literature classification and empirical analysis

The three dimensions of the EES framework constitute the core of the following literature classification of the relevant articles. However, we not only classify each of the relevant articles in terms of the attributes of the framework but also use additional attributes that describe their objective criteria and system of objectives, the underlying manufacturing model, the type of (optimization) model, and the applied solution method. Because of the limited space within this paper, we only present the additional attributes at an aggregated (category) level (the fully detailed classification is provided as supplementary data).

In addition to the classification, we present some empirical results to highlight specific topics.

4.1. *Literature classification*

The increase in the number of articles addressing EES in recent years is significant (see Fig. 5; the year 2015 is not considered in this analysis) and reflects an overall increased awareness of sustainability. This increase is not accompanied by a focus on particular topics or scheduling problems, as can be observed from the following literature classification (see Tables 3 and 4).

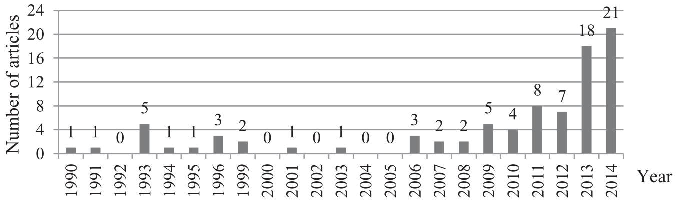

Fig. 5. Temporal development.

Table 3

Literature classification – part one (Boukas, Haurie & Soumis, 1990; Janiak, 1991; Nilsson & Söderström 1993; Nilsson, 1993; Mignon & Hermia 1993; Kondili, Shah, & Pantelides, 1993b; Kondili, Pantelides, & Sargent, 1993a; Papageorgiou, Shah, & Pantelides, 1994; Lee & Reklaitis, 1995; Mignon & Hermia, 1996; Boyadjiev et al., 1996; Georgiadis et al., 1999; Grau et al., 1996; Özdamar & Birbil 1999; Georgiadis & Papageorgiou, 2001; Adonyi, Romero, Puigjaner, & Friedler, 2003; Subaï, Baptiste, & Niel, 2006; Majozi, 2006; Ashok, 2006; Zhang & Hua, 2007; Mouzon et al., 2007; Mouzon & Yildirim, 2008; Babu & Ashok, 2008; Solding et al., 2009; Majozi, 2009; Halim & Srinivasan, 2009; Chen & Chang, 2009; Castro, Harjunkoski, & Grossmann, 2009; Yusta, Torres, & Khodr, 2010; Nolde & Morari, 2010; He & Liu, 2010; Agha et al., 2010; Wang, Li, & Huang, 2011; Halim & Srinivasan, 2011; Haït & Artigues, 2011b; Haït & Artigues, 2011a; Fang et al., 2011; Eren & Gautam, 2011; Castro et al., 2011; Capón-García, Bojarski, Espuña, & Puigjaner, 2011; Yildirim & Mouzon, 2012; Théry et al., 2012; Tang, Che, & Liu, 2012; Mitra, Grossmann, Pinto, & Arora 2012).

