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Operationalising Form Postponement from a Decision-Making Perspective

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Operationalising Form Postponement from a Decision-Making Perspective

Form postponement means delaying the commitment of inventory to the final configuration of a product as long as possible. Many firms today are striving to redesign their products and/or their manufacturing and supply chain processes to implement form postponement. Opportunities for form postponement, however, are sometimes lost in the companies' production-planning processes. By focusing on the deferring of product mix decisions in the master production scheduling process, this paper shows that form postponement opportunities can be divided into two components: one whose pursuit necessarily requires product and/or transformation process redesign, the other that can be pursued by changing the sales forecasting and master production scheduling process alone. We develop an operational procedure to identify and quantify, for a given product family, all opportunities for form postponement and their two respective components. Then, we discuss and empirically illustrate how the proposed measurement procedure may support companies in changing their decision-making routines to implement form postponement. Finally, we set future research directions on form postponement suggested by our results.

Keywords: form postponement; delayed product differentiation; production planning and control; forecasting; mass customisation.

1. Introduction

Form postponement (FP) means delaying the commitment of resources to the final configuration of a product as long as possible (Alderson 1950, Heskett 1977)[1]. By delaying the commitment of inventory to a specific end-product, FP allows for the collecting of new information about customer demands before product mix decisions are made (Yang *et al.* 2004a, Forza *et al.* 2008). Accordingly, FP is acknowledged as a means of eliminating, or at least reducing, the risk and associated costs of specifying the wrong mix of varieties in a forecast-driven manufacturing environment (Alderson 1950, Bucklin 1965, Zinn and Bowersox 1988, Whang and Lee, 1998, Aviv and Federgruen 2001a, Kumar and Wilson 2009).

Many companies today are striving to redesign their products and/or their manufacturing and supply chain processes to defer activities that specialise work-in-progress inventory into specific end-items (Matthews and Syed 2004, Wong *et al.* 2009). We refer to such transformational activities as product differentiation activities (PDAs). Many successful cases of product and/or manufacturing and supply chain process redesign aimed at implementing FP have been documented in the relevant literature, including Benetton sweaters (Dapiran 1992), Hewlett-Packard printers (Lee *et al.* 1993), Xilinx programmable logic devices (Brown et al. 2000), etc.

[1] The principle of FP "has also been termed as *delayed product differentiation* or *late customization*" (Swaminathan and Lee 2003: 199).

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Opportunities for FP, however, are sometimes lost by firms that engage in product and/or transformation process redesign but fail to realign the production-planning process. Failure to realign this process may imply that PDAs are eventually deferred but the corresponding product mix decisions are not, as illustrated by the case of a large electric motor manufacturer that motivated and inspired our research. To reduce working capital, this firm began in 2005 a lead-time reduction program that led to the deferral of a number of PDAs. These changes in the transformation process reduced work-in-progress inventory as expected. Yet, because of a lack of interfunctional coordination and the company's traditional focus on product and process technology rather than on administrative processes, the firm neglected to align the master production scheduling process with the revised transformation process. The company continued to freeze the master production schedule (MPS) over the entire cumulative lead-time of the make-to-stock electric motors. Consequently, the deferment of a number of PDAs did not lead to the delay of the decisions driving these activities and the risk of specifying the wrong mix of varieties did not decrease. The case of another company that had overlooked the problem of adapting the manufacturing planning and control system to implement FP is reported by Skipworth and Harrison (2004). Interestingly, difficulty of organisational alignment heads the list of operational challenges in FP implementation according to a recent executive survey across the membership of APICS–The Association for Operations Management (Matthews and Syed, 2004). More generally, Mason-Jones and Towill (1999) note that many firms mistakenly concentrate operations/supply chain improvement efforts within the material flow pipeline, neglecting the information flow pipeline and thus failing to fully realise performance improvement potential.

To date, the FP literature predominantly focuses on product and/or process design changes, such as product modularisation or process re-sequencing, that enable deferment of PDAs in the manufacturing and distribution process (e.g., Lee and Billington 1994, Lee and Tang 1997, Gupta and Krishnan 1998, Swaminathan and Lee 2003, Shao and Ji 2008). In fact, the majority of the extant FP literature assumes that PDAs are triggered by some *a priori*-defined inventory replenishment rule, instead of by a rolling MPS (e.g., Lee 1996, Garg and Tang 1997, Whang and Lee 1998, Brown *et al.* 2000, Aviv and Federgruen 2001b, Ma *et al.* 2002, Shao and Ji 2008). Under this assumption, deferring PDAs automatically leads to the delay of the corresponding product mix decisions.

In contrast, less attention has been paid to the changes in the sales forecasting and MPS process that enable FP. Particularly, the FP literature still lacks operational tools that help companies redesign this process when pursuing FP. To the best of our knowledge, the only operational tool discussed in the FP literature is the production variety funnel, which maps the number of physically different items occurring at each manufacturing stage (New 1974, Hines and Rich 1997) and, as such, can be used to examine whether the number of items proliferates in the final part of the transformation process. This tool focuses on the part complexity that has to be managed in the transformation process (Hines and Rich 1997), which incidentally is not always related to product variety (Howard *et al.* 2001), but is not intended to map production-planning decisions driving PDAs against time.

