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Making sustainability paradigms a part of PPC

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Abstract

The mounting pressure of the European legislative to improve the sustainability of production operations prompts companies to implement sustainability paradigms into their production planning and control (PPC). First results from an ongoing European project will show how the innovative Resource Networks Methodology can be used to alter the production organisation accordingly. In particular, novel PPC strategies improving the integration of renewable energy sources and other resource efficient technologies by using previously identified levels of flexibility will be presented. These are complemented by an approach for unifying the readiness levels for application (RLA) of similar methodologies. The latter will assist decision making during the development phase and in preparation for industrial implementations.

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1. Introduction

The “2020 climate and energy package” enacted by the EU aims to reduce the emission of greenhouse gases, to increase the reliance of renewable energy sources and to improve the overall energy efficiency [1]. Individual member states work towards these targets by changing their legislation, especially for the energy, production and transportation sectors. Typically, efficiency improvements in production facilities are reached by introducing more efficient equipment (e.g. new machines), reducing or recycling waste (e.g. better building isolation or utilisation of heat recovery), increasing staff awareness (e.g. energy trainings) or changing the production organisation (e.g. energy-aware production scheduling). While the earlier are state of the art in many companies, the latter still holds considerable potential for improvement.

This paper expands the Resource Networks Methodology (RNM) [2] and discusses how it makes sustainability paradigms a part of production planning and control (PPC). Complementarily, approaches for unifying the readiness levels and monetarily assessing similar methodologies are presented. Leading there, the following section summarises a state of the art and the fundamental concept of Resource Networks (RN).

2. Sustainable PPC and Resource Networks

PPC is a crucial part of any production organisation. It is responsible for ensuring that production aims are met and available resources are used efficiently. The introduction of sustainability paradigms in this context has previously been attempted (see 2.1), albeit mostly incomplete. Section 2.2 describes a more suitable approach based on Stoldt et al. [2].

2.1. State of the art

Sustainability consists of three components which need to be contemplated here: economy, environment and society [3]. Considering the most basic aim of manufacturing companies – making a profit from producing and selling goods – economy is the most important aspect considered in available PPC solutions. It can be measured using performance indicators such as utilisation, lead times, work-in-process, service level and tardiness, all of which concern either the costs of production or the achievable profit from selling the goods [4].

Due to the rising energy costs in recent years, new approaches to PPC aiming to improve the energy costs have

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been developed. These are closely related to pricing models of electricity or other energy carriers. They usually aim to flatten consumption profiles (to avoid additional costs on peak usage) [5-7], to shift the use of energy into times with lower prices (e.g. the night) [8,9] or to decrease energy consumption altogether (e.g. avoiding unnecessary idle times) [10-12]. All of these are inherently designed to improve both the economic and ecologic performance of manufacturing companies.

The previously cited approaches predominantly focus on influencing the energy consumption resulting from the actual production processes. However, production peripherals, i.e. suppliers and infrastructure, do not just cause a considerable portion of the overall consumption of a factory but also interact very closely with the production process while holding a considerable potential for realising savings [13]. Accordingly, they should also be regarded in a sustainable PPC, i.e. in operation, in order to pay heed to agile system behaviour [14].

Another aspect to consider in this is the social dimension. Production will only be possible, if skilled personnel are available for completing manual work steps or monitoring automated equipment. Hence, Vorderwinkler and Heiß included the evaluation of human labour in their approach to sustainable PPC [15] but did not consider peripherals.

2.2. The Resource Networks Methodology

A prime concern when introducing more target figures and increasing the scope for a PPC solution is the rising complexity of the problem to be solved. One premise of the Resource Networks Methodology (RNM) is that the decentralisation of the energy procurement as well as the reliance on renewable or alternative energy sources and energy storages will grow. This, in turn, will require sustainability paradigms to be introduced in all of production, resulting in a complexity which can no longer be handled as a single problem. However, it can be solved by breaking down the solution process into multiple smaller problems.

