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Energy-aware scheduling in reconfigurable multiple path shop floors

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Abstract

Individualization as a major driver in societal change forces companies to adapt to continuously changing customer-specific requirements. Therefore, companies incorporate novel enabling technologies such as digitalization, servitization, and reconfigurability in manufacturing systems. Even though the research on reconfigurable systems has continued over the last 20 years, the energy management of such systems has barely been considered. This work represents recent trends connected with energy efficiency and energy flexibility in reconfigurable manufacturing systems. A suitable attempt to model an energy-related system is proposed using scheduling operations which are subject to power requirements, i.e. variable power thresholds. The results of the optimization show that reconfigurable systems support the adaptation of energy consumption to variable thresholds.

Keywords: Reconfigurable Manufacturing Systems; Energy Efficiency; Energy Flexibility; Scheduling

1. Introduction

Initiated in the 1990s [1], research focusing on reconfigurable manufacturing has recently gained new attention due to the trend towards customer individualization [2]. The design of such production systems allows rapid changes within their structures (i.e. adding or removing machines or components in the production system). Scalability, convertibility, diagnosability, modularity, integrability and customizability are the main system characteristics [2]. Reconfigurable manufacturing systems (RMS) combine the advantages of dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS). In dedicated lines, a single part is produced at high production rates using tailored, simultaneously operating tools (mass production). Therefore, these dedicated manufacturing lines are limited in flexibility and scalability. On the other hand, FMS offer the potential to produce a variety of different parts in small quantities. The machines within flexible systems are not designed economically to use several pieces of equipment at the same time, implying generally lower production rates. Furthermore, these systems are characterized by comparably high costs. RMS aim to achieve higher throughputs than FMS while preserving flexibility. The system's capability to integrate, change, or remove machines at work stations is a decisive advantage.

Reconfigurable machine tools are important components in RMS, providing fast machine structure changes and the replacement of basic machine modules [3]. Compared to conventional CNC (computerized numerical control) machines used in FMS the final part family is already taken into account when the machine is being designed. In contrast, DML machines are designed for a single part [4]. Reconfiguration capabilities are considered in physical (changes in layout, machines, material handling or machine modules) and logical (routing, scheduling, planning, programming, augmentation) dimensions [5]. As discussed by Moghaddam et al. [6], research projects on RMS focus on analyzing the performance of various configurations or concentrate on developing approaches and mathematical models for design and configuration selections. Furthermore, special scheduling strategies are provided [7].

On the other hand, energy as a production factor is becoming increasingly important. According to the U. S. Energy Information Administration, the industry sector is responsible for approximately 50 % of the world's energy consumption [8].

Therefore, optimization and reduction of energy consumption has to be considered from the strategic level to the operational level, as it is important to take energy efficiency into account when making decisions during manufacturing operations [9]. To reduce the overall energy consumption of production systems, Rager et al. [10] suggest two types of measures: technological measures deal with new machines or manufacturing processes, whereas organizational measures focus on improving the existing system. The applicability of energy-aware machines may be limited due to high costs. An affordable alternative could focus on organizational measures such as scheduling approaches.

Most scheduling problems intend to minimize criteria such as the total production duration, the total delay and other time-related objective functions. However, energy minimization in manufacturing systems is of increasing interest in literature [9] and researchers to date have not considered the use of reconfigurable machine tools to deal with energy availability changes in the context of reconfigurable manufacturing systems.

For this purpose, this study will examine the impact of reconfigurable machine tools on schedules in the context of a multiple path shop floor subject to variations in power supply. A general model in the form of a scheduling problem is utilized. Therefore, the minimization of the total production duration will consider the power consumption of operations and a power threshold that can change over time which can represent variations in renewable, but also conventional, energy sources. It can be mentioned that the difference with problems considering energy is that power can be modelled as an instantly available resource, whereas energy consists in the integral of the power over time. If this last one can give an information on the total energy consumption required, it does not prevent the system to use excessive power during a time period.

In the next section, a brief review of research publications related to the field of energy-efficient and -flexible manufacturing is presented. Section 3 introduces the problem and its mathematical model, followed by the description of an exemplary use case in Section 4.

