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Design and Control of Manufacturing Systems for Enabling Energy-Efficiency and -Flexibility

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Abstract *Factories of the future will be embedded into a smart grid energy infrastructure, where energy suppliers and consumers are intelligently linked with each other. The smart grid will be characterized by a dynamic matching of energy generation and energy demand using short-term energy storages for buffering. The energy consumption of manufacturing systems must be capable of being adapted to these dynamic requirements of the smart grid. Energy-related objectives like energy-efficiency and energy-flexibility will thus become essential parts of an energy management system for factories. Energy-efficiency can be effectively achieved by the design of manufacturing process chains whereas energy-flexibility can be realized by an appropriate production planning and control. This paper describes a methodology for the design of manufacturing process chains by selecting manufacturing processes and equipment due to energy consumption as well as cost- and flexibility-related objectives. In terms of the production planning and control, a Shop-Floor-Scheduling methodology is presented. The Shop-Floor-Scheduling enables a high level of energy-flexibility by controlling the manufacturing system.*

1. Introduction

The fourth industrial revolution (Industry 4.0) will be characterized by ubiquitous communication systems across all stages of value creation networks and throughout all phases of product life-cycles. As a result, the value creation factors within and between value creation modules, in reference to [1], are intelligently linked with each other and are continuously interchanging information with and between all relevant stakeholders. This will lead to the manifestation and intelligent interplay of so called Smart Production, Smart Logistic, Smart Products and Smart Grids [2]. A Smart Grid will dynamically match the energy generation of suppliers with the energy demand of consumers using short-term energy storages for buffering.

Factories of the future will increasingly use renewable energies as part of a self-sufficient supply and can be an energy supplier and consumer at the same time [3]. The energy management system of a factory will have to be able to handle these dynamic requirements of the Smart Grid. Energy-efficiency and energy-flexibility will thus become essential objectives within manufacturing systems. Energy-efficiency can be effectively achieved by the design of manufacturing process chains via selecting energy-efficient manufacturing equipment for given manufacturing operations [4]. On the other hand, energy-flexibility can be realized by an appropriate Production Planning and Control (PPC) [5]. The Shop Floor Scheduling (SFS) as central part of the PPC can be utilized for dispatching the manufacturing jobs to the appropriate machine tools according to their machine-tool-specific energy consumption [6,7].
This paper describes a procedure for the energy-aware design of manufacturing process chains in the green- and brownfield application case. Besides, a procedure for the energy-aware Shop Floor Scheduling is outlined. For both, the design and the scheduling task, energy-related objectives in addition to traditional productivity-related objective such as time and costs are considered. For solving the complex design and scheduling task, an evolutionary algorithm is introduced and exemplarily validated. To be more precise, a methodology for a so called firefly algorithm is suggested and made available for downloading.

2. Research Scope and Focus, and State of the Art

The energy consumption of manufacturing systems can substantially be influenced during the design phase of a manufacturing process chain [4]. Thereby, the manufacturing equipment is selected based on the manufacturing processes [1] required for manufacturing the product portfolio of the manufacturing system. The design procedure described in this paper addresses the discrete parts manufacturing for the Greenfield and Brownfield application case. The Greenfield case covers the design of a new process chain with no constraints, such as already available manufacturing equipment. On the contrary, the Brownfield case comprises a design with constraints in terms of already existing equipment.
In current research, the energy-aware design of manufacturing process chains has been managed by comparing the resource-efficiency (including energy-efficiency) of alternative process chains based on monitored power consumption [7] or by using Environmental- or Life-Cycle-Assessment procedures [9,10].

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[1] Manufacturing processes according to DIN 8580 [8] and manufacturing technologies can usually be used as synonyms.

Additionally, mathematical modeling of power streams [11] and energy-related manufacturing simulation [12,13] can be applied for the design of manufacturing systems taking also into consideration the energy consumption of the auxiliary systems (e.g. compressed air, heating, cooling, lighting) [14], which is often also called the indirect energy consumption within a manufacturing system.