The basis for this is modelling the various elements of a factory, all of which can be associated with the flows found in production systems, i.e. the flow of material; energy; personnel; and information (see [2]). Any real object or piece of information in a factory can be described as at least one element of these flows, which has certain features. Fig. 1 depicts a selection of such elements and their features. Using these, an automated machine, for instance, would be modelled as a piece of production equipment as well as an energy drain, which requires job orders and generates product data.

In order to break down a complex production environment, the various system elements are grouped into individual Resource Networks, similar to micro grids (see [2]). They act as self-contained, pseudo-autonomous, virtual production systems including all prerequisites for their operation. Following sustainability paradigms in their PPC and design, they aim to complete their job orders as best as possible. Resource Networks may overlap wherever deemed necessary to adhere to the previous requirements. This is depicted in Fig. 2, where “Light zone 1”, the “chilled water supply” and the “Electricity grid” are part of Resource Network 1 (RN1) and 2 (RN2) as well as 3 (RN3), in case of the grid.

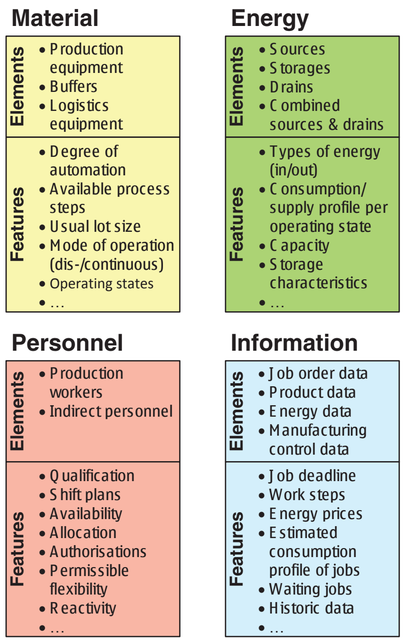

Fig. 1. Elements of the various flows in a production system [2].

The RNM can be used to solve one of the three following tasks which can arise for a new or an existing production system: (1) Selecting and implementing new energy technologies (system design); (2) Making sustainability paradigms a part of the PPC; (3) A combination of the earlier two. Therefore, individual Resource Networks need to be designed (i.e. elements selected and grouped together) according to the task at hand (both in green- and brownfield). The following section 3 details, how the task (2) can be solved making use of the methodology. It should be noted that these explanations focus on a fixed system although the effects can possibly be increased by introducing or changing elements (e.g. larger buffers, new storages, additional energy sources, etc.).

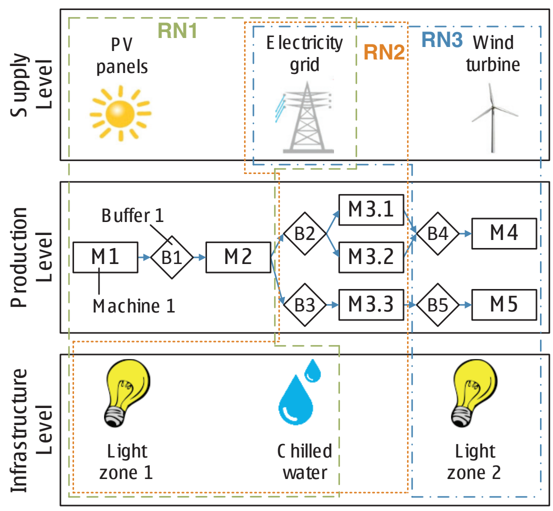

Fig. 2. Exemplary Resource Networks in a simplified production system [2].

3. Factory operation using Resource Networks

The basic strategy when operating a production system organised in multiple (virtual) Resource Networks is to identify and exploit flexibilities available or to handle volatilities present in the system. These can be found in the three levels depicted in Fig. 2: the supply level, the production level and the infrastructure level. Once identified, they can be matched with the requirements resulting from existing production orders and necessary production equipment in a suitable PPC solution which extends to all elements of a Resource Network. The afore-mentioned flexibilities, volatilities and requirements are elaborated in the following sections, as is the basic Resource Networks PPC procedure.