2. Related research

2.1. Energy efficiency and energy flexibility in manufacturing

Energy efficiency has been consistently pursued by industry and research. In addition to the reduction of the overall energy consumption, methods for lowering peak loads have been considered. The occurrence of the highest energy demand could give rise to a considerable portion of the overall electricity costs [11], since grid usage fees are primarily calculated on the basis of the peak load over a fixed period.

Neugebauer et al. [12] describe energy efficiency in production systems as "the relationship between a benefit achieved and the energy expenditure required to achieve it". According to that definition, the energy expenditure equals the total electricity consumed during the production cycles. The benefit is dependent on the amount of energy that contributes to the direct additional value of the product. It may also be used for secondary activities that are essential for maintaining the production processes. In order to achieve the optimal efficiency, the expenditure for the existing benefit must be minimized or the benefit from existing expenditure must be maximized. This is achieved by reducing the energy consumption of all value-adding and supporting work processes and eliminating all energy waste.

Energy efficiency can generally be improved by affecting either production equipment or production planning and control (PPC). Furthermore, methods can be applied at different production levels (machine components, individual machine tools, production cells and entire factories).

Renewable energies entail a fluctuation in the electricity supply. This results in a massive change in the energy management of production systems. Up to the present, research has focused on smoothing peak loads, whereas in the future, additional efforts could include synchronization of energy consumption and generation [13]. This requires enhanced energy flexibility of all production facilities. Reinhart et al. [14] define energy flexibility "as the ability of a production system [...] to quickly adapt to changes in the energy market at very low cost".

Considering other energy influencing factors in general will expand this definition beyond the adaptation to changes in the energy market. Such a factor could be the amount of self-produced energy with regard to decentralization in power generation [15]. Energy flexibility can be differentiated into organizational and technical approaches [16]. Energy flexibility during production planning is achieved by adapting the operational sequence on the basis of the consumption characteristics of the individual production steps [17]. These organizational adjustments require scheduling based on aspects such as weather or electricity generation forecasts. Particular examples are the planning of break times or the sequence of production steps. However, inaccuracies in the forecasts and unplanned disruptions then lead to a non-ideal load profile. Measures to implement technical flexibility might compensate for this using short-term adjustments. For example, the parameters of a machine tool might be changed to adapt the load profile to the respective current supply situation [18, 19]. These measures are based on a high degree of transparency with regard to the energy consumption of production systems and the particular machines [16]. Furthermore, suitable operating strategies and schedules have to be considered which can only be applied when machines are closely connected [20]. The two types of energy flexibility can be assigned to different operating levels taking into account the different time periods. Long-term measures are planned at company or production management levels, while short-term measures are only implemented at production levels [21].

Energy has already been considered as a factor in PPC, but the changes in the electricity market makes it a key flexibility factor [22]. In order to enable short-term, energy-flexible control the allocation of consumption capability must be aligned with the multi-layered target system of the central PPC. The main task is the economic comparison of all target

parameters (delivery reliability, product quality, throughput times, etc.) [23, 24]. To generate the correct target specifications for the production control, the energy consumption data must already be integrated into production planning. The planning process for in-house production then serves as the basis for the systematization of the energy consumption and procurement: batch size calculation, scheduling and capacity planning as well as sequence planning [23, 24]. Load curve prognoses are affected by target times and by power requirements resulting from in-house production planning with the information on the energy requirement per component [23]. These prognoses are then adapted to an energy supply or an energy price using optimization procedures.

However, the measures taken by production planning mainly relate to the postponement or exchange of production orders. No direct change in the load profiles of the individual orders have been tested; this is achieved through production control measures. They are assigned to the area of technical energy flexibility and directly influence the plant- and production-specific load profile. [25, 26]

A further distinction can be made regarding the time required in advance of activating a flexibility measure. Production planning approaches usually require a lead time of several days to adapt the machine occupancy or to generate an ideal-typical production program. In contrast, technical approaches can be applied by production control to achieve immediate changes in the consumption profile in order to react to short-term fine-grained price signals in the minute range. In addition, participation in the balancing energy market can be realized through short-term production control measures [16].