Shop Floor Scheduling controls the material flow throughout the manufacturing system by scheduling all present jobs in terms of their dispatching date on manufacturing equipment [6]. The scheduling procedure described in this paper focuses on the discrete parts manufacturing using a so called Flexible Job Shop Scheduling model which is able to cover different system configurations of the shop floor.
The energy-aware SFS for discrete part manufacturing in current research can be generally structured according to the addressed system configuration, such as Flow Shop or Job Shop configurations, and to the considered objectives, such as power peak or energy consumption. By taking into account at least one energy related-objective, energy-aware Flow Shop Scheduling approaches have been described in [15], [16], or [17], and energy-aware Job Shop Scheduling concepts have been presented in [18], [19], or [20]. An approach for Flow as well as for Job Shop system configurations addressing multiple energy-related objectives is proposed in [6].

Interrelated approaches for energy-aware design and energy-flexible scheduling of manufacturing systems have been barely described so far in current research. Furthermore, a procedure, which not only covers the description of the design and scheduling model, but also covers a recommendation for gathering the required planning data as well as an approach for finding a solution for the design and scheduling task, can be relevant for meeting the complexity of future manufacturing scenarios.

3. Energy-aware Design of Manufacturing Process Chains

The design of the manufacturing process chains covers the selection of manufacturing processes and related machine tools based on the required sequence of manufacturing operations for the manufacture of one or more products and its comprising variants. In a manufacturing system, the manufacturing processes are being performed by manufacturing equipment, which in most cases corresponds to a single machine tool. Consequently, the design also contains the selection of specific machine tools for each selected manufacturing process. Figure 1 shows the framework for the design of a manufacturing process chain.

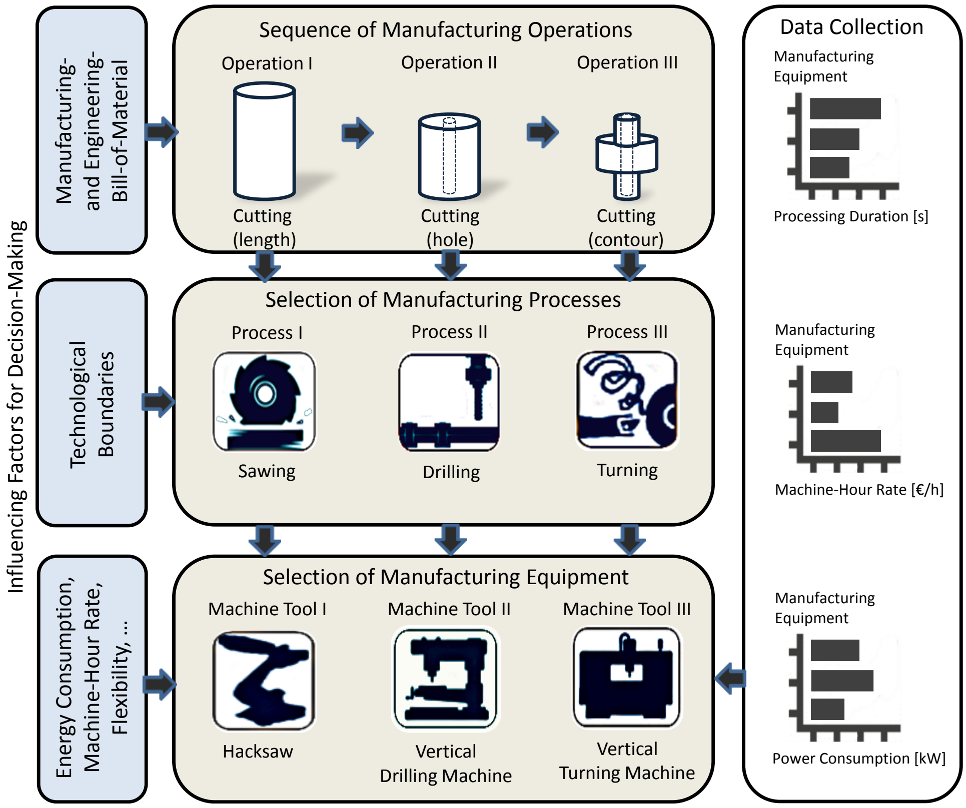

Figure 1. Framework for the Design of a Manufacturing Process Chain

The first step within the framework is to define the sequence of manufacturing operations. This sequence can usually be derived from the engineering- and/or manufacturing-bill-of-material (EBOM and MBOM) for a specific product. The second step covers the selection of manufacturing processes for each manufacturing operation. In many cases, a manufacturing operation can be executed by a set of different manufacturing processes depending on the technological boundaries. Cutting the product to the required length (Manufacturing Operation I) can be realized by using for instance sawing or shearing (Manufacturing Processes). Thereby, the design-parameters of the product (e.g. geometry, dimensions, and material) must be within the technological boundaries of the selected manufacturing process (e.g. maximum work piece dimensions, maximum surface quality). The third and last step of the framework contains the selection of a specific machine tool from the set of possible machine tools, which are capable of performing the operation-specific manufacturing process, e.g. many different drilling machines can be used for drilling a hole.