3.1. Supply level

In contrast to the other levels, the supply level is only concerned with electric or thermal energy which is provided to and can be used immediately (e.g. heat) or after an immediate transformation (e.g. using electric drives or a natural gas burner) in the production process. Taking the introduction of renewable energy sources into account, the (onsite) energy supply is signified by the greatest volatility which cannot be handled and dealt with unless sufficiently large energy storages or including additional (alternative or conventional) energy sources are introduced into the system and individual Resource Networks.

The key information provided on this level is the provisioning profile for a certain period of time. It can be compiled using weather forecasts (for renewable energy sources), a power generation plan for own sources (e.g. co-generation units) and market information, such as energy prices, if a grid connection is used. Storages may be used to match the provisioning to the actual demand. The possible extent for this depends on the storage characteristics (capacity, dis-/charging rates, cycle lifetime, self-discharge, etc.). In general, it can be assumed that the supply level holds the least flexibility to be exploited and, thus, provides input for implementing PPC strategies in the other two levels.

At the same time the supply level will have the most overlaps between individual Resource Networks, i.e. multiple networks include the same elements from the supply level. This is not an issue for those energy sources which have no capability to regulate their power generation and are preferably used to the fullest extent possible (e.g. wind turbine or solar panels). However, other sources or storages requiring active control are best integrated into only one Resource Network or controlled at a higher level (see section 3.4).

PPC strategies which focus on the supply level will try to maximise the utilisation of renewable or alternative, decentralised energy sources, to minimise the energy costs or to avoid the reliance on external supplies (autarkic operation).

3.2. Production level

All system elements in the production level are connected to the material flow responsible for either creating or supporting the creation of goods (i.e. production and transport equipment). Accordingly, this is the natural domain for PPC solutions where production plans are drawn up, implemented and controlled. This, in turn, requires energy, material and other process prerequisites as well as suitable workforce to be supplied at the right time in the right quantity at the right place in an economic fashion.

Production plans schedule job orders and individual tasks thereof for execution. In a typical push production, these plans predetermine the consumption of energy (as supplied by the supply level), the consumption of other energy carrying media or process prerequisites (as supplied by the infrastructure level) and the demand for workers. In a pull production, the information on the actual production schedule is determined on short notice, following rule-based control algorithms.

Further plans for shifts, maintenance tasks or similar intersect with the production schedule and, thus, also influence the energy consumption etc. [14]. As is the nature of plans, divergences from the plan due to unforeseen events (e.g. machine failures, wrong calculation of required time, etc.) are to be expected. This requires short term adaption of the production process and the according requirements. Correspondingly, the production level provides information on the required use of energy, personnel and material.

While the volatility in energy consumption stems from imbalances in the production process, flexibilities arise from temporal (e.g. production tasks in a non-critical path of a job order) or material buffers. These can be used to match the immediate demand of the production equipment with the available capacities in the supply level and possibly the infrastructure level. Furthermore, the knowledge on the actual demand for processing on certain equipment may be used to follow shutdown strategies which aim to lower the overall energy consumption without influencing the material flow.

These approaches require an economic as well as a social assessment to guarantee a sustainable operation. In particular, production tasks may only be shifted, buffers may only be filled excessively and equipment should only be shutdown, if the associated costs are less than possible benefits. Similarly, shifting work to night time, for instance, to save energy costs is only feasible, if workers are available (flexible shift model).

The actual implementation of such strategies depends on the nature of the production system in question. Hence, rule-based control algorithms aimed at reducing the energy consumption are better suited for pull systems (e.g. [12]); heuristic scheduling is better suited for push systems (e.g. [7]). If, however, no changes to the flow of production or the production equipment (operating state) can be made flexibilities in the supply or infrastructure level should be used to increase the sustainability of a production system.

3.3. Infrastructure level

Following the descriptions of the previous two levels, the infrastructure level is concerned with all elements which are neither supplying energy directly nor advancing the production process. They provide all kinds of supplementary services, media and process prerequisites (e.g. lighting, air conditioning, cooling water, etc.) which are a necessity for the production process but do not actually create any value.

