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Short Communication

A note on the paper "Resource-constrained project scheduling: Notation, classification, models and methods" by Brucker et al.

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Abstract

The great variety of project scheduling problems studied in the ever growing literature motivated the recent development of classification schemes. In a recent paper (European Journal of Operational Research 112 (1999) 3–41), Brucker et al. make the claim that, so far, no classification scheme exists which is compatible with what is commonly accepted in machine scheduling and introduce a new classification. In this note, we critically review major shortcomings of the suggested scheme which place heavy limitations on its potential use. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Project scheduling; Machine scheduling; Classification scheme

1. Introduction

The great variety of project scheduling problems studied in the literature (for recent reviews see Herroelen et al., 1998d; Brucker et al., 1999) motivated the introduction of a classification scheme. Inspired by discussions held at the *Workshop on Scheduling and Heuristic Search* held on 8 May 1997 at the A. Gary Anderson Graduate School of Management, University of California, Riverside, USA, a classification scheme was developed by Herroelen, Demeulemeester and De Reyck which, as the result of intensive interactions among various members of the project scheduling community, went through a series of modifications which emerged into the publication of the scheme as a leading chapter in the book edited by J. Weglarz *Project Scheduling – Recent Models, Algorithms and Applications* (Herroelen et al., 1998c) and the presentation of updated versions at recently held workshops and conferences (Herroelen et al., 1998a,b, 1999).

In their otherwise excellent review paper, Brucker et al. (1999) – without giving any justification whatsoever – made the undocumented

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claim that the classification scheme of Herroelen et al. (1998a,b,c) would not be compatible with "what is commonly accepted in machine scheduling" and claimed that "there is still a gap between machine scheduling on the one hand and project scheduling on the other hand with respect to both a common notation and a classification scheme". As a result, they deemed it necessary to "close the gap" and to provide their own classification scheme which they claim to be compatible with machine scheduling and to be capable of classifying the "most important models dealt with so far".

In this paper, we review in Section 2 the major shortcomings of the Brucker et al. scheme. These shortcomings will prove to be so many that they put heavy limitations on the potential use of the scheme. Overall conclusions are presented in Section 3. For ease of reference, the fundamentals of the project scheduling classification schemes are presented in Appendix A.

2. The classification scheme of Brucker et al.

In line with the original suggestion of Herroelen et al. (1998a,b,c), Brucker et al. (1999) provide a classification scheme for project scheduling problems which describes the resource environment, the activity characteristics, and the objective function as an extension of the $\alpha|\beta|\gamma$-scheme used in the machine scheduling literature. The scheme, however, differs in the precise settings used.

2.1. Field α: Resource environment

The α-field in the $\alpha|\beta|\gamma$-scheme used in the machine scheduling literature (Blazewicz et al., 1983; Brucker, 1995; Graham et al., 1979) uses a two-parameter string $\alpha_1\alpha_2$ to specify the machine environment. The empty symbol for α_1 refers to a single machine problem. Proper symbols are used for α_1 for specifying other types of single-stage production: parallel machines (P for identical, Q for uniform and R for unrelated parallel machines) and multi-purpose machines with identical ($PMPM$) and uniform speeds ($QMPM$). Multi-stage (multi-operation) production is accommodated by other settings: G for a general shop, J for a job shop, F for a flow shop, etc. The α_2 parameter is used to denote the number of machines. As such, the machine scheduling scheme separates *machines* from other types of resources which are described in the β-field used to describe the job characteristics.

Brucker et al. (1999) state that in order to *distinguish* between specific machine scheduling problems and project scheduling problems, they introduce in the α-field PS (project scheduling) or MPS (multi-mode project scheduling). PS can be augmented to PSm,σ,ρ according to the notation of Blazewicz et al. (1983) for resource-constrained machine scheduling. The m stands for m renewable resources; σ units of each resource are available and each activity requires at most ρ units of each resource. In the case of multi-mode project scheduling, the notation is analogously augmented by $MPSm,\sigma,\rho;\mu,\tau,\omega$ to accommodate the non-renewable resources: μ non-renewable resources, τ units of each non-renewable resource available, while each activity requires at most ω units of the resources. If an entry of $m,\sigma,\rho;\mu,\tau,\omega$ is replaced by $\cdot$, the values of the parameters are specified in the input. For $PSm,\cdot,\cdot$ and $PSm,\sigma,\cdot$ the authors write PSm and PSm,σ, respectively, for short. If all values in m,σ,ρ are specified in the input, they write $\cdot$ instead of $\cdot,\cdot,\cdot$. Likewise, for $PS\cdot$ and $MPS\cdot$; they write PS and MPS, respectively.