The selection of the machine tools can be made according to multiple objectives. In order to realize a design of the process chain that is energy- and cost-efficient as well as flexible as possible, three main objectives can be considered. The average energy consumption and total costs are two objectives that should be minimized. The flexibility of the process chain is considered as a third main objective that should be maximized. Machine tools could also be selected according to their resilience to black- and brown-outs, but this is not being considered further.

Modelling the Design Task:

Table 1 and 2 are exemplarily covering a task for the design of a process chain for a product consisting of four manufacturing operations, eight related manufacturing processes and six machine tools. Table 1 shows simulated tool parameters depending on the processed operation. Each operation is already connected with capable manufacturing processes, which are able to execute the operation. If a process P_k for operation O_l can be performed by a machine tool M_i, a valid positive value for the process duration $t_{l,k,i}$ and the average power consumption $P^{P\,\emptyset}_{l,k,i}$ depending on the performed operation is assigned to the capable machine tool. Table 2 shows the dedicated machine-hour rate and investment costs for the six different machine tools.

Table 1. Design task for four operation, eight processes, and six machine tools

		Parameter Set for Machine Tools M_i											
Oper-ations O_l	*Capable Manufacturing Processes P_k*	Process Duration $t_{l,K,i}$*[s]*						Average Power Consumption $P^{\rho,\emptyset}_{l,k,i}$ *[kW]*					
		$\boldsymbol{M_1}$	$\boldsymbol{M_2}$	$\boldsymbol{M_3}$	$\boldsymbol{M_4}$	$\boldsymbol{M_5}$	$\boldsymbol{M_6}$	$\boldsymbol{M_1}$	$\boldsymbol{M_2}$	$\boldsymbol{M_3}$	$\boldsymbol{M_4}$	$\boldsymbol{M_5}$	$\boldsymbol{M_6}$
$\boldsymbol{O_1}$	$\boldsymbol{P_1}$ (Centre Drilling)	27	-	-	25	-	-	8	-	-	9	-	-
	$\boldsymbol{P_2}$ (Facing)	-	54	60	-	-	-	-	13	12	-	-	-
	$\boldsymbol{P_3}$ (Circular Milling)	40	-	37	-	43	-	11	-	13	-	10	-
$\boldsymbol{O_2}$	$\boldsymbol{P_4}$ (Countersinking)	-	12	-	-	7	-	-	10		-	15	-
	$\boldsymbol{P_5}$ (Circular Sawing)	5	-	7	-	6	-	4	-	4	-	5	-
	$\boldsymbol{P_6}$ (Surface Grinding)	-	5	-	-	-	5	-	12	-	-	-	10
$\boldsymbol{O_3}$	$\boldsymbol{P_1}$ (Centre Drilling)	38	-	-	41	-	-	11	-	-	12	-	-
	$\boldsymbol{P_4}$ (Countersinking)	-	10	-	12	-	-	-	16	-	18	-	-
	$\boldsymbol{P_7}$ (Cylinder Sinking)	15	-	18	-	17	-	12	-	15	-	14	-
$\boldsymbol{O_4}$	$\boldsymbol{P_8}$ (Deburring)	-	350	-	-	-	300	-	6	-	-	-	4

Table 2. Machine-hour Rate and Investment Costs for the six machine tools

	Machine Tools M_i					
Parameters	$\boldsymbol{M_1}$	$\boldsymbol{M_2}$	$\boldsymbol{M_3}$	$\boldsymbol{M_4}$	$\boldsymbol{M_5}$	$\boldsymbol{M_6}$
Machine-Hour Rate C_i [€/h]	200	120	150	180	150	150
Investment Costs i_i [€]	300.000	300.000	200.000	100.000	150.000	100.000

4. Energy-aware Shop Floor Scheduling

The SFS aims to schedule the dispatching date of present jobs on already available manufacturing equipment [6]. This means, that all jobs are being assigned to available machine tools in a certain sequence [6]. A job is related to a certain batch size of a specific product and is directly derived from customer orders [6]. Furthermore, a job is defined by a predetermined processing sequence for the manufacturing operations [6]. Since, the manufacturing processes are already predefined by the available machine tools throughout the shop floor, the degree of freedom for the scheduling task results directly from the machine tool's flexibility. Flexibility ranges from not, over partly, to totally flexible. In other words, machine tools are capable of processing only one, several or even all manufacturing operations of a certain product. So called Flexible Job Shop Scheduling models can be applied to this type of SFS. Figure 2 shows the framework for the SFS on the basis of a Flexible Job Shop Scheduling model.

