Production scheduling with discrete and renewable additional resources

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Abstract. In this paper an approach to planning of additional resources when scheduling operations are discussed. The considered resources are assumed to be discrete and renewable. In most research in scheduling domain, the basic and often the only type of regarded resources is a workstation. It can be understood as a machine, a device or even as a separated space on the shop floor. In many cases, during the detailed scheduling of operations the need of using more than one resource, required for its implementation, can be indicated. Resource requirements for an operation may relate to different resources or resources of the same type. Additional resources are most often referred to these human resources, tools or equipment, for which the limited availability in the manufacturing system may have an influence on the execution dates of some operations. In the paper the concept of the division into basic and additional resources and their planning method was shown. A situation in which sets of basic and additional resources are not separable – the same additional resource may be a basic resource for another operation is also considered. Scheduling of operations, including greater amount of resources can cause many difficulties, depending on whether the resource is involved in the entire time of operation, only in the selected part(s) of operation (e.g. as auxiliary staff at setup time) or cyclic – e.g. when an operator supports more than one machine, or supervises the execution of several operations. For this reason the dates and work times of resources participation in the operation can be different. Presented issues are crucial when modelling of production scheduling environment and designing of structures for the purpose of scheduling software development.

1. Introduction
Formulating the problem of scheduling it is necessary to define the production resources first. The role of the decision maker at this stage is the proper selection of resources, which are directly involved in the execution of orders, and determination of the value of their parameters. The set of resources can be expanded iteratively, as a result of the feedback for further stages of the process of feasible schedule construction. This is due to the fact that production orders are specifying at the later stages of the scheduling, and that the decision-maker initially may not be sure which of the resources will be used for their realization. Modifications in the set of resources may also be associated with the production flow simulations concerning production capacity, the potential development of infrastructure and investment profitability.
The general classification of production resources distinguishes three types: renewable, non-
renewable and doubly constrained. Renewable resource is a resource that after the completion of one
task can be load by the next one. Examples of this type of resources are machines, workers, tools etc.
Limitations associated with the renewable resource concern the scope of its usage, e.g. capacity or
availability at the given period of time. In such kind of system resources the number of resource units
available at the every moment is usually limited. Non-renewable resources are not subject to
regeneration process, and related constraints apply to their consumption. For a non-renewable resource
its global quantity is mostly limited. Examples of non-renewable resources are the raw materials,
funds or energy. In a production system doubly constrained resources may also be considered –
for which both usage and consumption are limited. In this case limited availability at any given time, and
total consumption are calculated. Double-limited resource can be e.g. energy (a medium) with limited
power allocation and total consumption or funds, if the total capital of the entire project is defined and
which is assigned to subsequent periods in a certain amount.

Scheduling problems, which take into account the limited availability of resources, are called
Resource Constrained Scheduling Problems (RCSP) [1, 2, 3, 4]. In scheduling of manufacturing
systems, in planning of activities the methods from the area of Resource Constrained Project
Scheduling Problem (RCPSP) can also be used [1, 5].

From the scheduling point of view an important feature of resources is divisibility, according to
which resources are distinguished discrete and continuous [6, 7]. Discrete resources are planned at
fixed intervals and, in the planning period, they have a finite number of available and indivisible units
of time to be used for tasks execution. Unlike the above, tasks can be assigned to the continuous
resource at any time. Adoption of relatively small values of time unit and assumptions about
considering the resources as a discrete, in fact, does not limit the availability of the resource and
simplifies the planning of their work [8, 9, 10, 11].

In the rest of the paper only renewable and discreet type of resources are handled. The omission of
non-renewable and double constrained resources has its justification in the practical problems of
operation of manufacturing systems, among which the availability of positions, human resources, tools
and accessories is essential for production planning.

2. Production resources
In most researches primary and often the only type of resource is a machine. A "machine" in this case
can be understood as a literally machine but also as any kind of workstation, processor, device,
workbench, a separate space, etc. In manufacturing systems, with a large number of resources, as a
single resource can also be considered a production cell of a higher level, i.e. section, workcenter or
production line, division, department or production plant in a specific location [12,13,14]. In this case,
a schedule can be made in a hierarchical manner, by scheduling of higher level cells first, and then,
more detailed, at lower level cells.