In this paper, we formalise and operationalise FP from a decision-making perspective, developing a measurement procedure to identify and quantify all opportunities for deferring forecast-driven decisions pertaining to product mix in the sales forecasting and MPS process. In Section 2, we formalise this definitional perspective, using mathematical notation for the sake of

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conciseness in the rest of the paper, and show that opportunities for FP can be divided into two components, one related to the sales forecasting and MPS process and the other related to the transformation process. In Section 3, we describe the procedure to quantify all FP opportunities relative to a given product family and their two respective components. In Section 4, we discuss the utility of the proposed measurement procedure for decision-making, while we illustrate this by means of three real examples in Section 5. We conclude in Section 6 by discussing the contribution of our work as well as its limitations and associated directions for future research.

2. Formalising form postponement from a decision-making perspective

Consider, for the purpose of illustration, the case of a product family whose transformation process requires execution of K sourcing or manufacturing activities in a batch manufacturing environment (Figure 1, where K=7).

Insert Figure 1

For the purpose of production planning, each kth activity (k=1,…, K) has an associated planned lead-time l_k and must start no later than at time $T_{\text{Actitity } k}$ for production to be completed at $T_{\text{COMPLETION}}$=0. The planned lead-time represents an estimate of the time that will elapse between when an order is released for each kth activity and when the corresponding activity is completed (Orlicky 1975). The cumulative lead-time for the entire process is denoted by CLT and the transformation process must start no later than at time $T_{\text{Actitity } 1}$= -CLT (in Figure 1, CLT=10 weeks).

The mix of varieties completed at $T_{\text{COMPLETION}}$=0 is created by the PDAs within the transformation process. In general, there are I PDAs within the transformation process of a product family ($I \leq K$). We denote the ith PDA (i=1,…, I) by PDA_i and the number of its possible outcomes by M_i. In Figure 1, I=1 and Activity 4 is PDA_1, generating M_1 varieties.

The point in the material flow to which the customer's order penetrates is the customer order decoupling point, also known as order penetration point or decoupling point (Sharman 1984, Hoekstra and Romme 1992). The customer order decoupling point, which we denote by T_{CODP}, separates order-driven activities (downstream from it) from forecast-driven activities (upstream from it) and, as a rule, coincides with the last major stock point in the material flow (Sharman 1984, Hoekstra and Romme 1992). The customer order decoupling point has also been termed as material decoupling point because it does not always coincide with the information decoupling point, meant as the point in the information flow to which market sales information penetrates without modification (Mason-Jones and Towill 1999). The positioning of the customer order decoupling point is affected by many market, product and production characteristics, including primarily the relationship between the delivery time requested by the customer and the purchasing, production and distribution stacked lead-time (Hoekstra and Romme 1992, Olhager 2003, Wikner and Rudberg 2005). If the customer-expected delivery time is very short relative to the purchasing, production and distribution stacked lead-time, all sourcing and manufacturing activities must be carried out based on forecast, as happens in the case illustrated in Figure 1, where T_{CODP}= $T_{\text{COMPLETION}}$=0.

All sourcing and manufacturing activities in the transformation process are initiated by purchase or work orders issued weekly through the Material Requirements Planning (MRP) process. Since all l_k's are integer multiples of the time span between two successive order release cycles, all purchase and work orders are issued at the latest possible time, namely at $T_{\text{Actitity } k}$ (k=1,…, K).

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The MRP process is driven by the MPS process. In this setting, a rolling MPS is expressed in terms of finished products, is re-planned on a weekly basis, and has a frozen interval equal to *CLT*. Such an MPS freezing policy reflects a market context in which demand is predictable and the company may therefore focus on achieving stable schedules and the subsequent productivity and quality advantages (Harrison 1997, Olhager 2003). To satisfy market demand requirements at $T_{\text{COMPLETION}}$, at time T_{MPS}= -*CLT*= $T_{\text{Actitity 1}}$ the manufacturer generates a demand forecast for $T_{\text{COMPLETION}}$ and appends additional MPS quantities to the schedule. Doing so, the manufacturer specifies the amounts of the possible outcomes of PDA_1 to be produced. Notice that these quantities are "frozen", or firm planned, as the manufacturer freezes the MPS over the entire *CLT*. The frozen decision specifying the amount of the jth possible outcome of PDA_1 to be produced is denoted by $\text{MPS-MIX}_{1,\,j}$ (j=1,…, M_1), and the time at which this decision is made is indicated by $T_{\text{MPS-MIX}_{1,\,j}}$.[2]

Together, the salient characteristics of the product family (i.e., number of product variants), the transformation process (i.e., the K sourcing or manufacturing activities and associated $T_{\text{Activity}\ k}$'s), and the sales forecasting and MPS process (i.e., the $T_{\text{MPS-MIX}_{1,\,j}}$'s for the forecast-driven $\text{MPS-MIX}_{1,\,j}$ decisions) can be said to establish the system configuration for the product family and the associated MPS and transformation processes. In this study, FP is formalised as a change of this system configuration.