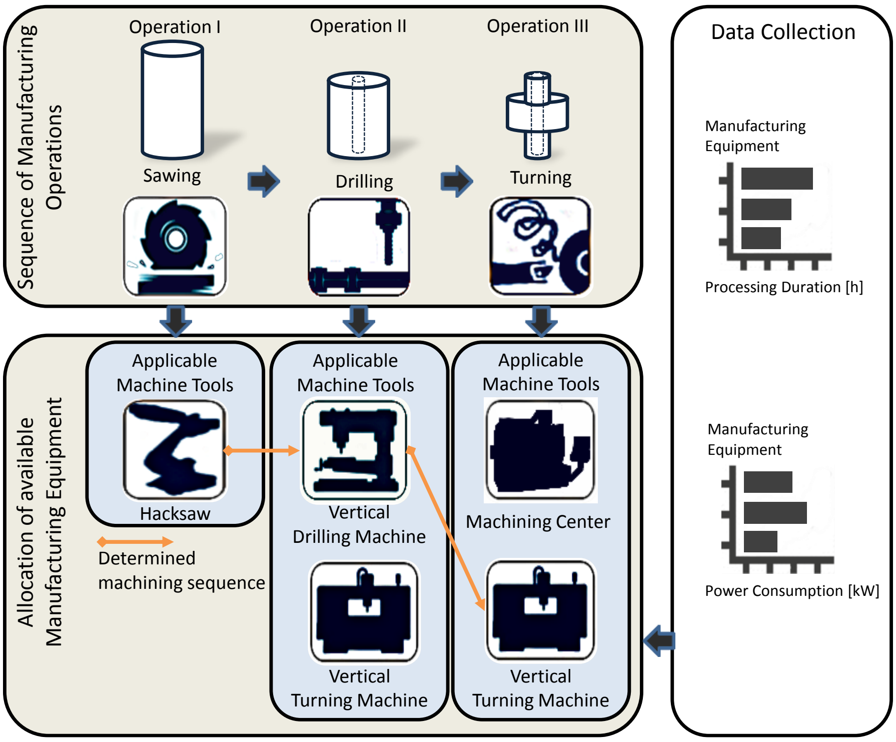

Figure 2. Framework for the Shop Floor Scheduling

The sequence of manufacturing operations which can be derived from the work plan of a certain product is already connected with dedicated manufacturing processes and corresponds to a single job. Each operation can be performed by one or more available machine tools, e.g. two machine tools are capable of processing Operation II (Drilling). Depending on the specific machine tool, an operation can be processed with different energy consumption and with different processing durations. The final schedule for the shop floor is determined by allocating the machine tools to the required operations considering multiple objectives. For realizing a high energy-flexibility by simultaneously achieving a best possible productivity, the total energy consumption and the power load as energy-related objectives, and the makespan as productivity-related objective are taken into account for the SFS [6,7]. All objectives should usually be minimized. The power load as well as the total energy consumption can additionally be scheduled in such a way that they always meet certain thresholds which in turn result from the present conditions of the smart grid energy supply [6].

Modelling the Scheduling Task:
A given set of Jobs J_j contains a set of different operations $O_{j,l}$. Each operation must be processed in its predetermined order $\{O_{j,1}; O_{j,2}; O_{j,3};\ldots\}$ for each job. An operation $O_{j,l}$ can be processed on a machine tool M_i if its eligibility parameter $e_{j,l,i}$ takes value 1. A machine tool needs a specific process duration $t_{j,l,i}$ and average power consumption $P_{j,l,i}^{P\,\emptyset}$ for processing a certain operation [6,7]. In addition a machine tool spends specific average power consumption in idle state $P_i^{P\,\emptyset}$ and requires average energy consumption $E_i^{S\,\emptyset}$ for being shut on/off [6,7]. Table 3 shows a possible scheduling task exemplarily for two jobs and two machine tools.