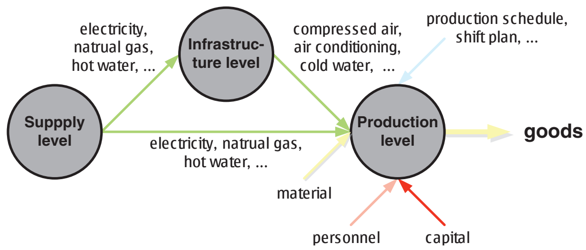

Fig. 3. Flows of production requirements in a Resource Network.

Hence, the infrastructure level makes use of the demand profile for auxiliary services (as provided by the production level) and provides a provisioning profile for these as well as a demand profile for the energy drawn from the supply level. This makes this level partially an intermediate level between the earlier two levels. Fig. 3 (colours relate to the colours in Fig. 1 with the addition of bright red for capital) depicts the flows required for producing goods in a Resource Network and, thus, the afore-mentioned connection between all levels.

The necessity for the operation of elements in the infrastructure level and, thus, the volatility therein is determined by the production plan. At the same time the elements can provide flexibility and are a starting point for the reduction of the energy consumption.

In particular, media (e.g. compressed air or cooling water) may be produced in larger quantity than required whenever an excess of energy supply is available and stored for later use, if the requirements of the production processes allow for it. The efficiency of a system, depending on the installed equipment, may also be increased by switching from a continuous to a stop-and-go modus operandi. Another approach is the model-based control of infrastructure following the control of production equipment to save energy in idle times (see [12]).

All of these approaches are limited to the infrastructure level. They aim not to influence the production processes and it is suggested that the supply level does not follow a variable regiment of infrastructure elements. Other approaches may still influence the infrastructure level or the production level.

3.4. Sustainable PPC across multiple Resource Networks

The flexibilities described in the previous sections can be used (and possibly increased by altering the existing system) to cope with the volatilities in the production system through the use of PPC, allowing for a more sustainable production. Implementing the RNM to follow these approaches still requires two additional considerations. On the one hand, conflicting approaches on different levels within one network need to be handled; on the other hand, conflicts arising from different aims of multiple networks overlapping in one or more elements need to be solved.

A solution to both issues is the use of a prioritized rule-based PPC strategy which uses an iterative approach to solve the problem in multiple phases. Upon the design of Resource Networks (see section 2.2) the PPC aims are decided, i.e. the level which leads the network internal procedure and the individual targets for each level are defined.

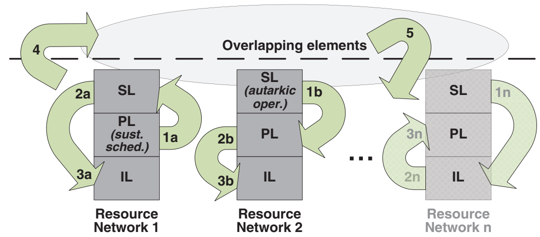

Fig. 4. Resource Networks PPC procedure.

In the example depicted in Fig. 4 the leading levels are the production level (PL) and the supply level (SL) in the first (RN1) and second network (RN2), respectively. The primary aim for the earlier is sustainable scheduling and autarkic operation for the other. These may be combined with specific aims for the other levels. Here, a reduction of all energy consumption will be assumed for other levels. The infrastructure level (IL) has the lowest priority and will try to reduce its consumption without influencing the SL or the PL.

Separately for each network, the leading level is optimised first (1a/b), i.e. a sustainable production plan considering the three dimensions will be created for RN1 (PL) and an energy supply profile aiming for maximum autarky will be compiled for RN2 (SL). Afterwards a plan will be created for the respective second highest level: RN1 tries to allocate a resource profile following the production plan (2a); RN2 creates a production plan based on the presumed energy supply which is the most sustainable given all restrictions (2b). The demand profiles for the infrastructure levels are calculated last (3a/b).