More specifically, FP from a decision-making perspective (or simply FP_{DM}) is defined here as the deferment of forecast-driven MPS decisions pertaining to product mix to the customer order decoupling point or to a time closer to the customer order decoupling point. This definition combines the concepts of FP and customer order decoupling point, in agreement with a rich stream of literature starting with Bucklin (1965) and including, among others, Heskett (1977), Lee and Billington (1994), Skipworth and Harrison (2004, 2006) and Wong *et al.* (2009).

In light of this definition, the amount of time $T_{\text{CODP}} - T_{\text{MPS-MIX}_{1,\,j}}$ may be considered as the "potential" for pursuing FP_{DM} for each $\text{MPS-MIX}_{1,\,j}$ decision (j=1,…, M_1). Consistent with the established notation in the physical sciences, we denote this "potential" by $U_{1,\,j}$, so that:

$$U_{1,\,j} = T_{\text{CODP}} - T_{\text{MPS-MIX}_{1,\,j}}.$$

This "potential" for FP_{DM} can be split into two constituent components:

$$(U_{\text{MPS-MIX}})_{1,\,j} = T_{\text{PDA}_1} - T_{\text{MPS-MIX}_{1,\,j}}$$

$$(U_{\text{TRANSF}})_1 = T_{\text{CODP}} - T_{\text{PDA}_1}$$

The former component is the maximum possible deferment of $\text{MPS-MIX}_{1,\,j}$ that can be achieved without having to defer PDA_1 along the transformation process. In Figure 1, $(U_{\text{MPS-MIX}})_{1,\,j}$ = 4 weeks. Were demand mix uncertainty to increase, the manufacturer could realise this FP_{DM} potential by shortening the frozen interval by four weeks, so that the product mix decisions driving PDA_1 may be revised until initiation of PDA_1.

The latter component may be interpreted as the maximum possible additional deferment of the $\text{MPS-MIX}_{1,\,j}$ decision, which deferment can only be achieved by delaying PDA_1 along the transformation process. Notice that while this interpretation assumes there is a sequential

[2] In general, $T_{\text{MPS-MIX}_{1,\,j}}$ could vary across the M_1 possible outcomes of PDA_1, for example, because different outcomes are produced at different locations, or because different outcomes require different processes with different cycle times. For the sake of simplicity, however, we assume in Figure 1 that $T_{\text{MPS-MIX}_{1,\,j}}$ is the same for all possible outcomes of PDA_1.

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modification in the system such that the MPS process is changed before the transformation one, it does not necessarily have to be so whenever FP_{DM} is implemented. On the contrary, the manufacturer could first defer PDA_1 along the transformation process and then redesign the sales forecasting and MPS routines to delay the decisions driving that activity.

Given the above definitions of $(U_{\text{MPS-MIX}})_{1,j}$ and $(U_{\text{TRANSF}})_1$, we can express $U_{1,j}$ as follows:

$$U_{1,j} = \left(U_{\text{MPS-MIX}}\right)_{1,j} + \left(U_{\text{TRANSF}}\right)_1 \tag{1}$$

Equation (1) allows for the quantification of the amount of deferment of the $\text{MPS-MIX}_{1,j}$ decision (j=1,…, M_1) resulting from FP_{DM} implementation. This quantification arises from comparing the initial system configuration (i.e., before FP_{DM} implementation) to the final system configuration (i.e., after FP_{DM} implementation) to compute $(FP_{DM})_{1,j}$ as follows:

$$\left(FP_{DM}\right)_{1,j} = \left(U_{1,j}^{isc} - U_{1,j}^{fsc}\right)^{+}, \tag{2}$$

where $U_{1,j}^{isc}$ and $U_{1,j}^{fsc}$ represent the FP_{DM} potentials for the $\text{MPS-MIX}_{1,j}$ decision in the initial and final system configurations, respectively.

While in the preceding discussion we have assumed, for the sake of illustration, that there is a single PDA and that the planned lead-times for the sole PDA and the downstream activities are invariant across the different end-products, the results are readily extended to the case of $1<I\leq K$ PDAs and varying planned lead-times $l_{k,j}$ for the kth activity across its possible outcomes j=1,…, M_k. Without derivation, we can show that in this case, Equation (1) can be stated as the following $Nx1$ vector:

$$\underline{U} = \begin{pmatrix} \left(U_{\text{MPS-MIX}} + U_{\text{TRANSF}}\right)_{1,1} \\ \vdots \\ \left(U_{\text{MPS-MIX}} + U_{\text{TRANSF}}\right)_{I,M_I} \end{pmatrix}, \tag{3}$$

where $N = \sum_{i=1}^{i=I} M_i$, $(U_{\text{MPS-MIX}})_{i,j} = T_{\text{PDA}_{i,j}} - T_{\text{MPS-MIX}_{i,j}}$, $(U_{\text{TRANSF}})_{i,j} = T_{\text{CODP}} - T_{\text{PDA}_{i,j}}$, and $T_{\text{PDA}_{i,j}}$ is the timing of PDA_i when its outcome is j (j=1,…, M_i). Equation (2) can then be computed for each element of the vector.