	Boukas et al. (1990)	Janiak (1991)	Nilsson & Söderström (1993)	Nilsson (1993)	Mignon & Hermia (1993)	Kondili et al. (1993b)	Kondili et al. (1993a)	Papageorgiou et al. (1994)	Lee & Reklaitis (1995)	Mignon & Hermia (1996)	Grau et al. (1996)	Boyadjiev et al. (1996)	Özdamar & Birbil (1999)	Georgiadis et al. (1999)	Georgiadis & Papageorgiou (2001)	Adonyi et al. (2003)	Subaï et al. (2006)	Majozi (2006)	Ashok (2006)	Zhang & Hua (2007)	Mouzon et al. (2007)	Mouzon & Yildirim (2008)	Babu & Ashok (2008)	Solding et al. (2009)	Majozi (2009)	Halim & Srinivasan (2009)	Chen & Chang (2009)	Castro et al. (2009)	Yusta et al. (2010)	Nolde & Morari (2010)	He & Liu (2010)	Agha et al. (2010)	Wang et al. (2011)	Halim & Srinivasan (2011)	Haït & Artigues (2011b)	Haït & Artigues (2011a)	Fang et al. (2011)	Eren & Gautam (2011)	Castro et al. (2011)	Capón-García et al. (2011)	Yildirim & Mouzon (2012)	Théry et al. (2012)	Tang et al. (2012)	Mitra et al. (2012)
Energetic coverage																																												
PS		x			x		x	x	x		x	x	x	x	x	x	x	x		x	x	x			x	x	x				x		x	x		x	x	x		x	x		x	
iCS										x										x					x							x										x		
eCS	x		x	x		x													x				x	x				x	x	x					x		x		x					x
Energy supply																																												
IS																																												
CS																																												
H										x															x																			
O																									x																			
P																																												
CHP																				x												x										x		
ERS								x	x		x	x		x	x	x		x							x	x	x							x										
ESS								x	x						x										x																			
MES																																												
CM																																												
PDR																																												
TOU			x	x		x													x				x	x				x	x										x					x
CPP	x																		x					x													x		x					
RTP																																												
LCP																														x					x									
EDR																																												
Energy demand																																												
NE																																												
MON													x								x																							x
MID																					x	x									x										x		x	
MSU													x		x							x																x		x	x			
MOF																					x																							
MST																								x										x										
PE																																												
JR	x	x				x		x				x				x			x							x	x	x			x	x	x	x			x	x	x			x		x
vJR							x		x	x	x																									x								
MR			x	x	x	x	x						x	x			x	x	x	x	x	x	x	x	x			x	x	x	x				x	x	x		x	x	x		x	x
FLX		x	x	x											x														x							x	x							
Objective criteria																																												
Monetary			x	x		x	x	x				x	x	x	x		x	x	x	x			x	x	x	x	x	x	x	x		x		x	x	x		x	x	x		x	x	x
Non-monetary	x	x	x	x	x	x			x	x	x	x		x		x	x	x	x		x	x	x	x	x	x		x			x	x	x	x	x	x	x	x	x	x	x	x		x
System of objectives																																												
Multi-objective											x										x	x		x							x			x			x	x		x	x			
Single objective	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x			x		x	x	x	x	x	x		x	x		x	x			x			x	x	x
Manufacturing model																																												
1			x	x																	x	x							x				x					x			x			
P	x					x							x			x												x			x					x								x
F		x			x		x	x	x	x	x	x						x	x	x				x	x	x	x			x		x		x	x		x		x	x		x	x	
J/PS																							x									x												
HS																	x																											
Other														x	x																													
Model type																																												
LP											x								x																									
MIP		x	x	x		x	x	x	x				x	x	x	x		x		x	x						x	x		x	x	x		x	x	x	x		x		x	x		x
MIQP																																												
MINLP	x							x				x			x		x					x	x		x	x			x											x			x	
QT & Sim.					x					x														x																				
Other analytical model																																	x					x						
Solution method																																												
Heuristic	x	x									x		x								x	x				x								x		x		x			x		x	
Exact						x	x	x								x					x													x										
Standard solver									x					x	x		x	x	x	x			x		x		x	x		x		x			x	x	x		x	x		x	x	x

Table 4
Literature classification – part two (Liu et al., 2012; He et al., 2012; Bruzzone et al., 2012; Zhang et al., 2013a; Wang & Li, 2013; Tan, Huang, & Liu, 2013; Moon et al., 2013; Mashaei & Lennartson, 2013; Luo et al., 2013; Le & Pang, 2013; Küster et al., 2013; Ji et al., 2013; Hadera & Harjunkoski, 2013; Fernandez et al., 2013; Fang et al., 2013; Fang & Lin, 2013; Dai, Tang, Giret, Salido, & Li, 2013; Chen et al., 2013; Castro, Sun, & Harjunkoski, 2013; Artigues et al., 2013; Adekola, Stamp, Majozi, Garg, & Bandyopadhyay, 2013; Zhang, Zhao, Fang, & Sutherland, 2014; Zheng & Wang, 2014; Zanoni, Bettoni, & Glock, 2014; Tan & Liu, 2014; Sun et al., 2014; Sun & Li, 2014; Shrouf et al., 2014; Seid & Majozi, 2014b; Seid & Majozi, 2014a; Rager et al., 2014; Pach et al., 2014; Moon & Park, 2014; Mattik, Amorim, & Günther, 2014; Liu et al., 2014c; Liu et al., 2014b; Liu et al., 2014a; Liu & Huang, 2014; Kong et al., 2014; He et al., 2014; Brundage et al., 2014; Bego et al., 2014; Lei & Guo, 2015).