2.2. Energy-aware scheduling in reconfigurable manufacturing systems

Previous research aimed to optimize certain criteria, such as total energy consumption [27, 28], the power required to operate the system [29, 30], or costs associated with time-of-use pricing [9, 10].

Reconfigurable manufacturing systems have many advantages with regard to these challenges. However, there are very few research projects focused on integrating reconfigurability and energy constraints or objectives. Choi & Xirouchakis [31] proposed a model that takes into account environmental effects and energy consumption on capacity changes in a flexible and reconfigurable environment. They studied configurations of an RMS to evaluate its performance based on energy-related, environmental, and productivity criteria. A configuration corresponds to a production plan and has an effect on the total amount of consumed energy, which is composed of the process-related energy, the transportation of equipment and waste removal. However, the authors neglected to include other energy-related criteria, such as the power required to perform single operations or the time-dependent load profile. Zhang et al. [32] introduced the concept of energy-efficient RMS (REMS) and proposed a discrete event simulation model to evaluate the system's energy efficiency. The model describes local reconfigurations, i.e. switching an active machine into sleep mode. Furthermore, they did not considered power peaks related to simultaneous operations and the approach also does not allow the system to be extended to external constraints such as requirements for energy savings within a given period. Liu et al. [33] investigated a reconfigurable system consisting of a rotary table and a set of machines and modules. The approach is split into two phases: the system's design and its control. The objectives relate to the minimization of the cycle time and the overall costs, which include energy expenditures (starting up the system, consumption related to the rotation of the table, turrets and operations). Ghanei & AlGeddawy [34] utilized the adaptive capabilities of the production system to optimize the planning according to real-time energy tariffs.

However, the research projects summarized in this section did not consider the effect of power thresholds at the operational level and during RMS scheduling. Hence, the mathematical formulation of a scheduling problem in the context of multiple path RMS with variable power limitation will be discussed further.

3. Problem formulation

Nomenclature

Parameters

J_g	g^{th} job
r	number of jobs
n_g	number of operations for J_g
O_i	i^{th} operation
V	set of operations
O^+	Set of dummy operations for power threshold variations
T_i	time for i^{th} variation in power threshold
V^+	set of operations adjoined with dummy operations for variable power threshold modelling
M	set of machine tools
M_i	set of machine tools available for operation O_i
K	set of stations
v, q	respective number of machine tools and stations
C_i	set of possible configurations for processing O_i
c	index for configuration selection
$M_{i,c}$	restricted set of available machine tools for O_i in configuration c.
$P_{i,m}$	processing time of O_i on machine tool m
$W_{i,m}$	power requirement of O_i on machine tool m
$DS_{i,c,j,c'}$	duration for reconfiguration between configurations c and c'
W_{max}	maximal available power overt time
H	large number

Variables

s_i	starting date of O_i
c_{max}	total production duration
p_i	processing time of O_i after machine assignment
w_i	power requirement of O_i after machine assignment
$y_{i,c}$	binary variable equal to 1 if operation O_i is assigned configuration c, 0 otherwise
$v_{i,m}$	binary variable equal to 1 if operation O_i is assigned machine tool m, 0 otherwise
$x_{i,j,m}$	binary variable equal to 1 if operation O_i is processed before operation O_j on machine tool m, 0 otherwise
$\varphi_{i,j}$	integer variable for power management
$\psi_{i,j}$	binary variable for detecting mandatory waiting time between operations because of power limitations
$u_{i,j,m}$	binary variable for detecting setup times when changing configurations.