Table 3. Scheduling task for two jobs and two machine tools [6]

		Parameter Set for Machine tools M_i					
		Eligibility $e_{j,l,i}$ [0;1]		*Process duration $t_{j,l,i}$ [h]*		*Average power consumption $P_{j,l,i}^{P\,\emptyset}$ for processing [kW]*	
Jobs J_j	*Operations $O_{j,l}$*	$\boldsymbol{M_1}$	$\boldsymbol{M_2}$	$\boldsymbol{M_1}$	$\boldsymbol{M_2}$	$\boldsymbol{M_1}$	$\boldsymbol{M_2}$
$\boldsymbol{J_1}$	$\boldsymbol{O_{1,1}}$	0	1	-	5	-	10
	$\boldsymbol{O_{1,2}}$	1	0	3	-	8	-
	$\boldsymbol{O_{1,3}}$	1	1	4	3	6	3
$\boldsymbol{J_2}$	$\boldsymbol{O_{2,1}}$	1	0	5	-	15	-
	$\boldsymbol{O_{2,2}}$	1	0	4	-	6	-
Average power consumption $P_i^{P\,\emptyset}$ for the Idle state [kW]						2	3
Average energy consumption $E_i^{S\,\emptyset}$ for On/Off [kWh]						20	30

5. Gathering of required Planning Data

In order to be able to model the design and scheduling task, different parameter sets for the machine tools are required. Table 4 gives a suggestion on how to gather the data for each task. Energy data aggregated according to the EnergyCube concept [6,7] is used as input for the subsequently described firefly algorithm. This concept can be applied to real-time monitored data streams [7].

Table 4. Gathering of required data for the design and scheduling tasks

Task	*Process Duration*	*Machine-Hour Rate*	*Power Consumption*
Process Chain Design (Greenfield)	Estimation based on empirical values and manufacturer's specifications for machine tools, e.g. cutting speed, or if not available, based on known manufacturing process parameters.	Estimation based on the investment costs of a machine tool divided by the operating hours for the depreciation period. Also tool costs, maintenance costs, energy costs based on the energy consumption, room costs and interest rates can be considered if available for the machine tool use phase.	Estimation based on manufacturer's specifications, e.g. power consumption in rated operation mode of a machine tool, or monitored energy data [7]. An overview of possible data acquisition procedures can be found in [11].
Process Chain Design (Brownfield)	Calculation based on already known machine tool time parameters, e.g. gained by monitoring.	Detailed calculation taking into account the actual operating costs of a machine tool: tool costs, maintenance costs, energy costs, room costs, and interests rates.	Calculation based on monitored energy data [6,7].
SFS	Same approach as for Brownfield case.	Not considered.	Same approach as for Brownfield case.

6. Solving the Design and Scheduling Task using the Firefly Algorithm

In 2007, X.S. Yang developed a nature-inspired evolutionary algorithm which was based on the behaviour of fireflies [21]. It was proven by many researchers to be an appropriate algorithm to solve NP-hard optimization tasks like Shop Floor Scheduling. Fireflies attract their partners or prey by flashing light. A special rhythm and its brightness make other insects feel attracted and move towards them [21]. The algorithm aims to find optimal solutions for a given tasks by a swarm of initially random individuals that communicate their position and solution quality [21]. The subsequently outlined firefly algorithm for solving the design and scheduling task implemented in Python script as well as the examples used for validation can be downloaded as open knowledge at: https://code.google.com/p/firefly-algorithm/.

Solving the Design Task using the Firefly Algorithm:

In order to solve the design task for the Greenfield case, a specific firefly algorithm has been developed in which every individual of the firefly population represents a selection of machine tools that is capable to manufacture the whole product in its given design. For validating the applicability of the developed firefly algorithm the exemplary design task presented in Table 1 and 2 has been solved. Therefore, a production volume of 10.000 units has been considered for the product. The selection of machine tools for the process chain design depending on the optimized objective is shown in Table 5. This example task was solved by using an initial population size of 10. The best solution has been found by the algorithm within the first 5 iteration steps, due to the simplicity of the task.