	Liu et al. (2012)	He et al. (2012)	Bruzzone et al. (2012)	Zhang et al. (2013a)	Wang & Li (2013)	Tan et al. (2013)	Moon et al. (2013)	Mashaei & Lennartson (2013)	Luo et al. (2013)	Le & Pang (2013)	Küster et al. (2013)	Ji et al. (2013)	Hadera & Harjunkoski (2013)	Fernandez et al. (2013)	Fang et al. (2013)	Fang & Lin (2013)	Dai et al. (2013)	Chen et al. (2013)	Castro et al. (2013)	Artigues et al. (2013)	Adekola et al. (2013)	Zhang et al. (2014)	Zheng & Wang (2014)	Zanoni et al. (2014)	Tan & Liu (2014)	Sun et al. (2014)	Sun & Li (2014)	Shrouf et al. (2014)	Seid & Majozi (2014b)	Seid & Majozi (2014a)	Rager et al. (2014)	Pach et al. (2014)	Moon & Park (2014)	Mattik et al. (2014)	Liu et al. (2014c)	Liu et al. (2014b)	Liu et al. (2014a)	Liu & Huang (2014)	Kong et al. (2014)	He et al. (2014)	Brundage et al. (2014)	Bego et al. (2014)	Lei & Guo (2015)
Energetic coverage																																											
PS	x	x	x	x				x		x	x	x			x	x	x	x			x		x	x					x	x		x		x	x	x	x			x			x
iCS				x							x																				x		x										
eCS					x	x	x		x		x		x	x					x	x		x	x		x	x	x	x					x					x	x		x	x	
Energy supply																																											
IS																																											
CS																																											
H				x																											x												
O				x																																							
P																																	x										
CHP				x							x																																
ERS				x																	x								x	x													
ESS																					x									x			x										
MES											x																						x										
CM																																											
PDR																																											
TOU					x	x	x		x				x	x					x			x			x	x		x					x								x		
CPP																				x			x										x					x	x			x	
RTP																																											
LCP											x		x						x																								
EDR																											x																
Energy demand																																											
NE																																											
MON								x									x											x								x							
MID		x						x	x								x	x						x			x	x				x			x	x		x					x
MSU																								x																x			
MOF								x									x											x								x							
MST																									x									x									
PE																																											
JR			x					x		x			x		x		x		x			x		x					x								x	x					
vJR											x									x			x							x	x				x				x	x			
MR	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x	x	x				x	x		x	x	x	x		x	x	x	x
FLX															x	x	x			x			x															x	x				
Objective criteria																																											
Monetary				x	x	x	x		x	x	x		x	x					x	x	x	x		x	x	x		x	x	x			x					x	x		x	x	
Non-monetary	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x
System of objectives																																											
Multi-objective	x	x					x		x		x		x			x	x		x			x	x	x								x			x	x	x	x	x	x			x
Single objective			x	x	x	x		x		x		x		x	x			x		x	x			x	x	x	x	x	x	x	x		x	x							x	x	
Manufacturing model																																											
1																												x								x							
P				x			x					x				x				x											x								x				
F		x	x		x	x		x	x		x		x	x	x		x	x	x		x	x		x	x	x	x		x					x				x			x	x	
J/PS										x													x							x		x	x		x					x			x
HS	x																																										
Other																																					x						
Model type																																											
LP																												x															
MIP			x			x	x			x		x	x		x	x	x		x	x		x	x										x	x	x		x			x			
MIQP																																	x										
MINLP	x			x	x			x						x							x			x	x	x			x	x	x					x			x			x	
QT & Sim.		x			x						x																					x									x		
Other analytical model											x							x									x																
Solution method																																											
Heuristic			x		x		x	x	x		x	x			x	x	x	x		x			x		x			x			x	x	x		x	x	x	x	x	x			x
Exact								x		x		x												x	x																		
Standard solver	x		x	x		x							x	x	x	x			x	x	x				x	x			x	x	x		x	x								x	