The purpose of this study is to provide a novel approach for a reconfigurable multiple path shop floor, particularly taking power limitations into consideration. It is formulated as follows: a set J of r jobs (product orders) $J = \{J_1, \dots, J_r\}$ must be scheduled on a set M of v machine tools $M = \{M_1, \dots, M_v\}$. These machine tools can be mounted on q specific stations $K = \{K_1, \dots, K_q\}$. Each job J_g consists of a number of n_g operations. Accordingly, N operations must be scheduled with $N = \sum_{i=1}^{r} n_i$. An operation $O_i \in V$ is allowed to be executed on any machine tool of a given set $M_i \subseteq M$. The processing time of an operation O_i on a machine tool $m \in M_i$ and its required power are respectively noted as $P_{i,m}$ and $W_{i,m}$. Furthermore, each operation can be performed on only one machine tool and one station at the same time. Each couple $\{m \in M_i; K_j\}$ is considered as a configuration for processing the operation. Moving from one configuration to another requires a specific setup time. Keeping in mind that there is an assignment and a schedule for all operations, the starting time of an operation O_i is noted s_i. The objective is to minimize the total production duration c_{max} considering a variable power threshold that cannot be exceeded during the scheduling horizon (exogenous constraint). Several assumptions are made for the classical optimization problem, including availability of all machines, no pre-emption (i.e. once started, an operation cannot be interrupted) and release dates of all jobs at time 0.

The complete mathematical formulation of the above problem is given below, starting with the objective function c_{max}, which is subjected to several constraints and is to be minimized.

The first set of constraints defines the total production duration as the end date of all operations:

$$s_i + p_i - c_{max} \leq 0, \forall i \in O. \quad (1)$$

The second set of constraints ensures that for each operation, a configuration is selected:

$$\sum_m y_{i,c} = 1, \forall i \in O. \quad (2)$$

In constraints 3 and 4, the processing time and the power requirement of the operation are set according to the selected configuration:

$$p_i - \sum_{c \in C_i} P_{i,c} y_{i,c} = 0, \forall i \in O, \quad (3)$$

$$w_i - \sum_{c \in C_i} W_{i,c} y_{i,c} = 0, \forall i \in O. \quad (4)$$

The technological order of the operations has to be followed:

$$s_i + p_i - s_j \leq 0, \forall i, j \in O, J_i = J_j, i < j. \quad (5)$$

Depending on the selected configuration $y_{i,c}$, all related machine tools are specifically assigned to the operation O_i using constraint set 6. This allows to track tools/components that are shared between different machines:

$$y_{i,c} - v_{i,m} \leq 0, \forall i \in O, \forall c \in C_i, \forall m \in M_{i,c}. \quad (6)$$

Constraints 7 and 8 allow to select an order for processing operations that are assigned to the same machines and/or tools:

$$2x_{i,j,m} + 2x_{j,i,m} - v_{i,m} - v_{j,m} \leq 0 \quad \forall i, j \in O, J_i \neq J_j, \forall m \in M_i \cap M_j. \quad (7)$$

$$x_{i,j,m} + x_{j,i,m} - v_{i,m} - v_{j,m} \geq -1 \quad \forall i, j \in O, J_i \neq J_j, \forall m \in M_i \cap M_j. \quad (8)$$

Constraint set 9 adjusts the starting date of operations according to their precedencies on a resource. If operation O_i is processed before operation O_j on a given machine (binary variable $x_{i,j,m} = 1$), the starting time of O_j has to be later or equal to the end time of O_i. If a setup occurs between the two operations when moving from configuration c to c', an additional waiting time is considered ($DS_{icjc'}$):

$$s_i + p_i - s_j + Hx_{i,j,m} + DS_{i,c,j,c'} u_{i,j,m} \leq H, \quad \forall i, j \in O, J_i \neq J_j, \forall c, c' \in C_i \cup C_j, \quad \forall m \in M_{i,c} \cap M_{j,c'}. \quad (9)$$

Constraint set 10 ensures that a setup time is considered when operations are executed with the same equipment but with different configurations:

$$x_{i,j,e} + y_{i,c} - y_{j,c'} - Hu_{i,j,e} \leq 2, \quad \forall i, j \in O, i \neq j, \forall c, c' \in C_i \cup C_j, \quad c \neq c', \forall e \in M_{i,c} \cap M_{j,c'}. \quad (10)$$

If no precedencies exist between the operations, no setup time is considered on a specific piece of equipment:

$$u_{i,j,e} - x_{i,j,e} \leq 0, \forall i, j \in O, i \neq j, \forall e \in M_i \cap M_j. \quad (11)$$