If compatibility is the issue, there seems to be no reason why separate symbols PS and MPS should be used to *distinguish* between project scheduling, multi-mode project scheduling, and machine scheduling. Machines are essentially renewable resources. A project consists of activities which are subject to precedence constraints and require renewable and non-renewable resources. A project schedule is then defined as a set of activity start times which is time-feasible and/or resource-feasible. Using separate symbols PS and MPS essentially denies the fact that project scheduling is essentially a *meta*-problem which comprises machine scheduling problems as special cases. Moreover, the distinction between single and multiple modes basically pertains to activity characteristics, and, hence, should preferably be specified in the β-field. In addition, there is no reason why the distinction between single and multiple execution modes should be promoted to serve as the single predominant characteristic to distinguish project scheduling from machine scheduling.

The $m,\sigma,\rho;\mu,\tau,\omega$-extension is rather unclear and may lead to misunderstandings. First, if the values of the parameters are specified in the input (such as in setting $PS\cdot$) or if the problem setting involves requirements for one renewable or non-renewable resource only (such as in setting $PS1$), the reader can only guess which resource type is actually at stake. Moreover, the use of PS or MPS as such provides no indication of whether or not the problem actually involves any resources. Second, the provision for only renewable and non-renewable resources ignores the existence of partially (non)renewable resources referring to resources, the availability of which is defined for a specific time interval (subset of periods). For each partially renewable resource type there are a number of subsets of periods, each characterized by a specific (non-renewable) availability of the resource type. Herroelen et al. (1998a,b,c) argue that partially (non)renewable resources, first introduced by Schirmer and Drexl (1996), can be viewed as a generic resource concept in project scheduling, as they include both renewable and non-renewable (and, hence, also doubly constrained) resources. A partially renewable resource with a specified availability for a time interval equal to the unit duration period is a renewable resource. A partially renewable resource with a specified availability for a time interval equal to the project horizon is essentially a non-renewable resource. Partially renewable resources with a specified availability on both a unit duration and a total project horizon basis can be interpreted as doubly constrained resources. Herroelen et al. (1998a,b,c) use the partially renewable resource concept in a generic way which allows for a straightforward identification of the various resource categories. Third, limiting σ and τ to denote the *constant* availability of *each* renewable and non-renewable resource, respectively, excludes the possibility of (deterministic or stochastic) resource availabilities which may not only differ among the resources but which may also vary over time. Using ρ and ω to denote the number of units of *each* renewable (respectively, non-renewable) resource required by *each* activity ignores the possibility that resource requirements (a) may differ among activities, (b) may vary over time, and (c) may be imposed according to a constant or discrete resource requirement function. Moreover, doing so denies the fact that resource requirements are essentially activity characteristics, and hence, should not be specified in the α-field, but in the β-field.

2.2. Field β: Activity characteristics

Brucker et al. (1999) state that they use established notations from machine scheduling, without, however, being specific about the precise meaning, nor the sequence, of each parameter setting in the β-field. As such the authors do not provide any clue nor capability for specifying activity preemption (preempt-resume and preempt-repeat) or activity deadlines. Neither do they allow for an unambiguous description of the precise nature of the activity resource requirements (constant; variable; discrete and continuous requirement-duration functions, intensity or rate functions; see Herroelen et al., 1998a,b,c), the financial activity characteristics (nature of cash flows, payment structure), the possibility of sequence-dependent change-over times, and the provision for mode identity constraints where the set of activities is partitioned into disjoint subsets and all activities in a subset must be executed in the same mode. The authors give no provision for distinguishing between continuous and discrete activity durations. Moreover, the authors use the notation *prec* to denote, what they call, *general* precedence constraints. Actually, the precedence constraints the authors have in mind are finish–start precedence relations with zero time lag, which are anything but general.