With respect to the objective criteria, we distinguish between the categories "monetary" and "non-monetary". The first category summarizes the criteria of "profit", "energy costs", "(other) production costs", and "penalty costs". The second category contains traditional scheduling objectives that are used by at least one of the EES approaches: "total completion time (makespan)", "total (weighted) tardiness", "maximum tardiness", "total throughput (production volume)", "demand fulfillment", and "product quality". In addition, we use the attribute "necessary energy" to indicate approaches that directly consider the amount of energy used within their objective systems. The objective system is also described according to two categories. The "multi-objective" category includes the attributes of "weighted sum", "Pareto efficiency", and "lexicographical ordering".

The category of "single objective" primarily represents EES approaches with a single, cost-oriented, objective function. Often, a single-objective function is combined with a special constraint that represents a satisficing objective. Therefore, we use the attributes "demand fulfillment constraint", "energy use constraint", and "makespan constraint" to mark the corresponding approaches. The underlying manufacturing model is classified as "single machine" (1), "parallel machines" (P), "flow shop" (F), "job shop/project scheduling" (J/PS), or "hoist scheduling" (HS). The model type is differentiated by the attributes "linear program" (LP), "mixed integer (linear) program" (MIP), "mixed integer quadratic (constrained) program" (MIQP), "mixed integer non-linear program" (MINLP), "queuing theory and simulation" (QT & Sim.), and "other analytical model" (e.g., Markov decision model). The last attribute represents approaches without an explicit mathematical optimization. In addition, some approaches do not specify a model. The solution method is classified according to the three categories of "heuristic", "exact", and "standard solver". The corresponding attributes for the first two categories are described and analyzed in detail below. The "standard solver" category represents commercial solvers like CPLEX, Gurobi, Xpress, DICOPT, and LINGO.

The results presented in Tables 3 and 4 can be summarized as a set of major findings. With respect to energetic coverage, the majority of relevant articles exclusively cover the production system. Approaches that focus on the iCSs are rare, only a few articles address combinations of systems (PS + iCs or PS + eCS), and only one article addresses all three systems (PS + iCS + eCS). Only a minority of EES approaches incorporate the internal infrastructure and for most of those approaches, heat is provided by the conversion system. If an approach uses a coordination mechanism, then it is normally price-driven, and time-of-use prices constitute the most widespread demand-response approach. The EES literature considers processing energy demands in more cases than non-processing energy demand and very often considers machine-related energy demands. With respect to the manufacturing model, job shops are widely neglected, whereas flow shops dominate. If we were asked to quote the most typical EES problem, we would state that no clear answer is possible.

Selected categories in Tables 3 and 4 are investigated in detail in the two following sections, in which additional information regarding previously unaddressed aspects (e.g., the applied energy sources used) is given.

4.2. Industry sector and applied energy sources

In this section, the relevant literature is analyzed to reveal the application of EES approaches in practice. Therefore, the articles are classified according to their industrial sectors (as defined and numbered by the "International Standard Industrial Classification of All Economic Activities (ISIC)"; United Nations, Department of Economic and Social Affairs, 2008). To complete this practice-oriented analysis,

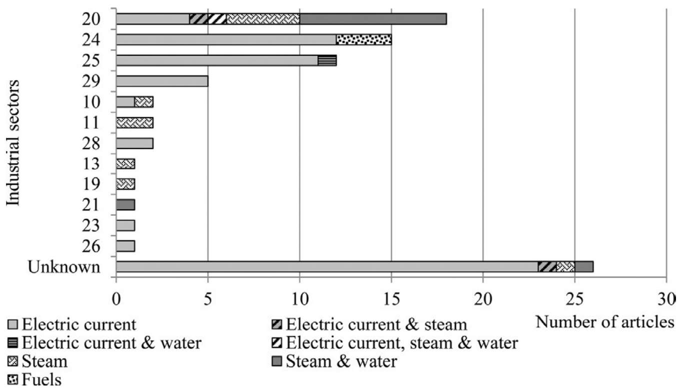

Fig. 6. Industrial sectors and applied energy sources.

we additionally identify the coherence of the industrial sector and type of AES. Fig. 6 shows the results of this analysis.