Constraints 12, 13 and 14 ensure that dummy operations representing the variable power threshold each start at the right time (12) and have the right duration (13) and power requirements (14):

$$s_i = T_i, \forall i \in O^+, \quad (12)$$

$$p_i = P_i, \forall i \in O^+, \quad (13)$$

$$w_i = W_i, \forall i \in O^+. \quad (14)$$

Constraint set 15 describes that the maximum power threshold can never be exceeded:

$$\sum_{i \in V^+} \varphi_{0,i} \leq W_{max}. \quad (15)$$

Each operation receives exactly the power it requires for its processing:

$$\varphi_{0,i} + \sum_{i \in V^+, i \neq j} \varphi_{i,j} - w_j = 0, \forall j \in V^+. \quad (16)$$

Constraint set 17 allows each operation to transfer fewer power than the power it requires for its processing:

$$\sum_{j \in V^+, i \neq j} \varphi_{i,j} - w_j \leq 0, \forall i \in V^+. \quad (17)$$

Constraints 18 and 19 detect flow occurrences between operations and set the binary variable ψ_{ij} to 1 if required:

$$\varphi_{i,j} - W_{max} \psi_{i,j} \leq 0, \forall i, j \in V^+, \quad (18)$$

$$\psi_{i,j} - \varphi_{i,j} \leq 0, \forall i, j \in V^+. \quad (19)$$

Within the optimization, the technological order of operations of the same job has to be followed:

$$\psi_{i,j} = 0, \forall i, j \in O, J_i = J_j, i > j. \quad (20)$$

Constraint set 21 adjusts the starting time of the operations according to the modeled power transfers with respect to the power threshold:

$$s_i + p_i - s_j + H\psi_{i,j} \leq H, \forall i, j \in V^+. \quad (21)$$

4. Scenario-based application and results

In order to explain the objective of the schedule in the context of a reconfigurable manufacturing system, two simplified exemplary scenarios are compared.

The initial system consists of three stations (K_1 to K_3) with four machine tools which are able to perform milling ($2\ x\ M_1$), drilling (M_2), and turning (M_3) operations. The system is subject to a variable power threshold. Jobs, in order to produce three different parts (J_1 to J_3), have to be processed with the available machinery. Figure 1 shows the processing order and the related machine tools M_1 - M_3.

job 1	milling → M_1	drilling → M_2	turning M_3
job 2	turning → M_3	milling → M_1	drilling M_2
job 3	drilling → M_2	milling → M_1	turning M_3

Fig. 1 Job description in the initial system

From Figure 1, it can be mentioned that if some drilling operations can be performed on milling machine tools, having both brings more flexibility to the shop floor. Table 1 shows the specific power requirements *W* and processing times *P* for each operation.

Table 1. Machine tools for processing operations in the initial system.

job	M_1		M_2		M_3	
1	10 min	20 kW	15 min	10 kW	5 min	14 kW
job 2	M_3		M_1		M_2	
	8 min	13 kW	5 min	17 kW	12 min	9 kW
job 3	M_2		M_1		M_3	
	20 min	11 kW	10 min	18 kW	5 min	27 kW

The implemented linear program provides a schedule for the given system. Figure 2 shows the assignment to the stations and the corresponding load profile. As can be stressed, the second machine tool M1 is never used, and hence, this solution is equal to a classical schedule in a multiple path shop floor.

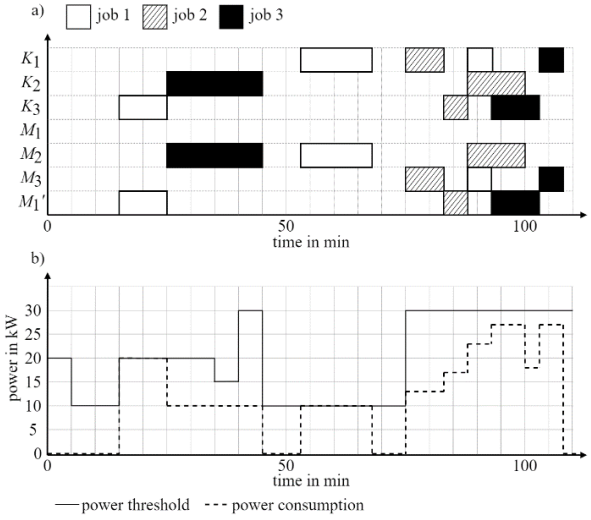

Fig. 2 Gantt chart (a) and power consumption (b) of a schedule in the initial system.

