Advances in Production Management Systems

“Competitive Manufacturing for Innovative Products and Services”

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Editors
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PREFACE

Welcome to the IFIP WG5.7 Annual Conference, Advances in Production Management Systems, APMS 2012, being held at Rhodes, Greece, from 24 to 26 September 2012.

Since the first conference that took place in Helsinki back in 1990, APMS is one of the major events and the official conference of the IFIP Working Group 5.7 on Advances in Production Management Systems. Recently, APMS successfully took place in Washington (USA, 2005), Wroclaw (Poland, 2006), Linköping (Sweden, 2007), Espoo (Finland, 2008), Bordeaux (France, 2009), Cernobbio (Italy, 2010), and Stavanger (Norway 2011).

APMS 2012 is sponsored by the IFIP WG 5.7 and co-sponsored by the ATHENA Research & Innovation Centre and the Hellenic Maintenance Society in Greece. In an era of increased globalization and ever pressing needs for improved efficiency, the APMS 2012 theme is "Competitive Manufacturing for Innovative Products and Services". In this setting, among the key elements of success in modern Manufacturing and Production Management are:

- **Resource efficiency**: the ability to perform in a resource efficient manner throughout the lifecycle of a production process, product use or offered services.
- **Key Enabling Technologies**: the exploitation of the latest materials, manufacturing and production control technologies to support competitive and sustainable production
- **Networked Enterprise** and **Global Manufacturing and Supply Chains**: the ability to operate as a globally interconnected organization and perform at a global scale, both at intra and inter-organizational scale.
- **Knowledge intensity and exploitation**: the efficient use of the enterprise and human resources tangible and intangible knowledge, including efficient knowledge lifecycle management.
- **Innovation**: the ability to efficiently port R&D results into competitive new forms of production, products or services.

The APMS 2012 conference brings together leading experts from industry, academia and governmental organizations to present and debate about the latest developments in Production Management Systems and shape up the future of Competitive Manufacturing. It comprises 7 keynote talks and 36 sessions, including a dedicated Industry Panel Session, to offer the practitioners view on linking research to industry, thus efficiently supporting the innovation process. The keynotes bring up key issues on

- the Business Perspective of Manufacturing Research
- Sustainable manufacturing to support a competitive industrial base in Europe
- Integration and interoperability as a key enabler of production efficiency
- Energy and resource efficiency in operations
- Governmental and non-governmental initiatives to foster greater co-operation between academia, research and industry for the Factories of the Future.

The conference sessions broadly cover the following thematic areas:

- Energy efficient manufacturing and related global research initiatives
- Sustainability in production process, products and services
- Management of international operations
- Emerging and ICT technologies in manufacturing, services, logistics and production management
- Enterprise integration and interoperability
- Mass customization, including design and supply chains for mass-customized products and services
- Supply networks and supply chain management
- Product and asset lifecycle management
- Services and service manufacturing systems
- Towards the products of the future
- Production management, operations and logistics
- Design of manufacturing systems
- Robotics in manufacturing

- Innovation and sustainability in developing countries
- Performance and risk management
- Human factors, innovation, quality and knowledge management
- Modern learning technologies in manufacturing and production management

Several special sessions are organised in the above areas and ongoing research initiatives and projects are presenting their progress and achieved results. A **PhD workshop** organised prior to the conference offers the opportunity to PhD researchers to present their research plans, objectives and achieved results to Scientific Discussants and gain valuable feedback to strengthen their research plan and activities.

Approximately 300 academics, researchers, practitioners and scientists from around the globe have joined the APMS 2012 conference, sharing their expertise and providing insight into what constitutes the currently best practice in Manufacturing and Production Management, while also projecting into the future of Competitive Manufacturing for Innovative Products and Services. The conference involved a high quality International Steering and a Scientific Committee of acknowledged excellence, while the review process involved in total 82 experts, all making key contributions to the Conference success.

We wish to acknowledge the support of **Intelligent Manufacturing Systems – IMS** as the USB Sticks & Lanyards for Badges sponsor. We particularly wish to thank the active members of the IFIP WG5.7 community for their contribution and support to the conference, their support to the papers review process and the promotion of APMS 2012 through their networks and collaborating partners. Particular thanks are due to the **ATHENA Research and Innovation Centre** and the **Hellenic Maintenance Society** in Greece for co-sponsoring and supporting the conference.