The authors use *temp* to denote general temporal constraints given by minimum and maximum start–start time lags between activities. First, there seems to be no reason for making a distinction between general *precedence* and general *temporal* constraints as the general precedence constraints they refer to are actually finish–start temporal constraints with zero time lag.

Moreover, and much more important, is the authors' restriction of the temporal constraints to minimal *and* maximal time lags of the *start–start* type only. First of all, it is well-known that the use of finish–start, start–start, start–finish and finish–finish time lags of the *minimal* type constitutes an important subclass (the so-called *precedence diagramming*) which certainly deserves an independent classification. A major drawback of the authors' restriction to start–start time lags, however, is that it does not allow for a proper classification of project scheduling problems in which the activities possess multiple execution modes and in which the precedence relations between the activities may represent arbitrary minimal and maximal time lags between their starting and completion times. In that case, it is not allowed to transform the minimal and maximal finish–start, start–finish and finish–finish precedence relations into equivalent minimal start–start time lags (using the rules presented in Bartusch et al., 1988), because the length of such a standardized time lag then depends on the execution mode of the activities participating in the precedence relation. Therefore, we strongly advise that the generalized precedence relations present in an activity network are *not* transformed into 'equivalent' minimal start–start time lags in order to prevent erroneous representations of project networks and because it yields a more natural representation of the actual conditions.

Last but not least, the authors do not make room for the important class of problems defined on activity networks of the probabilistic type, where the evolution of the corresponding project is not uniquely determined. This category encompasses generalized activity networks (Elmaghraby, 1977) such as GERT (Neumann and Steinhardt, 1979).

2.3. Field γ: Objective function

Brucker et al. (1999) prefer to describe objective functions by the corresponding formulas. In principle there seems to be nothing against this. However, the major drawback of this principle is that it does not allow for a concise classification of important problem categories. As an example, procedures have been developed for the resource-constrained project scheduling problem with generalized precedence relations which allow for the use of *any* regular objective function. Herroelen et al. (1998a,b,c) classify this general problem setting as $m,1,va|gpr,\rho_j,\delta_j,vr|reg$. The $m,1,va$ parameter setting in the α-field refers to an arbitrary number (m) of renewable resources (1) which are available in variable amounts (va). The setting gpr in the β-field refers to generalized minimal and maximal timelags, the ρ_j and δ_j refer to activity ready times and deadlines, respectively, while the variable resource requirements are denoted by the setting vr. The reg in the γ-field refers to any regular objective function. It is not clear how this setting could be classified by the Brucker et al., scheme.

As another example, Brucker et al. (1999) distinguish between the budget problem (for a given non-negative budget, find an assignment of processing times to activities with total cost within the budget which minimizes the makespan) and the deadline problem (for a given project deadline, find an assignment of processing times to activities with project makespan within the deadline that minimizes the total cost). They code the former as $MPS1|prec|C_{\max}$ and the latter as $MPS1|prec|\sum c_k r_k(S,t)$, with the drawbacks of leaving the reader without any precise information on the fact that the single resource is of the non-renewable type and giving no indication at all about the nature of the assumed time/cost trade-off function (linear, discrete, convex,...). There is also a problem with the authors' use of the setting $\sum c_k r_k(S,t)$ in the objective function field. The symbol k is used to denote a resource type while only a single resource is considered in the deadline problem. Moreover, the single resource is of the *non*-renewable type, for which the setting $r_k(S,t)$ is rather meaningless. The simple setting $\sum c_j(p_j)$ would do a much better job. Additionally, in some studies room is made for a third objective which involves the computation of the complete time/cost trade-off function for the total project. Again, it is not clear how the Brucker et al. scheme will go along in classifying this problem setting. Herroelen et al. (1998a,b,c) readily classify this problem for discrete time/cost trade-off functions as $1,T|cpm,disc,mu|curve$. The 1 refers to the use of a single resource; the T identifies this resource to be non-renewable; the *cpm* refers to finish–start precedence constraints with zero time lag; *disc* refers to the discrete time/cost trade-off function (*cont* would describe general continuous trade-off functions, *lin* would describe the linear case, *conc* the concave case, *conv* the convex case, etc.); *mu* specifies that the activities have multiple prespecified execution modes; and *curve* denotes the proper objective.