3. A measurement procedure for computing FP_{DM} potentials

To quantify Equation (3), we need to obtain the values for $T_{\text{PDA}_{i,j}}$, $T_{\text{MPS-MIX}_{i,j}}$, and T_{CODP} (i=1,…, I; j=1,…, M_i). To do so, we design and illustrate, by means of an example, a measurement procedure comprising the following six tasks:

<u>Task 1</u>: Identify all the sourcing and manufacturing activities for the product family of interest, their precedence relationships, and retain only the *K* activities that are driven by the MPS.

This task serves to specify all sourcing and manufacturing activities and their execution sequence that need to be completed in order to produce the varieties within the product family. Moreover, any activities whose executions are not driven by a rolling MPS, but are triggered by *a priori*-defined inventory replenishment rules such as order-point inventory control systems are eliminated from further consideration.

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Consider, for the example, a batch manufacturer of bird-cages who makes eight different bird-cage variants in a make-to-stock environment. The process for making bird-cages involves 11 sourcing or manufacturing activities and is depicted as the graph in Figure 2(a). The six sourcing activities, in this example, are not driven by the MPS and are consequently depicted as "black boxes." The MPS-driven activities are activities {B–E, H}.

Insert Figure 2

<u>Task 2</u>: Draw the operations setback chart, set the end time of the last activity to zero, and identify the order release timings for all *K* activities with respect to zero.

This task creates the operations setback chart based on each activity planned lead-times. The operations setback chart indicates the latest possible time at which orders for each possible j^{th} outcome of each kth activity are to be released for production to be completed at time zero, namely $T_{\text{Actitity } k,\, j}$'s (Vollmann *et al.* 2005). If all planned lead-times $l_{k,\, j}$'s are integer multiples of the time span between two successive order release cycles, then $T_{\text{Actitity } k,\, j}$'s also represent the timings of actual order releases. Otherwise, the timings of actual order releases are determined by setting back each $T_{\text{Actitity } k,\, j}$ to the latest order release cycle preceding $T_{\text{Actitity } k,\, j}$.

For the bird-cage batch manufacturer, the operations setback chart is shown in Figure 2(b). For the sake of illustration, we assume that planned lead-times for activities {B–E, H} are invariant across the possible product variants, so that for example $T_{\text{B},\, 1} = T_{\text{B},\, 2} = T_{\text{B},\, j}$. Instead, if planned lead-times for a given activity varied across the possible end-items, distinct operations setback charts should be drawn for these varieties. Suppose, for instance, that packaging lead-time is greater for the varnished cages than for the brass-plated ones, as the former require a more careful handling due to more easy-to-damage coating. In this case, distinct operations setback charts should be drawn for varnished cages and brass-plated cages. By superimposing these two charts, we could derive the operations setback chart for the entire product family and, then, we could determine order release timings. Notice that because of the different planned lead-times associated with the packaging activity, packaging orders would be issued earlier for the varnished cages than for the brass-plated ones. Consequently, coating orders, bird-cage housing fabrication orders, grid fabrication orders and plastic bottom moulding orders would also be released earlier for the varnished cages than for the brass-plated ones. Evidently, proliferation of planned lead-times leads to proliferation of order release timings, thereby increasing the computational burden of Task 2. As an option for reducing Task 2 complexity, the maximum planned lead-time among all product variants could be used for all the varieties. For example, the packaging lead-time associated with the varnished cages could be used for the brass-plated cages as well.

<u>Task 3</u>: Sequence the order release timings for the *K* activities in increasing order, determine whether or not a kth activity is a PDA and, if not, eliminate it from further consideration.

This task pares the *K* MPS-driven activities down to *I* relevant PDAs. A PDA is commonly defined as any activity that specialises work-in-progress inventory into specific product variants by adding a differentiating feature to a product (Lee and Billington 1994, Garg and Tang 1997, Aviv and Federgruen 2001b).

In identifying PDAs, we have to consider that distinct product-differentiating features may be bundled (Lee and Tang 1998). In the case of the bird-cage manufacturer, for instance, the

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colour of the bird-cage housing and the colour of the plastic bottom are two bundled product-differentiating features, since blue housings go only with blue bottoms and brass-plated housings go only with gold bottoms.

When there are bundled product-differentiating features, identification of PDAs requires that the K MPS-driven activities be examined in order of increasing $T_{\text{Actitity } k,\, j}$'s. If the kth activity in this sequence adds a differentiating feature and this feature is not bundled with other differentiating features created by previously examined activities, then the kth activity is a PDA. Otherwise, there are two possibilities.