After solutions for the individual Resource Networks have been found, the demand and capacity of overlapping elements (here: only in supply level) are checked (4). Any identified discrepancies will be noted and returned to the evaluation and calculation of the individual resource networks along with directions for suggested changes (5). For instance, if a lack of energy supply is identified it will be noted along with the suggested change to reduce the demand in this time frame.

In order to solve any issues for overlapping elements, all Resource Networks are assigned a priority which, again, decides which network takes precedence over the other. Using the information from the previous iteration and the priorities, the process starts anew and another solution is calculated. The process is continued until a satisfactory solution has been found. This criterion, in turn, is evaluated using previously defined sustainability indicators and thresholds. Human interaction may also be used to find a suitable solution.

4. Assessment for methodologies for sustainable factory operation

In order to assess the applicability of a methodology, which makes sustainability paradigms a part of PPC, it is useful to know about its current development stage. At the same time, detailed knowledge about its economic viability is vital. The following sections discuss approaches aiming to solve these issues for the RNM and similar methodologies.

4.1. Readiness levels for novel approaches to PPC

The current development stage may be evaluated using a maturity scale which characterises the suitability of novel approaches to PPC and is called readiness levels for application (RLA). In this context maturity is understood as the assessed development status of a PPC methodology at a specific time in relation to phase-dependent requirements on them [16]. The below maturity scale was inspired by the concept of Technology Readiness Levels (TRL) – which was developed by NASA [17] – and the Technology Maturity Assessment (TMA) according to Brousseau et al. [18].

The defined scale consists of seven levels which are described in the following:

I. Conception: As part of the first level, scientific research activities have taken place and general theories are conceived. That means an abstracted description of the methodological concept and the included steps exists. On that basis, possible applications in production are formulated. In this development stage, the use of the methodology is speculative and there are no virtual or physical experiments to support the assumptions. Examinations are limited to analytic studies.

II. Feasibility studies: By means of analytical studies, i.e. virtual models as well as experiments, the predicted applications of the first level are verified. The investigations should show that certain functions and principles do not exclude each other and can be realised in combination. At this point a use case from the field of production is identified.

III. System analysis: Referring to this use case, the actual state of the object of investigation is analysed. For this purpose, information on the structure and the behaviour of the system elements is gathered, which also includes influencing variables and target figures. As a result economic and ecologic manufacturing as well as quality objectives can be defined. Furthermore, requirements and qualitative characteristics of the production system can be derived. In this stage it is advantageous, if preliminarily studies with respect to the economic benefit and risks take place.

IV. Modelling: At this development stage different concepts for the application of the methodology to the considered system are elaborated and appropriate goals and tasks are defined. Additionally, an assessment and a selection of alternative solutions are carried out. The objective of the stage is the estimation of the dependencies and interactions between the application environment, the performance requirements of the system and its components as well as the elements of the methodology. Relevant model parameters are identified, making use of mathematical models, calculations and simulations. Finally all required information is available in order to create a model for demonstration in a virtual environment.

V. Virtual demonstration: At the beginning of this stage it is necessary to select a suitable tool (e.g. simulation) to verify the results, which can be obtained by applying the methodology. Prior to the first examination the model validity has to be proven in order to be able to generate representative results, considering the future production tasks. On that basis, assumptions of the previous development stage can be tested. Following the creation of an experimental design, first examinations using the virtual model can be performed and evaluated. Thereby, a monetary evaluation represents a useful supplement (see section 4.2). Depending on the outcomes, either the model is critically reviewed and improvements are made or realistic demonstration can commence.

VI. Realistic demonstration: At this development stage the aim is to confirm the results of the virtual experiments in a production environment which is close to those found in a common industrial surrounding. An appropriate subsystem is selected and its boundaries are determined. By analogy with the previous level, a design of experiments is carried out and the examinations are performed and evaluated. It is of particular importance that production-specific indicators, like throughput, processing time, costs per unit, as well as ecologic and social indicators are included in the study. Similar to a continuous improvement process, results and other insights have to be fed back to the model. Thus, a virtual optimisation can support the realistic tests and the model can be verified further so that the degree of abstraction is reduced step by step. Finally, the development stage of the methodology has reached an application level wherein the risk is insignificant or at least manageable.