As a last example, Brucker et al. (1999) classify the general net present value problem as $PS|temp|\sum c_j^{\mathrm{F}}\beta^{c_j}$. Again the reader is not informed about the possible use of resources and if this is the case, which resource types are used. In the objective function, c_j^{F} refers to the cash flow associated with activity j, which is assumed to occur at the completion time C_j of activity j, while β denotes the discount rate per period. Herroelen et al. (1998a,b,c) classify this problem as $gpr,c_j|npv$ if no resources are considered or as $m,1|gpr,c_j|npv$ for the resource-constrained case using $m,1$ to specify the use of renewable resources, *gpr* to denote the generalized precedence relations, c_j to specify the activity cash flows and *npv* for the objective. Some models, however, deal with periodic cash flows (e.g. payments at regular intervals) or assume that the cash flows are not given and that both the amount and the timing of the cash flows have to be determined (the so-called payment scheduling problem). Herroelen et al. (1998a,b,c) would readily classify the former problem as $m,1|gpr,per|npv$ and the latter as $m,1|gpr,sched|npv$. Again, it is not clear what settings to use in the Brucker et al., scheme.

3. Conclusions

In this note, we reviewed the numerous drawbacks of the classification scheme developed by Brucker et al. (1999). These drawbacks put a burden on the Brucker et al. scheme which is so heavy that the workability of the scheme can be seriously questioned.

These shortcomings are not shared by the scheme developed by Herroelen et al. (1998a,b,c) who relied on intense communication and Delphi-type of interaction of a number of researchers in the project scheduling field to develop a workable scheme which combines flexibility with sufficient rigour. Their scheme has been demonstrated to be capable of classifying the overwhelming variety of project scheduling problems studied in the literature and occurring in practice. Its effective use has been readily demonstrated by a number of authors (including Alcaraz and Maroto, 1998; Crespo-Abril et al., 1998; de Boer, 1998; Kolisch and Hartmann, 1998; Lova et al., 1998; Maroto et al., 1998). It has been recently extended into an integrated scheme for resource scheduling, which allows for the unique classification of both machine and project scheduling problems (Herroelen et al., 1999).

Appendix A

A.1. The classification scheme of Brucker et al. (1999)

A.1.1. Field α: Resource environment

PS	project scheduling
MPS	multi-mode project scheduling
PSm,σ,ρ	m resources, σ units of each resource available, each activity requires at most ρ units of the resources
$MPSm,\sigma,\rho;\mu,\tau,\omega$	multi-mode project scheduling with m renewable resources, σ units of each resource available, each activity requires at most ρ units of the resources, μ non-renewable resources, τ units of each resource available, each activity requires at most ω units of the resources.

If an entry for $m,\sigma,\rho;\mu,\tau,\omega$ is replaced by $\cdot$, the values of the parameters are specified in the input.

For $PSm,\cdot,\cdot$ and $PSm,\sigma,\cdot$. the authors write PSm and PSm,σ, respectively, for short. If all values in m,σ,ρ are specified in the input, they write $\cdot$ instead of $\cdot,\cdot,\cdot$. Likewise, for $PS\cdot$ and $MPS\cdot$; they write PS and MPS, respectively.

A.1.2. Field β: Activity characteristics

p_j	processing times
$p_j = 1$	all processing times (activity durations) are equal to one
$p_j = sto$	stochastic processing times
$\overline{d}$	deadline for project duration
prec	general precedence constraints between activities
chains, intree, outtree, tree…	precedence relations between activities are specified by chains, intree outtree, tree …
temp	general temporal constraints given by minimum and maximum start–start time lags between activities

A.1.3. Field γ: Objective function

Objective functions are described by the corresponding formulas. Besides the classical objective functions $C_{\max}, L_{\max}, \sum w_j C_j, \ldots$:

$\sum c_j^{\mathrm{F}} \beta^{c_j}$	net present value (c_j^{F} cash flow, β discount factor)
$\sum c_k f(r_k(S,t))$	resource levelling (c_k cost per unit of resource k, $r_k(S,t)$ usage of resource k at time t given schedule S)
$\sum c_k \max r_k(S,t)$	resource investment

A.2. The classification scheme of Herroelen et al. (1998a,b,c)

A.2.1. Field α: Resource characteristics

The resource characteristics of a project scheduling problem are specified by a set α containing at most three elements α_1, α_2 and α_3. Let $\circ$ denote the empty symbol which will be omitted when presenting specific problem types. Parameter $\alpha_1 \in \{\circ, 1, m\}$ denotes the number of resource types:

$\alpha_1 = \circ$	no resource types are considered in the scheduling problem
$\alpha_1 = 1$	one resource type is considered
$\alpha_1 = m$	the number of resource types is equal to m

Parameter $\alpha_2 \in \{\circ, 1, T, 1T, v\}$ denotes the specific resource types used:

$\alpha_2 = \circ$	absence of any resource type specification
$\alpha_2 = 1$	renewable resources, the availability of which is specified for the unit duration period (e.g. hour, shift, day, week, month, …)
$\alpha_2 = T$	non-renewable resources, the availability of which is specified for the entire project horizon T
$\alpha_2 = 1T$	both renewable and non-renewable resources (including also doubly constrained resources, the availability of which is specified on both a unit duration period and a total project horizon basis)
$\alpha_2 = v$	partially (non-)renewable resources the availability of which is renewed in specific time periods

Parameter $\alpha_3 \in \{\circ, va, \tilde{a}, v\tilde{a}\}$ describes the resource availability characteristics of the project scheduling problem:

$\alpha_3 = \circ$	(partially) renewable resources are available in constant amounts
$\alpha_3 = va$	(partially) renewable resources are available in variable amounts
$\alpha_3 = \tilde{a}$	a stochastic resource availability which remains constant over time
$\alpha_3 = v\tilde{a}$	a stochastic resource availability which varies over time

A.2.2. Field β: Activity characteristics

The second field β specifies the activity characteristics of a project scheduling problem. It contains at most nine elements β_1, β_2, β_3, β_4, β_5, β_6, β_7, β_8, and β_9. Parameter $\beta_1 \in \{°, pmtn, pmtn\text{-}rep\}$ indicates the possibility of activity preemption:

$\beta_1 = °$	no preemption is allowed
$\beta_1 = pmtn$	preemptions of the preempt-resume type are allowed
$\beta_1 = pmtn\text{-}rep$	preemptions of the preempt-repeat type are allowed

The second parameter $\beta_2 \in \{°, cpm, min, gpr, prob\}$ reflects the precedence constraints:

$\beta_2 = °$	no precedence constraints (the activities are unordered)
$\beta_2 = cpm$	strict finish–start precedence constraints with zero time lag, as used in the basic PERT/CPM model
$\beta_2 = min$	precedence diagramming constraints of the type start–start, finish–start, start–finish and finish–finish with minimal time lags
$\beta_2 = gpr$	generalized precedence relations of the type start–start, finish–start, start–finish and finish–finish with both minimal and maximal time lags
$\beta_2 = prob$	the activity network is of the probabilistic type where the evolution of the corresponding project is not uniquely determined in advance

This category encompasses generalized activity networks such as GERT. The β_2-parameter can be set to *gert* to specify a GERT network, to *deor* to specify GERT networks with exclusive-or node entrance and deterministic node exit, to *steor* to specify GERT networks with exclusive-or node entrance and stochastic node exit, etc.