The production system is described by a set of resources. In a situation when some operations
require more than one resource the set of resources \( S = \{ S_i, i=1,\ldots,m \} \) into two, not necessarily disjoint,
sets \( S = M \cup R \), including the main resources \( M = \{ M_a, a=1,\ldots,mm \} \) and additional resources \( R = \{ R_e, \)
e=1,\ldots,\mr \} ; where \( mm \) is the number of main resources, \( \mr \) - the number of additional resources, and
\( m \) - the number of all the resources, with relationship \( m \leq mm + \mr \).

In order to improve the process of scheduling of alternative resources - resource groups can be
defined. \( GRz = \{ GRz_s, s = 0,\ldots,\mg \} \), where \( GRz \) is a set of resources groups, \( \mg \geq 0 \). A resource
group indicates set of resources that can perform the selected operation or group of operations. The
preference of choice (qualifications degree) of a i-th resource in the s-th group is expressed by the
priority (weight) \( wzi,s \). Resource membership of different groups represents the range of possibilities
for its use, e.g. universality of production means, qualifications and skill level of the workers.
The production resource \( S_i \) (renewable, discrete) is described by:

\[
S_i = (c_i, kzi, Lgz, Ka) \quad (1)
\]
where: \( c_i \) – the capacity of \( i \)-th resource, \( k_z \) – the unit cost, \( L_g z_i \) – the list of resource groups, which include the \( i \)-th resource, \( K_a b \) – \( b \)-th calendar, specifying the availability of the resource.

The resource capacity \( c_i \) refers to efficiency, and determines the maximum number of possible tasks, concurrently performed in the resource \( (c_i \geq 1) \). Resource with a capacity greater than 1 can process more tasks simultaneously. That resource can be treated as a set of resources with \( c_i = 1 \), assuming additional restrictions related to the synchronous loading/unloading, technological similarity etc. Unit cost of resource \( k_z \) is a parameter used in calculation of the order cost in a given production route. List of groups of \( L_g z_i \) determines the ability to perform a given operation or group of operations, with the qualification degree expressed by priority. Membership of \( i \)-th resource is defined by resource list \( L_g z_i \subset GRz \). The working time calendar \((K_a b)\) determines the availability of the resource for performing assigned operations. Resources in the production system work according to arbitrary generated calendars. The calendar is independent of the resource but resources can use the same calendar. The set \( K_a \) determines the system-defined calendars, \( K_a = \{K_a b, b=1, \ldots, m_k\} \), where \( m_k \) is the number of defined calendars. Working time calendar contains periods of availability \( K_a b = \{O_d b, d=1, \ldots, m_d b\} \), where \( m_d b \) is the number of availability periods in the \( b \)-th calendar. Each period is determined by the start date and finish date, \( O_d b, d = (t r_d b, t z_d b) \).

3. Generation of calendar
Siemens Calendar time as the list of availability periods is generated from a set of calendar periods \( O_k b, c = \{O_k b, c, c=1, \ldots, m_c b\} \), where \( m_c b \) represents the number of calendar periods defined in the \( b \)-this calendar. The calendar period is described by:

\[
O_k b, c = (t r_{b, c}, t z_{b, c}, \text{dost}_{b, c}, \text{cykl}_{b, c}, \text{typ}_{b, c}),
\] (2)

where: \( t r_{b, c} \) – starting date of the \( c \)-th calendar, \( t z_{b, c} \) – finishing date, \( \text{dost}_{b, c} \) – availability of a resource, \{available, unavailable\}, \( \text{cykl}_{b, c} \) – periodicity, \{ cykl_{b, c} = 0 - non-cyclic, cykl_{b, c} > 0 - cyclic \}, \( \text{typ}_{b, c} \) – category of period \{work, failure, maintenance, overtime, \ldots \}.