As a second exemplary use case, the system is changed by replacing the second milling machine with a milling machine of another type (M_4). Machine tool M_4 can process the same operations as M_1, but has different power requirements and processing times (Table 2). To illustrate the importance of having an energy-efficient machine tool in an RMS, Figure 3 shows an optimal schedule for the adapted system. If the overall power supply is sufficient, simultaneous operation of all jobs is possible and the best total production duration should be achieved, since the available tools (M_1, M_2, M_3) are the most performant ones (i.e. high speed and high power requirements).

Table 2. Machine tools for processing operations in the adapted system.

job	M_1		M_2		M_3	
1	10 min	20 kW	15 min	10 kW	5 min	14 kW
	M_4					
	30 min	5 kW				
job 2	M_3		M_1		M_2	
			5 min	17 kW		
	8 min	13 kW	M_4		12 min	9 kW
			15 min	5 kW		
job 3	M_2		M_1		M_3	
			10 min	18 kW		
	20 min	11 kW	M_4		5 min	27 kW
			26 min	5 kW		

However, as stressed in Figure 2, an insufficient power supply is observed while starting the first operation of job 1 (at *T = 0 min*) and it is not possible to process it completely as the available power decreases at *T = 5 min*. Due to the power limitation and the absence of an energy efficient machine tool, six operations still need to be processed at time *T = 75 min* (Figure 2). Having an energy-efficient machine tool allows a reaction and a reconfiguration of the production system. In Figure 3, the operation of job 1 starts with M_4 on K_2. Later, M_4 is changed to M_1 in order to process the second operation of job 2 during the time window *[40 min; 45 min]* where the power supply is higher. Three operations still need to be processed at time *W = 75*. In this example, the energy-aware schedule reaches a total production duration which is almost 15 % lower than the one for the initial system. One advantage of the approach presented here is that it is not mandatory to change the whole system in order to produce only one product family. Nevertheless, if these two small scale scenarios show the purpose and the advantages of the approach in energy efficient production systems, larger scale use cases will be addressed in the future in order to get closer to traditional manufacturing environments.

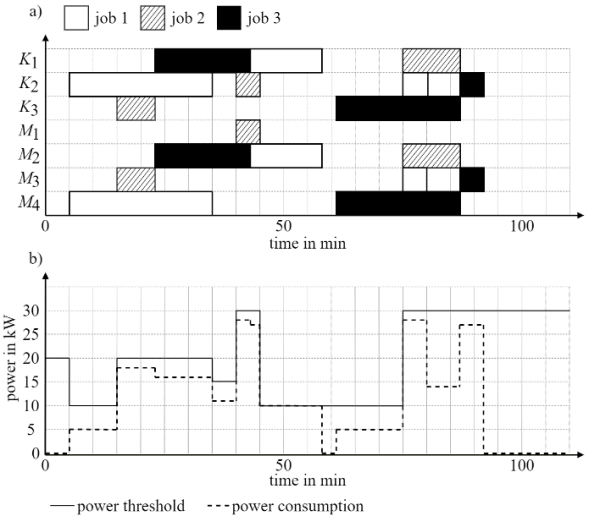

Fig. 3 Gantt chart (a) and power consumption (b) of a schedule in the adapted system.

5. Conclusion

In summary, this study provides a mathematical formulation of a reconfigurable multiple path shop floor. The approach demonstrates that considering energy-efficient machine tools in RMS will allow productivity on the shop floor to be maintained when the power supply is fluctuating. The results indicate that small-scale problems can be solved using linear solvers. However, larger-scale instances should be addressed to even better approximate present-day industrial production systems. In the future, the approach could be extended to consider a renewable energy source forecast to compute the power threshold dynamically, anticipate changes, and reconfigure the production system accordingly, with expected changes in scheduled activities. The concept of scalability could also be addressed. Reconfiguration costs should also be included. Finally, the dependence between the rescheduled activities, the load thresholds and reconfiguration costs could be investigated.

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