One possibility is that while adding a differentiating feature bundled with another differentiating feature created by a previously examined activity, the kth activity may alter the product mix generated by the preceding activity. If this is the case, then the kth activity is a PDA. Consider, for example, bird-cage housing coating (Activity D). Activity D adds a differentiating feature–housing colour–that is bundled with another differentiating feature–bottom colour–created by a preceding activity–plastic bottom moulding (Activity H). However, Activity D may create a mix of housing colours that is different from the mix of bottom colours previously created. This is because pre-coloured housings fabricated by Activity C and coloured bottoms produced by Activity H are stored before being processed by the subsequent activities. Hence, at time $T_{\text{D},\, j}$= -6, some of the previously ordered pre-coloured housings and coloured bottoms may be left in stock, so that the mix of housing colours is different from the mix of bottom colours previously created.

Conversely, if the kth activity cannot alter the product mix generated by the preceding activity, it is not a PDA. This is the case, for example, of bird-cage housing fabrication (Activity C). Activity C adds a differentiating feature–housing size–that is bundled with another differentiating feature–grid size–created by a preceding activity–grid fabrication (Activity B). However, Activity C cannot create a mix of housing sizes that is different from the mix of grid sizes previously produced. This is because grids fabricated by Activity B are not stored before being fed to Activity C. Therefore, Activity C has to process all the large grids and all the small grids from Activity B to form respective bird-cage housings.

All the PDAs in the bird-cage manufacturer example, together with their order release timings and possible outcomes, are shown in Figure 2(c).

<u>Task 4</u>: Identify the timing of each MPS-MIX$_{i,\, j}$ (j=1,…, M_i) tied to each PDA$_i$ (i=1,…, I).

This task identifies when the MPS-MIX$_{i,\, j}$ decision for the jth possible outcome of the ith PDA is made without violating $T_{\text{PDA}_{i,\, j}}$. To do so, two parameters for the MPS are required–the re-planning interval and the frozen interval. The re-planning interval (R) is the time span between two successive re-plannings of the MPS (Lin and Krajewsky 1992, Yeung *et al.* 1998)[3]. The frozen interval (F) is the time span for which the schedules are implemented according to the original plan, and must never be smaller than R (Lin and Krajewsky 1992, Yeung *et al.* 1998)[4].

[3] We assume that a period-based approach is used to re-plan the MPS, instead of an order-based approach. While the latter advocates that the manufacturer updates the MPS after executing a preset number of MPS orders, the former procedure requires that re-planning occur after rolling a specified number of time periods ahead (Sahin *et al.* 2008). Period-based re-planning approaches are easier to implement and often employed in industry (Zhao *et al.* 2001).

[4] We assume that a period-based method is used to freeze the MPS, instead of an order-based method. While the latter advocates that a certain number of MPS orders placed in the planning horizon are executed as originally

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F and R determine the latest point in time, relative to $T_{\text{COMPLETION}}$, at which the mix of varieties to be completed at $T_{\text{COMPLETION}}$ may be changed, namely T_{Frozen}. By definition, T_{Frozen} is time-phased with MPS cycles, and is computed as follows[5]:

$$T_{\text{Frozen}} = \left[-\left\lceil \frac{F}{R} \right\rceil - \left(1 - \boldsymbol{I}_{\mathbf{Z}_+}\left(\frac{F}{R} \right) \right) \right] R \,, \tag{4}$$

where $\boldsymbol{I}_{\mathbf{Z}_+}(x)$ is the indicator function of the positive integers.

To determine $T_{\text{MPS-MIX}_{i,\,j}}$ (i=1,…, I; j=1,…, M_i), the following rules are then applied:

Rule 1: For $T_{\text{Frozen}} \le T_{\text{PDA}_{i,\,j}} < 0$, set $T_{\text{MPS-MIX}_{i,\,j}} = T_{\text{Frozen}} - z_{i,j}\, R$

Rule 2: For $T_{\text{PDA}_{i,\,j}} < T_{\text{Frozen}}$, set $T_{\text{MPS-MIX}_{i,\,j}} = \left[\left\lceil \frac{T_{\text{PDA}_{i,\,j}}}{R} \right\rceil - \left(1 - \boldsymbol{I}_{\mathbf{Z}_+}\left(\frac{\left| T_{\text{PDA}_{i,\,j}} \right|}{R} \right) \right) - z_{i,\,j} \right] R$,

where $z_{i,j}$ is the minimum non-negative integer such that at $T_{\text{MPS-MIX}_{i,\,j}}$, new forecast information about market demand for the jth outcome of PDA$_i$ at $T_{\text{COMPLETION}}$ is available.

To understand the logic of Rules 1 and 2, we need to recall that if FP$_{DM}$ is to reduce the risk of forecasting an incorrect demand mix, $T_{\text{MPS-MIX}_{i,\,j}}$ must not simply be the latest point in time at which the decision specifying the quantity of the jth outcome of PDA$_i$ to be produced may be changed. $T_{\text{MPS-MIX}_{i,\,j}}$ must be the latest point in time at which this decision may be changed based on a new forecast for $T_{\text{COMPLETION}}$. To determine $T_{\text{MPS-MIX}_{i,\,j}}$, therefore, we need to consider the forecast process driving the MPS and identify the latest point in time at which a new forecast for the jth outcome of PDA$_i$ is generated. Notice that if a new forecast is generated in each re-planning cycle between T_{MPS} and T_{Frozen}, then $z_{i,j}$=0 for each jth possible outcome of each PDA$_i$ (i=1,…, I; j=1,…, M_i).