On the basis of defined parameters of each period is assigned to one of four sets: cyclic periods of availability \( \text{COD}_b \), cyclic periods of unavailability \( \text{CON}_b \), non-cyclic periods of availability \( \text{NOD}_b \) or non-cyclic periods of unavailability \( \text{NON}_b \). The identification and aggregation of these periods enables creating the availability periods of a calendar (figure 1):

\[
K_a b = \text{COD}_b \setminus \text{CON}_b \cup \text{NOD}_b \setminus \text{NON}_b
\] (3)

4. Operations
The manufacturing process can be considered by the set of operations \( P_k = \{O_{k, g}, g=1, \ldots, n_o k\} \), where \( n_o k \) is the number of operations in the \( k \)-th process. An operation \( O_{k, g} \) is described by:

\[
O_{k, g} = (L_w z_{k, g}, \text{pre}_{k, g}, \text{re}_{k, g}),
\] (4)

where: \( L_w z_{k, g} \) – the list of resources requirements, \( \text{pre}_{k, g} \) – the possibility of preemption, \( \text{re}_{k, g} \) – the resumability (all applies to \( g \)-th operation in the \( k \)-th process).

The list of resources requirements \( (L_w z_{k, g}) \) determines the main and additional resources required for the operation executing. Alternative operations differ in this configuration of the required resources and are used for creating different routes of processes \([15, 16, 17]\). It was assumed that dates and work times of additional resources in the operation can be different (figure 2) so the list consists of set \( L_w z_{k, g} = \{R_{k, g, h}\} \), where \( R_{k, g, h} \) is a \( h \)-th requirement of \( O_{k, g} \), and is described by:
Aggregated periods of calendar

\[ \text{NON}_1 = \{\text{Ok}_1, 4\} \]

\[ \text{NOD}_1 = \{\text{Ok}_1, 3\} + \]

\[ \text{CON}_1 = \{\text{Ok}_1, 2\} + + + \]

\[ \text{COD}_1 = \{\text{Ok}_1, 1\} \]

Figure 1. Construction of the resource work calendar.

\[ \text{RR}_{k,g,h} = (\text{So}_{k,g,h}, Ls_{k,g,h}, \text{cor}_{k,g,h}, t_{j,k,g,h}, \text{tpz}_{k,g,h}, k_{o,k,g,h}), \] (5)

where \( \text{So}_{k,g} \) is a subset of the group of resources or specific resources required in \( g \)-th operation in the \( k \)-th process, \( \text{So}_{k,g} \subseteq S \), \( Ls_{k,g} \) – the list of quantitative requirements of particular resources in \( \text{So}_{k,g} \), \( \text{cor}_{k,g,h} \) – start date correction, \( t_{j,k,g,h} \) – the operation time, \( \text{tpz}_{k,g,h} \) – the setup time, \( k_{o,k,g,h} \) – the cost.

Figure 2. Resources requirements of an operation.

The setup time (\( \text{tpz}_{k,g} \)) can be fixed or variable, depending on the previous operation in the schedule. Taking into account the variable setup times allows precise scheduling of workstations, which setup times largely depends on the number of exchanged tools (if the capacity of tools magazine
is not sufficient). This also allows minimizing setup times by sequencing of operations with similar tools requirements. The value of operations cost ($k_{o_{\theta}}$) is used for calculation of the total cost of the given production order route. Preemption ($pre_{\alpha}$) determines the admissibility of breaking execution of an operation, in order to carry out the other, e.g. with a higher priority. Resumability ($re_{\alpha}$) determines if the operation may be resumed after the resource unavailability, resulting from the breakdown, calendar etc.

5. The method of operations scheduling with additional resources

The proposed method applies to operation scheduling with additional resources and is an extension of the method of scheduling presented in [17, 18]. Stages of the proposed method are presented in figure 3.