The majority of articles are located either in the sector of "20 – chemicals and chemical products", "24 – basic metals", or "25 – fabricated metal products, except machinery and equipment". Other relevant sectors are: "29 – motor vehicles, trailers and semi-trailers", "10 – food products", "11 – beverages", "28 – machinery and equipment", "13 – textiles", "19 – coke and refined petroleum products", "21 – basic pharmaceutical products and pharmaceutical preparations", "23 – other non-metallic mineral products", and "26 – computer, electronic and optical products". For 26 articles, the industrial sector is not specified ("unknown").

The number of industrial sectors that apply EES is very small compared to the total number of sectors specified in United Nations, Department of Economic and Social Affairs (2008). Obviously, energy-intensive industries tend to use EES approaches more often. As observed from the different colors in the figure, most approaches address planning problems using the AES "electric current". The second-most-used AES is "steam", which is typically connected to the use of "water". However, "fuels" are only of interest in the "basic metals" sector. Generally, Fig. 6 notes that there is a strong link between the industrial sector and the type of AES used.

4.3. Objective system, model types, and solution methods

The aim of this section is to enrich the literature analysis with scientific insights. As a first step, the "monetary/non-monetary" distinction of Tables 3 and 4 is broken down in more detail in Fig. 7. The different methods for modeling those objectives within an objective system are shown in Fig. 8. Finally, this scientific analysis is completed with a discussion of the model types used and the associated solution methods.

EES approaches mostly incorporate energy efficiency by modeling energy-related objective criteria (57.5 percent consider energy costs

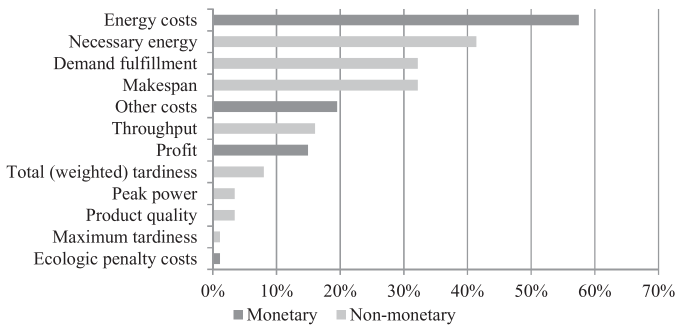

Fig. 7. Relative usage of objective criteria.

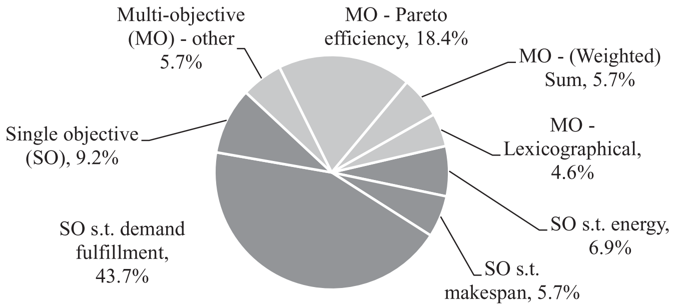

Fig. 8. Objective systems.

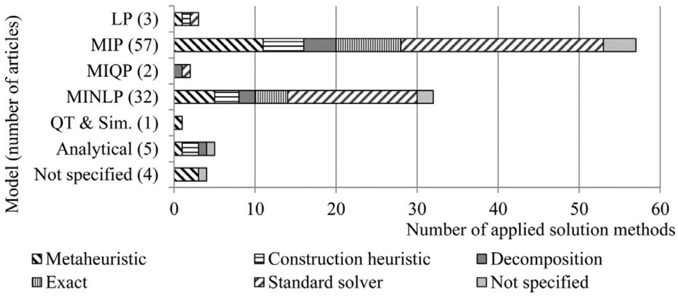

Fig. 9. Types of EES models.

and 41.4 percent consider necessary energy, i.e., the amount of energy used) in their objective system instead of using constraints. This result indicates that as soon as energy is considered, it is at least equally as important as traditional criteria. If other objectives are considered, then "demand fulfillment" and "makespan" are used in the majority of cases.