The conference is hosted in the island of Rhodes, in Greece, a world-class destination, boasting a unique mixture of ancient, modern and holiday attractions, with a continuing history of well over three millennia. According to myth, Rhodes was created by the union of Helios, the sun Titan, and the nymph Rhode. The ancient city of Rhodes hosted one of the ancient wonders of the world, the Colossus of Rhodes, the giant statute of the ancient Greek Titan, Helios. Manufacturing and production management have made giant strides and contributed significantly towards a world of smart, sustainable and inclusive growth but much more needs to be done and a global effort is needed to this end. The APMS 2012 conference constitutes a focused effort to support such aims.

We wish to thank you all for your contribution and participation in APMS 2012.

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Incorporating Regularity of Required Workload to the *MMSP-W* with Serial Workstations and Free Interrumption of the Operations

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Abstract. We propose a mathematical model to solve an extension to the to the mixed-model sequencing problem with work overload minimization *(MMSP-W)* for production lines with serial workstations and parallel homogeneous processors and regularizing the required workload. We performed a computational experience with a case study of the Nissan engine plant in Barcelona.

Keywords: Manufacturing, Sequencing, Work overload, Linear programming.

1 Introduction

Manufacturing lines with mixed products are very common in Just in Time (*JIT*) and Douky Seisan (*DS*) environments. These lines, composed of multiple workstations must be flexible enough to treat different product types.

These lines usually consist of a set (K) of workstations laid out in series. Each workstation ($k = 1,\ldots,|K|$) is characterized by the use of the human resources, tools and automated systems necessary to carry out the work assigned to the workstation. The set of tasks assigned to the workstation is called the workload, and the average time required to process these tasks at normal activity rates is called the workload time or the processing time.

An important attribute of these production lines is flexibility. The products (such as engines or car bodies) circulating through the lines are not completely identical. Although some of the products may be similar or of the same type, they may require different resources and components and therefore may require different processing times.

The desired flexibility of these mixed-product lines requires that the sequence in which the product types are manufactured follow two general principles: (1) to minimise the stock of components and semi-processed products and (2) to maximise the efficiency of the line, manufacturing the products in the least amount of time possible. A classification of sequencing problems arising in this context was given in [1]:

1. *Mixed-model sequencing.* The aim in this problem is to obtain sequences that complete the maximum work required by the work schedule.

2. *Car sequencing.* These problems are designed to obtain sequences that meet a set of constraints related to the frequency with which the workstations are required to incorporate special options (e.g., a sunroof, special seats or a larger engine) within the products.
3. *Level scheduling.* These problems focus on obtaining level sequences for the production and usage of components.

The *MMSP-W* ([2] and [3]) consists of sequencing T products, grouped into a set of I product types, of which d_i are of type i ($i = 1,\ldots,|I|$). A unit of product type i ($i = 1,\ldots,|I|$), when entering workstation k ($k = 1,\ldots,|K|$), requires a processing time equal to $p_{i,k}$ for each homogeneous processor (e.g., operator, robot or human-machine system) at normal activity, whereas the standard time granted at each station to work on an output unit is the cycle time, c.

Sometimes a workstation, k, can work on any product a maximum time l_k, which is called time window, and is longer than the cycle time ($l_k > c$), which causes that the time available to process the next unit is reduced. When it is not possible to complete all of the work required, it is said that an overload is generated.

The objective of *MMSP-W* is to maximize the total work completed, which is equivalent to minimize the total work overload generated (see Theorem 1 in [4]), sequencing the units on the line, considering the interruption of the operations at any time between the time of completion of one cycle and the time of termination marked by the time window associated with that cycle [5]. In addition, in our proposal we will maintain constant the cumulative time of work required at the workstations in all positions of the product sequence.

Table 1. Comparison of the major differences of models *M*1 to *M*4 and *M*4∪3.

	*M*1	*M*2	*M*3	*M*4	*M_*4∪3
Objective	*Max V*	*Min W*	*Max V*	*Min W*	*Min W/ Max V*
Start instants	Absolute s_{kt}	Relative $\hat{s}_{kt}$	Absolute s_{kt}	Relative $\hat{s}_{kt}$	Relative $\hat{s}_{kt}$
Variables	v_{kt}	w_{kt}	v_{kt}	w_{kt}	w_{kt}, v_{kt}
Time window	$l_k\ \forall k$	$c\ \forall k$	$l_k\ \forall k$	$l_k\ \forall k$	$l_k\ \forall k$
Rank for b_k	$b_k \geq 1$	$b_k = 1$	$b_k \geq 1$	$b_k = 1$	$b_k \geq 1$
Links between stations	No	No	Yes	Yes	Yes

2 Models for the *MMSP-W*

2.1 Reference Models

For the *MMSP-W* with serial workstations, free interruption of the operations and homogeneity of required workload, we begin with several models as reference (see table 1).