VII. Industrial application: At the last level, the methodology is successfully applied in a real existing production system. The results which are generated by the application of the methodology are recorded and documented. Regular training sessions are established. Advancements only take place to a small extent and are only expected to improve sustainability indicators incrementally in specific use cases.

Making use of this scale, it can be ascertained that the development of the RNM is approx. in levels III and IV. This ambiguous assessment is the result of different development strands being followed in this research (IV for PPC-related tasks and III for other two tasks, see end of section 2.2).

4.2. Monetary evaluation of the feasibility

From section 3 can be derived that the Resource Networks Methodology (RNM) allows for a supply side-motivated shifting and a demand side-motivated reduction of energy consumption, amongst others. It may also implicate changes of the output, the material flows, the stocks of inventory and other parameters. To support decision making for Resource Network (RN) configurations, monetary evaluations investigate the profitability of the RNM-based factory operation, the impacts on profitability of different configurations, or profitability changes compared with traditional factory operation.

In a running factory, a certain RN configuration may influence the profitability by cost and output variations. A possible approach to evaluate alternative configurations is the formulation of a model indicating the impact of the configurations on the profit (profit [P] = revenues [R] – costs [C]; see [19]). Based on the current operation strategy, the profitability analysis of a certain RN configuration can be limited to the variation of the profit and its components, respectively, caused by the configuration alternative: $\Delta P = \Delta R - \Delta C$.

In a given factory the profitability of a RN configuration is determined by variations of the:

- goods produced [ΔG], as changes of the contribution margin caused by alternative output [$\Delta CM_{\Delta G}$],
- stocks of inventories [ΔI], as invent. cost variations [ΔC_I],
- buffer capacity utilisation [ΔB], as variations of the cost of the work in process [ΔC_{WiP}],
- material flows [ΔQ_M], as changes in the logistics cost [ΔC_L], and
- energy consumption [ΔE], as changes in energy cost [ΔC_E].

Given that, the monetary consequences can be assessed as:

$$\Delta P = \Delta CM_{\Delta G} - \Delta C_I - \Delta C_{WiP} - \Delta C_L - \Delta C_E \quad (1)$$

Since energy supply and demand is an important component of RNM-based factory operation, the composition of the energy cost should be specified in more detail. Assuming the electricity demand can be satisfied by a PV panel, a gas-powered combined heat and power unit as well as the public electricity grid (see also Fig. 2 for example). Then the energy cost variations will include not only cost variations from electricity bought from the public utility [C_{epu}], but also variations of cost of operation [C_o] incurred by the PV panel and the combined heat and power unit (depreciation [C_{depr}], maintenance cost [C_{maint}], cost of natural or biogas, etc.). Further, the compensation [CE] for the varying amount of electricity fed into the grid [$\Delta Q_{feeding}$] should be included. All the variations can result from changes in the energy quantities supplied [ΔQ_{epu}], produced by the PV panels and/or the combined heating and power unit (i.e. gas consumed [ΔQ_{gas}]) as well as the prices paid for purchased energy [p_{epu}] and/or gas [p_{gas}]. Therewith, the variations of energy cost consist of:

$$\begin{aligned}\Delta C_E &= \Delta C_{epu} + \Delta C_o - \Delta CE = \Delta p_{epu} \cdot \Delta Q_{epu} + \\ &C_{depr} + C_{maint} + \Delta p_{gas} \cdot \Delta Q_{gas} - CE \cdot \Delta Q_{feeding}\end{aligned} \quad (2)$$

Since depreciation and maintenance cost are usually fixed cost, they will only influence the cost in partial analysis (economic analysis of only one network), but not in total (complete resource network-based factory operation analysis).

Summarising, it can be noted, that the profitability of alternative RN configurations can be evaluated using the "profit" as objective. However, since the evaluation problem can grow complex when considering more than one RN, the validity of the evaluation results strongly depend on the reasonable detail and simplifying assumptions made. Nevertheless, the economic analysis can contribute useful and objective information to a multi-perspective appraisal of various RN configurations.