For the bird-cage batch manufacturer, Figure 2(d) shows how Rules 1 and 2 translate $T_{\text{PDA}_{i,\,j}}$ into the corresponding $T_{\text{MPS-MIX}_{i,\,j}}$, assuming that R=F=5 days and that a new demand forecast for $T_{\text{COMPLETION}}$ is available in each MPS cycle between T_{MPS} and T_{Frozen}.

<u>Task 5</u>: Identify the customer order decoupling point and eliminate any order-driven PDAs from further consideration.

This task identifies T_{CODP}, defined as the point in the material flow where actual demand pull gives way to forecast-driven push. In a make-to-stock environment, such as the bird-cage manufacturer in this example, T_{CODP}= $T_{\text{COMPLETION}}$=0 and all PDAs are forecast-driven. In any other manufacturing environment (e.g., assemble-to-order), T_{CODP}< $T_{\text{COMPLETION}}$ and one or more PDAs may be order-driven. To remove such PDAs from further consideration, adjust the $T_{\text{PDA}_{i,\,j}}$ by T_{CODP} (Adjusted $T_{\text{PDA}_{i,\,j}}$= $T_{\text{PDA}_{i,\,j}} - T_{\text{CODP}}$) and eliminate Adjusted $T_{\text{PDA}_{i,\,j}} \ge 0$. Then, based on the remaining Adjusted $T_{\text{PDA}_{i,\,j}}$'s, repeat Task 4 and go to Task 6.

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scheduled, the former method requires that all MPS quantities within a certain portion of the planning horizon be implemented according to the original plan (Sridharan *et al.* 1987). Period-based freezing policies are easier to implement in multi-product manufacturing environments with uncertain demand such as those considered in this study (Yeung *et al.* 1998, Xie *et al.* 2003).

[5] We assume that the MPS quantities planned for a given time period must be available at the end of that period. We also set $T_{\text{COMPLETION}}$ to the end time of the most distant future period in the MPS planning horizon just before a new re-planning occurs.

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A possible complication in identifying T_{CODP} is represented by hybrid production situations in which different end-items within the same product family have different customer order decoupling points (Giesberts and van der Tang 1992). Many companies, for example, produce standard varieties to stock but also assemble or make product variants to customer specification. If this is the case, FP_{DM} potentials are different across the end-items of the product family and, consequently, the present measurement procedure must be applied to a subset of product variants that are characterised by the same T_{CODP}.

Task 6: Apply Equation (3).

Figure 2(e) shows the various FP_{DM} potentials for the MPS-MIX$_{i,j}$'s driving all the PDAs in the bird-cage manufacturer example. The splitting of the FP_{DM} potentials into their two respective components, according to Equation (1), can be presented in either tabular form (Figure 3(a)) or graphical representation (Figure 3(b)).

Insert Figure 3

4. Utility of the measurement procedure for decision-making

The proposed measurement procedure offers a holistic view of how all the forecast-driven MPS decisions driving PDAs are distributed across time for a given product family. This allows identification and quantification of all opportunities for pursuing FP_{DM}. For example, the graphical representation in Figure 3(b) shows the curve of all FP_{DM} potentials in the case of the bird-cage manufacturer (solid curve). The measurement procedure also offers a holistic view of the splitting of these FP_{DM} potentials into their two respective components according to Equation (1). Besides the curve of all the $U_{i,j}$'s, in fact, the diagram in Figure 3(b) shows the curve of all the $(U_{\text{TRANSF}})_{i,j}$'s (dashed curve). We envisage at least three ways in which the splitting of FP_{DM} potentials and, more generally, the proposed measurement procedure may support decision-making about FP_{DM}.

Detecting FP_{DM} opportunities not requiring transformation process redesign

Comparing the curve of all the $U_{i,j}$'s with the one of all the $(U_{\text{TRANSF}})_{i,j}$'s allows immediate understanding of the extent to which extant opportunities for FP_{DM} can be pursued without redesigning the transformation process. This piece of information may be numerically and succinctly communicated by defining the index O as follows:

$$O = \frac{\sum_{i=1}^{i=I}\sum_{j=1}^{j=M_i}\left(U_{i,j} - \left(U_{\text{TRANSF}}\right)_{i,j}\right)}{\sum_{i=1}^{i=I}\sum_{j=1}^{j=M_i} U_{i,j}}$$