![Diagram](attachment:image.png)

**Figure 3.** The preparation to operation scheduling in case of additional resources.

At the first stage the identification of all the resources of operation to scheduling stored in $L\omega_{\alpha_{\theta}}$ – the list of resources requirements is done. Then the procedure iteratively considers time constraints of each resource, starting from the main resource. Next, the map of resource(s) availability is created. If the item in the list indicates the resource group and more resources from the group – indicated is only the availability of required amount of resources. As was shown in figure 2 the working times of individual resources may vary from the time of main resource. In this case, particular availability maps should be transformed according to defined differences in dates and times of their work. Aggregation of all transformed maps of required resources availability enables scheduling of given operation.
6. Summary
Additional resources scheduling is one of the fundamental problems in most real manufacturing systems. Discussion is limited to systems with discrete production flow and considered resources are renewable (machines, tools, human resources). The paper presents the model of the production system and the general method for scheduling operations, as an extension of manufacturing system scheduling procedure, if more than one resource at the same time is required. The most important characteristics of resources, including time calendars are described. Such functionality greatly increases the usefulness of scheduling system for practical applications.

References
[1] Błażewicz J, Ecker K H, Pesch E, Schmidt G and Weglarz J 2007 Scheduling computer and manufacturing processes (Springer: Berlin)
[2] Van den Bergh J, Beliën J, De Brucker P, Demeulemeester E and De Boeck L 2013 Personnel scheduling: A literature review European Journal of Operational Research 226 pp 367-385.
[3] Rattanatamrong P and Fortes J 2010 Real-time scheduling of mixture-of-experts systems with limited resources Proceedings of the 13th ACM International Conference on Hybrid Systems: Computation and Control (Stockholm) pp 71-80
[4] Kolisch R and Padman R 2001 An integrated survey of deterministic project scheduling Omega 29 pp 249-272
[5] Artigues C, Demasse S and Neron E 2010 Resource-Constrained Project Scheduling: Models, Algorithms Extensions and Applications (John Wiley & Sons: Portland)
[6] Edis E B, Oguz C and Ozkarahan I 2013 Parallel machine scheduling with additional resources: Notation, classification, models and solution methods European Journal of Operational Research 230 pp 449-463
[7] Slowinski R 1980 Two approaches to problems of resource allocation among project activities – a comparative study Journal of the Operational Research Society 31 pp711-723.
[8] Ćwikla G 2014 The methodology of development of the Manufacturing Information Acquisition System (MIAS) for production management Applied Mechanics and Materials 474 pp 27-32
[9] Zolkiwski S 2010 Dynamical Flexibility of Complex Damped Systems Vibrating Transversally in Transportation Solid State Phenomena 164 pp 339-342
[10] Dzitkowski T and Dymarek A 2013 Active synthesis of discrete systems as a tool for stabilisation vibration Applied Mechanics and Materials 307 pp 295-298
[11] Jurczyk-Bunkowska M 2013 Characteristics of Decision Problems In Innovation Process Planning Proceedings of the 14th European Conference on Knowledge Management (Kausas) pp 795-804
[12] Sękala A, Banaś W and Gwiazda A 2014 Agent-based systems approach for robotic workcell integration Advanced Materials Research 1036 pp 721-725
[13] Hetmanczyk M and Michalski P 2014 Self-excitation phenomenon of quasi shielded inductive proximity switches Advanced Materials Research 837 pp 405-410
[14] Płaczek M 2014 Computer Aided Analysis of Systems with MFC Actuators Advanced Materials Research 1036 pp 711-714
[15] Kalinowski K, Grabowik C, Paprocka I and Kempa W 2014 The model of discrete production scheduling system in UML notation - classes diagrams Advanced Materials Research 837 pp 416-421
[16] Kalinowski K, Grabowik C, Paprocka I and Kempa W 2014 Interaction of the decision maker in the process of production scheduling Advanced Materials Research 1036 pp 830-833
[17] Kalinowski K, Grabowik C, Kempa W and Paprocka I 2014 The graph representation of multivariant and complex processes for production scheduling Advanced Materials Research 837 pp 422-427
[18] Kalinowski K, Kręczeny D and Grabowik C 2013 Predictive-reactive strategy for real time scheduling of manufacturing systems Applied Mechanics and Materials 307 pp 470-473