The models from the literature, *M*1 [2] and *M*2 [3], do not consider links between workstations. *M*1 is focused on maximize the total work performed, using an absolute time scale at each station and considering more than one homogeneous processor at each workstation. *M*2 is focused on minimize the total work overload with relative time scale at each station corresponding to each processed product unit and only considers one processor at each workstation.

An extension of these models, considering links between consecutive stations, are models *M*3 (*M*1 extended) and *M*4 (*M*2 extended) proposed by [4]. Moreover, considering the equivalence of the objective functions of *M*3 and *M*4, we can combine them and obtain the *M*_4∪3 [6] model that considers the relative times scales used in *M*4.

2.2 Regularity of Required Workload

The overload concentrations at certain times during the workday may be undesirable. One way to avoid this occurrence is to obtain product sequences that regulate the cumulative time of required work at the workstations in all positions of the product sequence.

To do this, first we consider the average time required at the k^{th} workstation to process a product unit, which is the processing time for an ideal unit at workstation k. If $\dot{p}_k$ is the average time, then the ideal work rate for station k $(k = 1,\ldots,|K|)$ is determined as follows:

$$\dot{p}_k = \frac{b_k}{T}\sum_{i=1}^{|I|} p_{i,k} \cdot d_i \qquad k = 1,\ldots,|K| \tag{1}$$

Consequently, the ideal total work needed to complete t units of output at workstation k is:

$$P^*_{k,t} = t \cdot \dot{p}_k \qquad k = 1,\ldots,|K| \; ; \; t = 1,\ldots,T \tag{2}$$

Moreover, if we consider the actual total work required at the k^{th} workstation to process a total of t product units, of which $X_{i,t} = \sum_{\tau=1}^{t} x_{i,\tau}$ are of type i $(i = 1,\ldots,|I|)$, then we have:

$$P_{k,t} = b_k \sum_{i=1}^{|I|} p_{i,k} \cdot X_{i,t} = b_k \sum_{i=1}^{|I|} p_{i,k}\left(\sum_{\tau=1}^{t} x_{i,\tau}\right) \qquad k = 1,\ldots,|K| \; ; \; t = 1,\ldots,T \tag{3}$$

Where $x_{i,t}$ ($i = 1,\ldots,|I|$; $t = 1,\ldots,T$) is a binary variable that is equal to 1 if a product unit i is assigned to the position t^{th} of the sequence, and to 0 otherwise.

One way to measure the irregularity of the required workload at a set of workstations over the workday is to cumulate the difference between the actual and the ideal work required to each unit of output at each workstation:

$$\Delta_Q(P) = \sum_{t=1}^{T}\sum_{k=1}^{|K|} \delta^2_{k,t}(P), \quad \text{where} \quad \delta_{k,t}(P) = P_{k,t} - P^*_{k,t} \tag{4}$$

If we consider the properties derived from maintaining a production mix when manufacturing product units over time, we can define the number of units of product type i, of a total of t units, which should ideally be manufacture to maintain the production mix as:

$$X^*_{i,t} = \frac{d_i}{T} \cdot t \qquad i = 1,\ldots,|I| \ ; \ t = 1,\ldots,T \tag{5}$$

Therefore, the ideal point $\vec{X}^* = \left(X^*_{1,1},\ldots,X^*_{|I|,T}\right)$ presents the property of level the required workload, because to that point, the non-regularity of the required work is optimal, $P_{k,t} - P^*_{k,t} = \delta_{k,t}(P) = 0$ and then $\Delta_Q(P) = 0$, as shown in (6) (see theorem 1 in [6]):

$$P_{k,t} = b_k \sum_{i=1}^{|I|} p_{i,k} \cdot X^*_{i,t} \iff P_{k,t} = b_k \sum_{i=1}^{|I|} \frac{p_{i,k} \cdot d_i \cdot t}{T} = t \cdot \left(\frac{b_k}{T} \sum_{i=1}^{|I|} p_{i,k} \cdot d_i \right) = t \cdot \dot{p}_k = P^*_{k,t} \tag{6}$$