The third parameter $\beta_3 \in \{°, \rho_j\}$ describes ready times:

$\beta_3 = °$	all ready times are zero
$\beta_3 = \rho_j$	ready times differ per activity

Parameter $\beta_4 \in \{°, cont, d_j = d, \tilde{d}_j\}$ describes the duration of the project activities:

$\beta_4 = °$	activities have arbitrary integer durations
$\beta_4 = cont$	activities have arbitrary continuous durations
$\beta_4 = (d_j = d)$	all activities have a duration equal to *d* units
$\beta_4 = \tilde{d}_j$	the activity durations are stochastic

Parameter $\beta_5 \in \{°, \delta_j, \delta_n\}$ describes deadlines:

$\beta_5 =°$	no deadlines are assumed in the system
$\beta_5 = \delta_j$	deadlines are imposed on activities
$\beta_5 = \delta_n$	a project deadline is imposed

Parameter $\beta_6 \in \{°, vr, \tilde{r}, v\tilde{r}, disc, cont, int\}$ denotes the nature of the resource requirements of the project activities:

$\beta_6 = °$	constant discrete resource requirements
$\beta_6 = vr$	variable discrete resource requirements
$\beta_6 = \tilde{r}$	stochastic constant discrete resource requirements
$\beta_6 = v\tilde{r}$	stochastic discrete variable resource requirements

If the activity durations have to be determined by the solution procedure on the basis of a resource requirement function, the following settings are used:

$\beta_6 = disc$	the requirements are a discrete function of the activity duration
$\beta_6 = cont$	the requirements are a continuous function of the activity duration
$\beta_6 = int$	the requirements are expressed as an intensity or rate function

We leave it up to the user to be more specific in the specification of the resource requirement function.

The type and number of possible execution modes for the project activities is described by parameter $\beta_7 \in \{\circ, mu, id\}$:

$\beta_7 = \circ$	activities must be performed in a single execution mode
$\beta_7 = mu$	activities have multiple prespecified execution modes
$\beta_7 = id$	activities are subject to mode identity constraints

Parameter $\beta_8 \in \{\circ, c_j, \tilde{c}_j, c_j^+, per, sched\}$ is used to describe the financial implications of the project activities:

$\beta_8 = \circ$	no cash flows are specified in the project scheduling problem
$\beta_8 = c_j$	activities have an associated arbitrary cash flow
$\beta_8 = \tilde{c}_j$	cash flows are stochastic
$\beta_8 = c_j^+$	activities have an associated positive cash flow
$\beta_8 = per$	periodic cash flows are specified for the project
$\beta_8 = sched$	both the amount and the timing of the cash flows have to be determined

Parameter $\beta_9 \in \{\circ, s_{jk}\}$ is used to denote change-over times:

$\beta_9 = \circ$	no change-over (transportation) times
$\beta_9 = s_{jk}$	sequence-dependent change-over times

A.2.3. Field γ: Performance measures

The third field γ is reserved to denote optimality criteria (performance measures):

$\gamma = reg$	the performance measure is any early completion (regular) measure
$\gamma = nonreg$	the performance measure is any free completion (non-regular) measure

The user is provided with sufficient degrees of freedom to introduce suitable measures through a proper setting of the parameter value or through the specification of the mathematical expression of the objective function(s). The following are some examples:

$\gamma = C_{\max}$	minimize the project makespan
$\gamma = \overline{F}$	minimize the average flow time over all subprojects or activities
$\gamma = L_{\max}$	minimize the project lateness
$\gamma = T_{\max}$	minimize the project tardiness
$\gamma = early/tardy$	minimize the weighted earliness-tardiness of the project
$\gamma = n_{\mathrm{T}}$	minimize the number of tardy activities
$\gamma = \sum sq.dev.$	minimize the sum of the squared deviations of the resource requirements from the average
$\gamma = av$	minimize the resource availabilities in order to meet the project deadline

$\gamma = rac$	minimize the resource availability costs
$\gamma = curve$	determine the complete time/cost trade-off curve
$\gamma = npv$	maximize the net present value of the project
$\gamma = E[\cdot]$	optimize the expected value of a performance measure
$\gamma = cdf$	determine the cumulative density function of the project realization date
$\gamma = ci$	determine the criticality index of an activity or of a path
$\gamma = mci$	determine the most critical path(s) or activities based on the criticality index
$\gamma = multi$	different objectives are weighted or combined
$\gamma = multicrit$	multicriteria functions

For multi-projects it is suggested to combine the different networks into a single network. For hybrid multi-project programs, the authors suggest to use the parameter setting corresponding to the most general case.

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