Using Equation (3), we can show that:

$$O = \frac{\overline{U}_{\text{MPS-MIX}}}{\overline{U}} = \frac{\overline{U}_{\text{MPS-MIX}}}{\overline{U}_{\text{MPS-MIX}} + \overline{U}_{\text{TRANSF}}}, \tag{5}$$

where $\bar{U}_{\text{MPS-MIX}}$, $\bar{U}_{\text{TRANSF}}$ and $\bar{U}$ are the arithmetic means of the $(U_{\text{MPS-MIX}})_{1,j}$'s, the $(U_{\text{TRANSF}})_{i,j}$'s and the $U_{i,j}$'s, respectively. The index O is constrained between zero and one. A low O value indicates that, on average, there are few opportunities for deferring forecast-driven MPS-MIX decisions without first redesigning the transformation process so as to delay the

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corresponding PDAs. Conversely, a high O value is indicative that, on average, a large fraction of FP_{DM} potentials is accounted for by the forecasting and MPS process and, hence, can be pursued without redesigning the transformation process. The index O is, therefore, a simple tool to make managers aware of how important the forecasting and MPS process is, relative to the transformation process, in determining the timings of forecast-driven MPS-MIX decisions and the values of FP_{DM} potentials for a given product family. Obviously, the index O does not inform managers about the absolute values of FP_{DM} potentials and, hence, must be supplemented with these values, which are clearly communicated in the visualization in Figure 3(b) and may be numerically and succinctly represented by $\bar{U}$.

Redesigning the sales forecasting and MPS process to implement FP_{DM}

The proposed measurement procedure supports forecasting and MPS process redesign to minimise O and, therefore, implement all FP_{DM} opportunities not requiring transformation process changes. To achieve this goal, the company may need to work in one or more of the following three directions[6]. First, the manufacturer may need to change the MPS freezing policy. Companies traditionally use a single frozen interval (Yeung *et al.* 1999), which often covers the entire *CLT* to avoid disruption to shop floor operations and the subsequent costs (Kadipasaoglu and Sridharan 1995, Yeung *et al.* 1998). If this is the case, minimising O requires replacing the single frozen interval with multiple time fences, so as to improve MPS flexibility and enable the schedule to be re-planned according to the latest demand forecast (Yeung *et al.* 1999, 2003, Vollmann *et al.* 2005). More specifically, the manufacturer needs to define a product differentiation time fence for each jth outcome of each ith PDA, denoted by $PDTF_{i,j}$ and computed as follows:

$$PDTF_{i,j} = -\left\{\left\lceil \frac{T_{\text{PDA}_{i,j}}}{R} \right\rceil - \left[1 - \boldsymbol{I}_{\mathbf{Z}_+}\left(\frac{\left|T_{\text{PDA}_{i,j}}\right|}{R}\right)\right]\right\}R \quad . \tag{6}$$

Within the $PDTF_{i,j}$, no changes to the amount of the jth outcome of PDA_i to be produced are permitted. Outside the $PDTF_{i,j}$, the amount of the jth outcome of PDA_i to be produced can be increased, subject to availability of the required materials and production capacity, or decreased, subject to availability of the required storage capacity. Product differentiation time fences add to other two commonly used time fences: namely, the demand time fence and the planning time fence (Vollmann *et al.* 2005). The former bounds the zone in the MPS planning horizon where only firm customer orders exist and is, therefore, determined by the customer order decoupling point. The planning time fence indicates the time at which additional MPS quantities should be appended to the schedule and is, therefore, determined by the *CLT*. Product differentiation time fences give the company the chance to modify MPS-MIX decisions within the planning horizon zone spanning from the demand time fence to the planning time fence without violating $T_{\text{PDA}_{i,j}}$.

To minimise O, the company may also need to redesign the forecast process driving the MPS. Sales forecasts are generated with a frequency that is usually geared to the MPS cycle (Orlicky 1975). This means that new forecasts for more distant future periods (not previously

[6] This can be formally shown by expressing $T_{\text{MPS-MIX}_{i,j}}$ (i=1,…, I; j=1,…, M_i) in $\bar{U}_{\text{MPS-MIX}}$ definition by means of Task 4 and subsequently minimising $\bar{U}_{\text{MPS-MIX}}$ given the values of $T_{\text{PDA}_{i,j}}$'s and T_{CODP}. When $\bar{U}_{\text{MPS-MIX}}$ =0, also O=0 and no more opportunities for FP_{DM} can be found in redesigning the sales forecasting and MPS process without first redesigning the transformation process.

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scheduled) are appended to the planning horizon in each MPS cycle. This does not mean, however, that forecasts for the previous planning horizon are revised in every cycle. Hence, to defer each MPS-MIX$_{i,\ j}$ as long as the corresponding $PDTF_{i,j}$ would permit, the manufacturer may need to change the forecast process so that new forecast data concerning market demand for the jth outcome of PDA$_i$ are generated in the latest possible MPS cycle preceding $T_{\mathrm{PDA}_{i,\ j}}$.