5. Summary and outlook

The presented work expands the Resource Networks Methodology (RNM) with a focus on its use to make sustainability paradigms a part of PPC. Therefore, the levels of production regarded in the methodology, their respective characteristics and basic PPC strategies have been elaborated. These are used in an iterative, multi-phase procedure to find suitable production and equipment operation plans. Approaches to assess the readiness and the economic viability of methodologies like the RNM were presented. Future work will focus on the design of Resource Networks and the application of the RNM for selecting energy technologies.

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References

[1] European Commission. The 2020 climate and energy package. http://ec.europa.eu/clima/policies/package/index_en.htm [Acc. 20/10/14].
[2] Stoldt J, Franz E, Schlegel A, Putz M. Resource Networks: Decentralised factory operation utilising renewable energy sources. Procedia CIRP 2015 [presented at CIRP-sponsored GCSM 2014, awaiting publication].
[3] United Nation General Assembly: 2005 World Summit Outcome – Resolution A/60/1.
[4] Altendorfer K: Capacity and Inventory Planning for Make-to-Order Production Systems. 2014, Springer International Publishing.
[5] Klose L, Petzoldt K-H: Ressourcenmanagement eines Automobilzulieferers mit Presswerk und Rohbau. Proc. of the 5th Chemnitz Carbody Colloquium, Chemnitz, 2008, pp. 329-345.
[6] Pechmann A, Schöler I, Hackmann R: Energy Efficient and Intelligent Production Scheduling – Evaluation of a New Production Planning and Scheduling Software. Proc. of the 19th CIRP Conference on Life Cycle Engineering, Berkley, 2012, pp. 491-496.
[7] Bruzzone AAG, Anghinolfi D, Paolucci M, Tonelli F: Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops. CIRP Annals 2012;61/1:459-462.
[8] Junge M. Simulationsgestützte Entwicklung und Optimierung einer energieeffizienten Produktionssteuerung. Dissertation, Kassel, 2007.
[9] Graßl M, Reinhart G: Evaluating measures for adapting the energy demand of a production system to volatile energy prices. Procedia CIRP 2014;15:129-134.
[10] Bücker D, Deuse J: Concept of Energy-Efficient Job Sequencing for Heat Treatment Processes. Proc. of the 19th CIRP Conference on Life Cycle Engineering, Berkley, 2012, pp. 417-421.
[11] Weinert N, Mose C: Investigation of advanced energy saving stand by strategies for production systems. Procedia CIRP 2014;15:90-95.
[12] Langer T, Schlegel A, Stoldt J, Putz M: A Model-based Approach to Energy-saving Manufacturing Control Strategies. Procedia CIRP 2014;15:123-128.
[13] Mose C, Weinert N: Energy efficiency optimization of joining processes on shop floor process chain level. Procedia CIRP 2014;15:86-89.
[14] Ghadimi P, Kara S, Kornfeld B: Advanced On-Site Energy Generation towards Sustainable Manufacturing. Nee AYC, Song B, Ong S-K (Eds.): Re-engineering Manufacturing for Sustainability. 2013:153-158.
[15] Vorderwinkler M, Heiß H: Nachhaltige Produktionsregelung. 2011, Steyer-Gleink, Berichte aus Energie- und Umweltforrschung 40/2011.
[16] Weckenmann A, Akkasoglu G: Maturity determination and information visualization of new forming processes considering uncertain indicator values. AIP Conf. Proc. 2012;1431:899-911.
[17] Mankins JC: Technology Readiness Level – A White Paper. Advanced Concepts Office. Office of Space Access and Technology.
[18] Brousseau E, Barton R, Dimov S, Bigot S: A Methodology for Evaluating the Technological Maturity of Micro and Nano Fabrication Processes. IFIP. Advances in Information and Communication Technology 2010;315/1: 329-336.
[19] Putz M, Götze U, Stoldt J, Franz E: Fostering energy efficiency by way of a techno-economic framework. Proc. of the 11th Global Conference on Sustainable Manufacturing, Berlin. 2013;371-346.