The objective criteria are modeled as single-objective functions in 65.5 percent of all scheduling approaches and incorporate a demand-fulfillment constraint most of the time (see Fig. 8). If a multi-objective approach is used, then Pareto efficiency is usually applied.

Beyond the question of whether the objective system is modeled by a single- or a multi-objective approach, an interesting aspect regarding the formulation of the EES models is shown in Fig. 9.

Potentially hard-to-solve MIPs and MINLPs are used quite often, whereas easier-to-solve LPs account for a minority of models. Despite this situation, standard solvers are used frequently, and metaheuristics are often used to solve the models. Note that solution methods can be used in combination (e.g., simulation and metaheuristics) or more than one solution method can be used to solve a model.

5. Energy-efficient scheduling – the benefits in numbers

The following brief description of the benefits of EES approaches aims to demonstrate that these approaches can make a substantial contribution to the more sustainable production of goods. In this section, we describe the benefits of all of the articles that are explicitly described as based on a real-world application case. The energetic coverage of the first group of articles is PS; that of the second is eCS; that of the third is iCS; and that of the fourth is PS and iCS.

Mignon and Hermia (1993) (PS||MR) demonstrate that better standardization of a brewing plant combined with limitation of steam availability and adequate production planning can reduce energy demand by up to 46 percent. Through the optimum timing of tasks in a batch-sequencing problem in the chemical industry, Grau, Graells, Corominas, Espuña, and Puigjaner (1996) (PS|ERS|vJR) achieve an energy saving of 13.2 percent by accepting an increase in the accumulated makespan of 1.36 percent. For a leading ceramic wall and floor tile manufacturer in Turkey, Özdamar and Birbil (1999) (PS||MON,MSU,MR) can reduce the overall costs (energy and inventory holding costs) by 9.5 percent; the energy costs increase by 6.9 percent but the inventory holding costs decrease by 78.9 percent. Majozi (2006) (PS|ERS|MR) analyzes the heat integration of multipurpose batch plants. Compared with the standalone mode without heat integration, the profit can be improved by 18.5 percent. Thereby, the throughput is unaltered, but the utility demands for steam and cooling water are reduced from 12 tons to zero tons and from 20 tons to 18 tons, respectively. The machining shop floor of a gear-producing facility is used in a case study presented by He and Liu (2010) (PS||MID,JR,MR). Those authors report savings of 1.88 kilowatt-hours when processing only seven jobs and they state that this amount would increase proportionally with the number of jobs processed. Liu, Zhao, and Xu (2012) (PS||MR) consider an electroplating line with 16 processing units in their cycle hoist scheduling case study. The original cycle time for this electroplating line is 538 seconds with an electric current demand of 13.85 kilowatt-hours per cycle and 42.8 liters/minute of freshwater consumption. The new EES approach achieves an increase in the production rate by 6 percent, a decrease in the electric current demand by 6 percent, and a decrease in freshwater consumption by 20 percent. To demonstrate the application of their EES approach, He, Liu, Zhang, Gao, and Liu (2012) (PS||MID,MR) use a real-world example of two jobs (parts of a hobbing machine tool). Selecting an appropriate process (batching) scheme for the two jobs leads to energy savings of 8.9 percent. Moreover, the minimal makespan is achieved by this process scheme. Chen, Zhang, Arinez, and Biller (2013) (PS||MID,MR) investigate a painting shop in an automotive assembly line that is responsible for approximately 60 percent of the total energy used in an automotive assembly plant (in 2000, $420 million energy expenditures in 37 U.S. automotive assembly plants). The total energy demand and demand per part are reduced by 5.34 percent and 7.33 percent, respectively. Seid and Majozi (2014a) (PS|ERS|JR) report the benefits for a petrochemical plant described in Kallrath (2002). Their approach is able to reduce the steam usage and cooling water usage by 83 percent and 80.9 percent, respectively. Thus, profit is improved by 20 percent. Liu et al. (2014b) (PS||MON,MID,MOF,MR) demonstrate the suitability of their EES approach through its application to a Chinese machinery and equipment manufacturer. They achieve energy savings of as much as 37.3 percent (22.5 percent) when accepting makespan degradation of 9.1 percent (1.3 percent).