2.3 *MMSP-W* Model for Workload Regularity

Considering the properties described above and the reference model $M\_4\cup3$ [6], we limit the values of the cumulative production variables, $X_{i,t}$ ($i = 1,\ldots,|I|; t = 1,\ldots,T$), to the integers closest to the ideal values of production, $X^*_{i,t} = d_i \cdot t/T$, and then we obtain a new model, the *M_4∪3_pmr*. The parameters and variables are presented below:

Parameters

K	Set of workstations ($k = 1,\ldots,\lvert K\rvert$)
b_k	Number of homogeneous processors at workstation k
I	Set of product types ($i = 1,\ldots,\lvert I\rvert$)
d_i	Programmed demand of product type i
$p_{i,k}$	Processing time required by a unit of type i at workstation k for each homogeneous processor (at normal activity)
T	Total demand; obviously, $\sum_{i=1}^{\lvert I\rvert} d_i = T$
t	Position index in the sequence ($t = 1,\ldots,T$)
c	Cycle time, the standard time assigned to workstations to process any product unit
l_k	Time window, the maximum time that each processor at workstation k is allowed to work on any product unit, where $l_k - c > 0$ is the maximum time that the work in progress (*WIP*) is held at workstation k

Variables

$x_{i,t}$	Binary variable equal to 1 if a product unit i ($i = 1,\ldots,\lvert I\rvert$) is assigned to the position t ($t = 1,\ldots,T$) of the sequence, and to 0 otherwise

$s_{k,t}$	Start instant for the t^{th} unit of the sequence of products at station k ($k=1,\ldots,\lvert K\rvert$)
$\hat{s}_{k,t}$	Positive difference between the start instant and the minimum start instant of the t^{th} operation at station k. $\hat{s}_{k,t}=\left[s_{k,t}-(t-1)c\right]^{+}$ (with $[x]^{+}=\max\{0,x\}$).
$v_{k,t}$	Processing time applied to the t^{th} unit of the product sequence at station k for each homogeneous processor (at normal activity)
$w_{k,t}$	Overload generated for the t^{th} unit of the product sequence at station k for each homogeneous processor (at normal activity); measured in time.

Model $M\_4\cup3\_pmr$:

$$Min \quad W=\sum_{k=1}^{|K|}\left(b_k\sum_{t=1}^{T}w_{k,t}\right)\Leftrightarrow Max \quad V=\sum_{k=1}^{|K|}\left(b_k\sum_{t=1}^{T}v_{k,t}\right) \tag{7}$$

Subject to:

$$\sum_{t=1}^{T}x_{i,t}=d_i \qquad i=1,\ldots,|I| \tag{8}$$

$$\sum_{i=1}^{|I|}x_{i,t}=1 \qquad t=1,\ldots,T \tag{9}$$

$$v_{k,t}+w_{k,t}=\sum_{i=1}^{|I|}p_{i,k}x_{i,t} \qquad k=1,\ldots,|K|;\ t=1,\ldots,T \tag{10}$$

$$\hat{s}_{k,t}\geq\hat{s}_{k,t-1}+v_{k,t-1}-c \qquad k=1,\ldots,|K|;\ t=2,\ldots,T \tag{11}$$

$$\hat{s}_{k,t}\geq\hat{s}_{k-1,t}+v_{k-1,t}-c \qquad k=2,\ldots,|K|;\ t=1,\ldots,T \tag{12}$$

$$\hat{s}_{k,t}+v_{k,t}\leq l_k \qquad k=1,\ldots,|K|;\ t=1,\ldots,T \tag{13}$$

$$\hat{s}_{k,t}\geq 0 \qquad k=1,\ldots,|K|;\ t=1,\ldots,T \tag{14}$$

$$v_{k,t}\geq 0 \qquad k=1,\ldots,|K|;\ t=1,\ldots,T \tag{15}$$

$$w_{k,t}\geq 0 \qquad k=1,\ldots,|K|;\ t=1,\ldots,T \tag{16}$$

$$x_{i,t}\in\{0,1\} \qquad i=1,\ldots,|I|;\ t=1,\ldots,T \tag{17}$$

$$\hat{s}_{1,1}=0 \tag{18}$$

$$\sum_{\tau=1}^{t}x_{i,\tau}\geq\left\lfloor t\cdot\frac{d_i}{T}\right\rfloor \qquad i=1,\ldots,|I|;\ t=1,\ldots,T \tag{19}$$

$$\sum_{\tau=1}^{t}x_{i,\tau}\leq\left\lceil t\cdot\frac{d_i}{T}\right\rceil \qquad i=1,\ldots,|I|;\ t=1,\ldots,T \tag{20}$$