Table 5. Considered objectives and optimization results for the design task

Description of the Objectives for the Design Task				
Energy Consumption per Operation (ECO): The ECO is defined as the arithmetic mean of every operation's average power consumption multiplied with its processing time. This objective corresponds to the energy-efficiency of the manufacturing process chain.				
Total Costs: The Total Costs are determined as the sum of the investment and the operating costs.				
Flexibility: The flexibility is defined as the average quantity of relevant manufacturing operations that can be performed by a machine tool.				
Equally weighted: The three objectives (Average Energy Consumption, Total Costs and Flexibility) are weighted equally (1/3:1/3:1/3) for the design task.				
Results of the optimization	**ECO** [kWs]	**Total Costs** [€]	**Flexibility** [Operations]	**Selected Machine Tools**
Minimizing ECO	703	407.000	4,0	2, 4, 5
Minimizing TC	1078	319.000	3,6	1, 3, 4, 5, 6
Maximizing Flexibility	753	442.000	5,0	1, 2
Equally weighted	703	407.000	4,0	2, 4, 5

Solving the Scheduling Task using the Firefly Algorithm:

For solving the scheduling task, a specific firefly algorithm has been compiled for a partly flexible job shop scheduling problem. For validating the performance of the developed firefly algorithm for the scheduling task an expanded version of the standardized Brandimarte's MK1 [22] partly flexible job shop scheduling problem has been used. The problem consists of 10 jobs containing 5 to 6 operations each and has been expanded by energy and power parameters oriented on real machine tool energy data. An average power consumption for processing has been randomly assigned in a range from 1 to 10 kW for each operation. Additionally, an average power consumption for the idle state has been randomly determined in a range from 1 to 3 kW for each machine tool.

The energy consumed for shutting a machine tool off and on again ranges from 7 to 10 kWh. Table 6 shows the results of the optimization depending on the considered objectives for the energy-related MK1 problem. The optimization results in the table shows the average objective values for the schedule for 20 runs of the algorithm with a constrained processing time of 10 minutes, which is equivalent to ~250 iteration steps, using an initial population size of 50. The firefly algorithm solves the expanded MK1 problem with comparatively very good results in terms of achieved makespan and runtime. The power load and energy consumption of the schedule can be essentially influenced and optimized nearly in real time.

Table 6. Considered objectives and optimization results for the scheduling task

Description of the Objectives for the Scheduling Task			
Makespan: The makespan of a schedule is the time span between time period 0 (dispatching date of the first job) and the completion time of the last job.			
Energy Consumption: The energy consumption throughout a determined schedule results from different types of energy consumption which are referring to the different operational states of a machine tool: the average energy consumption for the processing state and the average energy consumption for the idle state [6,7]. Energy consumption during the idle state can be avoided by shutting off a machine tool. But the energy saving in such a case must be greater than the energy required for shutting the tool off and on again [23].			
Power Load: The power load of the schedule to a certain time is the sum of the power consumption of each machine tool at this point in time.			
Equally Weighted: The three objectives (Makespan, Energy Consumption and Power Load) are weighted equally (1/3:1/3:1/3) for the scheduling task.			
Initial Random Population: The average objective values for the initial random population of the firefly algorithm.			
Results of the optimization	**Makespan** [h]	**Energy Consumption** [kWh]	**Power load** [kW]
Minimizing Makespan	43	6056	36
Minimizing Energy Consumption	59	4685	38
Minimizing Power Load	130	14345	15
Equally weighted	50	5829	26
Initial Random Population	92	11786	29

7. Conclusion

Within this paper a procedure for the energy-efficient design of manufacturing process chains as well as for the energy-flexible SFS has been described. For the design and the scheduling task, energy-related objectives in addition to traditional productivity-related objectives, such as time and costs, have been considered.

For solving the complex design and scheduling task, a firefly algorithm has been outlined and validated. This algorithm allows the implementation of user-individual design and scheduling tasks according to the models defined in Table 1, 2 and 3. The objectives can be adopted to own requirements such as time-of-use energy tariffs. The algorithm can be used to design manufacturing process chains with respect to energy-efficiency as well as to total costs and flexibility. The application of the firefly algorithm seems particularly suitable for large-scale design tasks, with many different products and available machine tools. In terms of the scheduling task, the application of the firefly algorithm can be especially used for levelling the power load and energy consumption of the production in real time. This provides energy-flexibility to respond to short-term changes of the energy supply and to actively participate in a smart grid.

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