Solding et al. (2009) (eCS|TOU,CPP|MST,MR) report in a case study for a medium-sized Swedish steel foundry a reduction of electric-current demand of 5 percent (with a constant productivity). Nilsson and Söderström (1993) investigate three cases (a dairy, a part of a steel process, and a salt bath in the mechanical engineering industry) with identical energy characteristics (eCS|TOU|MR,FLX). The energy costs can be reduced by 0.2 percent (dairy), 3.3 percent (steel), and 9.6 percent (salt bath). The case study of Babu and Ashok (2008) (eCS|TOU|MR) evaluates a typical caustic-chlorine plant in India. Depending on the tariff (I, II, and III), their scheduling approach results in the following annual savings of electric current costs: 3.97 percent (15.93 million INR), 9.06 percent (54.48 million INR), and 0.41 percent (1.8 million INR), respectively. Even if the annual savings are not significant (tariff III), the peak demand reductions are impressive: 19.3 percent, 17.16 percent, and 18.34 percent. Mitra, Grossmann, Pinto, and Arora (2012) (eCS|TOU|MON,JR,MR) investigate two different air separation plants: a plant with one liquefier and a plant with two liquefiers. The evaluation of these two plants combined with five different demand settings results in mean energy savings of 7.75 percent. Fernandez, Li, and Sun (2013) (eCS|TOU|MR) investigate a section of an automotive assembly line comprising of seven machines and six buffers. Their case study shows a reduction of the power demand during peak periods by 20.1 percent and a corresponding cost reduction by 20.1 percent, whereby the throughput nearly is constant. The same problem is addressed by Sun, Li, Fernandez, and Wang (2014), but the authors reduce the relative importance of the throughput objective.

However, the latter reported throughput is only 1.27 percent worse, the peak power demand and the total costs are lower: 8.7 percent and 8.6 percent, respectively. A two-stage flow shop is analyzed by Liu and Huang (2014) (eCS|CPP|MID,JR,MR,FLX). The results reveal a significant trade-off between the total weighted tardiness and peak electric current demands. If on-time delivery has first priority, a minimum total weighted tardiness can be achieved, at the expense of a high peak demand of 8.44 kilowatt. If the peak electric current demand has first priority, it can be reduced to 6.98 kilowatt. This reduction comes along with a total weighted tardiness that is approximately 50 times larger.

Kong, Chai, Ding, and Yang (2014) optimize the energy efficiency of a magnesia-smelting plant (eCS|CPP|vJR,FLX). Their case study demonstrates that the proposed multifurnace optimization strategy can increase production output by 12.30 percent (8.85 tons/day), reduce the use of magnesia by approximately 0.46 percent, and reduce electric-current demand by 2.36 percent (1419 CNY/day). Sun and Li (2014) (eCS|TOU,CPP|MID,MR) develop the only event-driven demand-response EES approach to date and reduce electric-current demand by 22.6 percent at the expense of a throughput decrease of 0.2 percent.

Mignon and Hermia (1996) (iCS|H|vJR) primarily address the operating costs of a brewery's boiler house. The efficiency improvement ranges from 0.7 percent to 3.2 percent (depending on the boiler house's operating policy). These improvements result in an annual fuel cost savings of between 0.21 and 0.95 million BEF. The authors also consider some rules of thumb for boiler house design and estimate the effects of EES on strategic boiler house design. With respect to the highest peak energy demand that results from EES, the investment costs could be reduced by 44 percent (8.2 million BEF). The scheduling of a parallel machine manufacturing model in a textile company is investigated by Rager et al. (2014) (iCS|H|vJR). Their evaluation of several scenarios (with a different number of jobs) demonstrates a reduction of the conversion unit's fuel costs by 20.5 percent on average.