In the model, the equivalent objective functions (7) are represented by the total work performed (V) and the total overload (W). Constraint (8) requires that the programmed demand be satisfied. Constraint (9) indicates that only one product unit can be assigned to each position of the sequence. Constraint (10) establishes the relation between the processing times applied to each unit at each workstation and the overload generated in each unit at each workstation. Constraints (11)-(14) constitute the set of possible solutions for the start instants of the operations at the workstations and the processing times applied to the products in the sequence for each processor. Constraints (15) and (16) indicate that the processing times applied to the products and the generated overloads, respectively, are not negative. Constraint (17) requires the assigned variables to be binary. Constraint (18) establishes the earliest instant in which the assembly line can start his operations. Finally, the constraints (19) and (20) are those that incorporate, indirectly, the regularity of required workload to the *MMSP-W*.

3 Computational experience

To study the behavior of the incorporation of the regularity work required restrictions into the $M\_4{\cup}3$, we performed a case study of the Nissan powertrain plant in Barcelona. This plant has an assembly line with twenty-one workstations ($m_1,\ldots,m_{21}$) assembling nine types of engines ($p_1,\ldots,p_9$) that are grouped into three families (4x4, vans and trucks) whose processing times at stations ranging between 89 and 185 s.

For the experiment, we considered a set E of 23 ($\varepsilon = 1,\ldots,23$) instances associated to a demand plan of 270 engines, an effective cycle time c = 175s and an identical time window for all stations $l_k = 195$ s ($k = 1,\ldots,21$) (see tables 5 and 6 in [4]).

To implement the models, the Gurobi v4.5.0 solver was used on a Apple Macintosh iMac computer with an Intel Core i7 2.93 GHz processor and 8 GB of RAM using MAC OS X 10.6.7. The solutions from this solver were obtained by allowing a maximum CPU time of 7200 *s* for each model and for each of the 23 demand plans in the NISSAN-9ENG set.

To estimate the quality of the experimental results, we use the following indicators:

$$RPD(f,\varepsilon) = \frac{f\left(S^*_{4\cup3}(\varepsilon)\right) - f\left(S^*_{4\cup3\_pmr}(\varepsilon)\right)}{f\left(S^*_{4\cup3}(\varepsilon)\right)} \cdot 100 \qquad \left(f \in \Im = \{W, \Delta_Q(P)\ ;\ \varepsilon \in \mathrm{E}\right) \quad (21)$$

$$\overline{RPD}(f) = \frac{\sum_{\varepsilon=1}^{|\mathrm{E}|} RPD(f,\varepsilon)}{|\mathrm{E}|} \qquad \left(f \in \Im = \{W, \Delta_Q(P)\right) \quad (22)$$

Table 2 and figure 1 show the results obtained.

Table 2. Values of RPD for the functions W, $\Delta_Q(P)$ and average values ($\overline{RPD}(W)$, $\overline{RPD}(\Delta_Q(P))$) for the 23 instances of the NISSAN-9ENG set.

ε	W	$\Delta_Q(P)$	ε	W	$\Delta_Q(P)$	ε	W	$\Delta_Q(P)$	ε	W	$\Delta_Q(P)$
1	0.53	96.40	*7*	1.48	91.12	*13*	-17.48	95.59	*19*	0.00	94.96
2	-12.32	89.70	*8*	-15.11	94.25	*14*	-0.71	94.35	20	-7.91	96.31
3	0.94	89.24	*9*	-2.60	94.61	*15*	-2.08	94.58	21	-0.18	86.39
4	0.97	92.35	*10*	0.00	87.04	*16*	-10.57	90.42	22	0.30	90.16
5	-4.42	97.67	*11*	-56.41	95.25	*17*	-2.09	88.91	23	13.57	86.55
6	-15.74	94.26	*12*	-1.06	96.26	*18*	-2.31	92.08	$\overline{RPD}$	**-5.79**	**92.54**