A second approach by Majozi (2009) considers not only an energy recovery system but also its combination with an energy storage system and interdependencies with the iCS (PS,iCS|H,O,ERS,ESS|MR). In their case study, direct and indirect heat integration result in a 90 percent reduction of external steam requirements. Additionally, without using the energy storage capabilities, the external cold utility requirements decrease by 25 percent; when using the storage system, the external cold utility requirements decrease by 25 percent. Simultaneously, the profit increases by 5.22 percent and 6.45 percent, respectively. Zhang, Luo, Chen, and Chen (2013a) analyze two refineries (both of which are classified as (PS,iCS|H,O,CHP,ERS|MR)) and three energy integration levels. In the first case, the resulting energy costs of 7508 CNY/hour, 6509 CNY/hour, and 6013 CNY/hour indicate that the lowest cost can be achieved with "a complete steam integration between process plants and utility systems" (level 3; Zhang et al., 2013a). This observation is confirmed by the energy costs for the second case: 12,168 CNY/hour, 956 CNY/hour, and -3323 CNY/hour, where the energy expenses become revenue for the level-3 integration.

Generally, the benefits of EES can be underlined and emphasized by the energy savings reported in the aforementioned articles. Nevertheless, sometimes, energy savings are accompanied by degradation of other objective criteria. In these cases, a reasonable trade-off must be found.

6. Conclusion

The growing concern about sustainability in recent years has led to increased attention to incorporating sustainability aspects into operational production planning. Because energy has a substantial impact on manufacturing companies' sustainable development, it is of utmost importance to enhance energy efficiency. Whereas the adoption of new and improved production equipment is a broadly acknowledged method of achieving more efficient production processes, EES approaches offer great (additional) potential to increase energy efficiency. This potential is substantiated by the fact that scheduling is an organizational measure and thus does not require high investment costs. Consequently, a strong boost in the number of EES publications in recent years can be observed (see Section 4), and the reported benefits are remarkable (see Section 5).

Although the growing number of publications to consider EES is welcome, the speed of the growth and transdisciplinarity of the researchers involved (including chemists, engineers, mathematicians, operations researchers, computer scientists, among other) has resulted in a very heterogeneous research field and ambiguous terms and definitions. Furthermore, it is often difficult to classify research and to assess the aims, scopes, and conditions of the different approaches. To unify the research stream regarding EES, a common framework is desperately needed. In this article, we propose such a framework to classify the literature and to help scholars both structure research about EES and detect opportunities for further research.

Among other advantages, the EES framework enables us to carve out the two alternatives to improve energy efficiency: EES can influence the total amount of AES demand and/or the course of that demand. Whereas reductions in total AES demand reduce the energy demand of the PS, changes in the course of the AES demand improve the efficiency of the energy conversion in the upstream iCS or the eCS. PSs and iCSs belong to the manufacturer; therefore, energy efficiency criteria can be directly integrated into the objective system. In contrast, a coordination mechanism (usually pricing) is needed to connect the eCS with the iCS and PS. Thus, the energy supplier defines incentives for EES at the manufacturing company. Accordingly, from the perspective of the manufacturing company, eCS-related approaches can be characterized as "reactive" (the company reacts to the incentives of the energy provider), and iCS- and PS-related approaches can be classified as "active" (the company actively decides the energy supply). Another aspect of the approaches classified as PS and iCS is the possibility of directly measuring energy demand reductions and, e.g., the corresponding greenhouse gas emission reductions. Together, these two aspects can be used to influence consumer perception of the company, e.g., by actively reporting about reduced emissions (e.g., Garetti & Taisch, 2012; Jayaraman, Singh, & Anandnarayan, 2012).

Based on the literature classification that accompanies the EES framework, we can identify several opportunities for further research. The inclusion of energy leads to increased complexity for two reasons. On the one hand, in addition to traditional objectives, energy-oriented objectives are considered; thus, multi-objective optimization models arise. On the other hand, the (technical) characteristics of energy supply and demand often lead to non-linear constraints. Despite the high complexity of most models, the use of standard solvers prevails. Thus, perhaps more specialized solution methods (as are common for traditional scheduling) must be developed to improve the performance and the ability to treat increasingly comprehensive problems. Simultaneously, benchmark instances must be developed to enable comparisons of solution methods.

Before developing such efficient solution methods, a deeper understanding of the scheduling-relevant energy characteristics of the involved systems and the corresponding interdependencies seems necessary. To achieve such an understanding, researchers from different disciplines must collaborate in a structured manner. The proposed EES framework –including its dimensions, categories, and attributes used to classify scheduling approaches – could be a first step to achieve this goal and thus to foster sustainability in manufacturing.

Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ejor.2015.07.017.

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