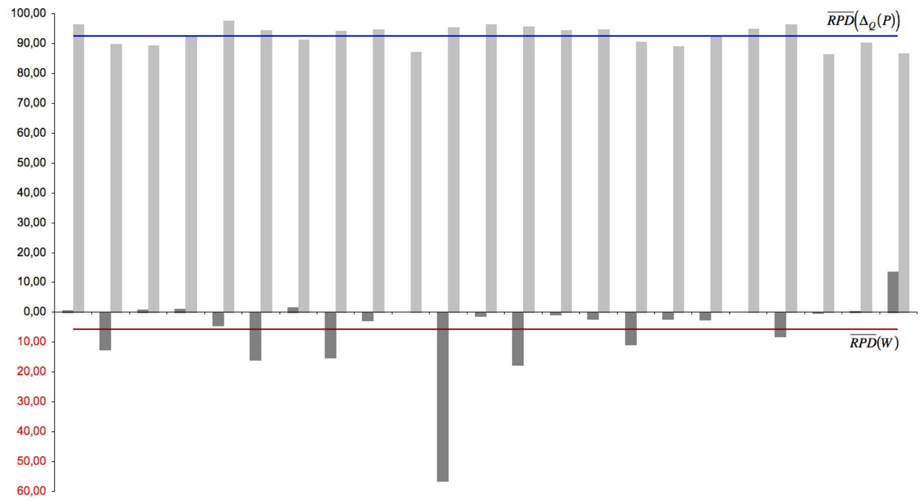

Fig. 1. Values of RPD for the functions W (dark grey), $\Delta_Q(P)$ (grey) and average values ($\overline{RPD}(W)$ (red line), $\overline{RPD}(\Delta_Q(P))$ (blue line)) for the 23 instances of the NISSAN-9ENG set.

According to the results (see table 2 and figure 1) we can conclude the following:

- With the limitation of a run time of 7200 s, we can only guarantee the optimal solutions for instances 10 and 19.
- The reference model $M\_4{\cup}3$ achieves a better average overload than $M\_4{\cup}3\_pmr$ (a difference of 5.79% in $\overline{RPD}(W)$) on the set of 23 instances.
- The incorporation of constraints (8) and (9) into the reference model $M\_4{\cup}3$ produces a significant improvement in the regularity of the required work ($\overline{RPD}(\Delta_Q(P)) = 92,54\%$).

4 Conclusions

We have formulated a model for the *MMSP-W*, $M\_4{\cup}3\_pmr$, that minimizes the total work overload or maximizes the total work completed, considering serial workstations, parallel processors, free interruption of the operations and with restrictions to regulate the required work.

A case study of the Nissan engine plant in Barcelona has been realized to compare the new model with the reference model $M\_4{\cup}3$.

The case study includes the overall production of 270 units of 9 different types of engines, for a workday divided into two shifts, and assuming that the particular demands of each type of engine may vary over time. This is reflected in 23 instances, each of them representing a different demand plan.

For the computational experience, the solver Gurobi 4.5.0 was used. The solutions have been found for the 23 instances, allowing a maximum CPU time of 7200 *s* for each instance. Using this CPU time, we can only guarantee the optimal solutions for the instances 10 and 19.

The results show that the incorporation of the restrictions to regulate the required work into the reference model $M\_4\cup3$ produces an average gain of 92,54%, in terms of regularity of required work, while gets worse by an average of 5,79%, in terms of work overload.

We propose as future research lines: (1) to design and to implement heuristics and exact procedures to solve the problem under study; (2) to consider the minimization of the work overload and maximizing the regularity of the work required as simultaneous objectives of the problem; and (3) to incorporate to the proposed models, other desirable productive attributes such as maintenance of the production mix and the regular consumption of parts of products, for example.

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5 References

1. Boysen, N., Fliedner, M., Scholl, A.: Sequencing mixed-model assembly lines: Survey, classification and model critique. European Journal of Operational Research, 192/2, 349-373 (2009).
2. Yano, C. A., Rachamadugu, R.: Sequencing to minimize work overload in assembly lines with product options. Management Science, 37/5, 572-586 (1991).
3. Scholl, A., Klein, R., Domschke, W.: Pattern based vocabulary building for effectively sequencing mixed-model assembly lines. Journal of Heuristics, 4/4:359-381 (1998).
4. Bautista, J., Cano, A.: Solving mixed model sequencing problem in assembly lines with serial workstations with work overload minimisation and interruption rules. European Journal of Operational Research, 210/3:495-513 (2011).
5. Bautista, J., Cano, A., Alfaro, R.: A bounded dynamic programming algorithm for the MMSP-W considering workstation dependencies and unrestricted interruption of the operations, Proceedings(CD). ISBN: 978-1-4577-1675-1, 11th International Conference on Intelligent Systems Design and Applications (ISDA 2011), Córdoba, Spain (2011).
6. Bautista, J., Cano, A., Alfaro, R.: Modeling and solving a variant of the mixed-model sequencing problem with work overload minimisation and regularity constraints. An application in Nissan's Barcelona Plant. Expert Systems with Applications, 39/12, 11001–11010 (2012).