Finally, to minimise O, the company may need to change the MPS re-planning frequency. Suppose the manufacturer uses the $PDTF_{i,j}$'s according to Equation (6), but does not frequently update the MPS in order to reduce computational burden, schedule instability and the associated costs (Sridharan and Berry 1990, Zhao and Lee 1993). If this is the case, to maximize the potential benefit of using the $PDTF_{i,j}$'s, the firm needs to increase the re-planning frequency so that all $T_{\mathrm{PDA}_{i,j}}$'s are integer multiples of R and, hence, each $PDTF_{i,j}$ hits its minimum (i.e., $PDTF_{i,j}= -T_{\mathrm{PDA}_{i,\ j}}$). By doing so, the company has the opportunity to revise product mix decisions until initiation of the corresponding activities.

Implementing FP_{DM} through multi-level supply control

Underlying FP_{DM} implementation through forecasting and MPS process redesign is the idea that in a transformation process with several steps, at the beginning of each step the manufacturer only needs to make such decisions as are required to trigger just that step. The same idea can be applied outside the company boundaries to first-tier suppliers of component families, thereby implementing multi-level supply control. Multi-level supply control means that instead of placing a fully specified order with the supplier, the manufacturer gradually specifies the order at various steps, until the component variant to be delivered is uniquely identified at the last step (van der Vlist *et al.* 1997). More specifically, at the beginning of each step in the supplier's transformation process, the manufacturer provides only such information as is needed by the supplier in order to govern that step. By means of multi-level supply control, the manufacturer defers the MPS-MIX decisions specifying the amount of each possible component variant to be purchased without any changes to the supplier's transformation process (van der Vlist *et al.* 1997).

The proposed measurement procedure supports implementation of multi-level supply control by offering a holistic view of how all the PDAs within the supplier's transformation process are distributed across time for a given component family. This enables the manufacturer to determine, by means of Equation (6), the latest point in time at which the supplier needs information about the requirement of each possible outcome of each PDA. In turn, this allows the manufacturer and the supplier to establish a stepwise exchange of information such that the manufacturer's decisions pertaining to component mix are deferred as long as possible without any changes to the supplier's transformation process.

5. Empirical illustrations

To illustrate the utility of the proposed measurement procedure, three brief case examples will be reviewed. The first involves a large company operating in the motor-driven centrifugal pump sector and offering over 1,000 make-to-stock products grouped into 12 product families. The measurement procedure was applied to one of these families, which comprises plastic submersible pumps for handling, lifting and evacuating waste water. Product-differentiating features were, for this family, the type of fluid that can be pumped, the maximum power of the

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pump, the automatic or manual engagement mechanism, the power supply voltage, and the power supply cable.

Application of the measurement procedure indicated that opportunities for FP_{DM} were substantial ($\bar{U}$=9.6 weeks) and that, on average, more than 50% of FP_{DM} potentials could be pursued without redesigning the transformation process (O=0.56)–see Figure 4(a). Three reasons explained the gaps between the timings of the MPS-MIX decisions (solid curve) and initiation of the corresponding PDAs (dashed curve). First, MPS orders for $T_{\text{COMPLETION}}$ were appended to the schedule at time T_{MPS}= -20 weeks, more than five weeks before release of the earliest purchase orders for critical long lead-time materials such as ferromagnetic steel coils and stainless steel rods. This was due to the fact that the company concurrently re-planned the MPS for all their make-to-stock product families and employed the same planning horizon for all these families. Since other make-to-stock products, such as cast iron pumps, had longer *CLT*s than the plastic pumps under consideration, the MPS planning horizon was longer than the *CLT* of the product family selected (equal to 14.4 weeks). Secondly, while F was minimum (F=R), the MPS re-planning frequency was relatively low (R=1 month) and sales forecasts for $T_{\text{COMPLETION}}$ were not revised in every MPS cycle between T_{MPS} and T_{Frozen}. More precisely, forecast data generated at T_{MPS} were revised only three MPS cycles later, before initiation of manufacturing activities. This means that the MPS-MIX decisions for the various PDAs were made only at two points in time: T_{MPS}= -20 weeks and T= -8 weeks. Finally, in the last few years the company had gradually implemented a number of changes in the transformation process. For instance, sourcing lead-times of a few product-differentiating materials, such as drawn copper wires, capacitors and pump casings, had been shortened or, to give another example, the firm had decided to shrink the rotor pack on the pump shaft instead of die-casting the rotor pack directly around the shaft. As a consequence of these changes, a number of PDAs, such as pump casing sourcing and shaft fabrication, had been deferred and $\bar{U}_{\text{TRANSF}}$ had decreased. During the same years, however, the company had never revised its forecasting and MPS routines and, hence, $\bar{U}$ had remained unaltered. The reduction of $\bar{U}_{\text{TRANSF}}$ had thus entirely translated into an increase of $\bar{U}_{\text{MPS-MIX}}$, meaning that the gaps between the timings of the MPS-MIX decisions and initiation of the corresponding activities had become larger.

Insert Figure 4

Application of the measurement procedure not only made the company aware of the significant opportunities for FP_{DM} that existed in the redesign of the forecasting and MPS process without need for costly product and/or transformation process changes. The work also assisted the firm in at least partially realising these opportunities. The results of applying Equation (6) showed that given the same monthly re-planning frequency, almost 62% of all *PDTFs* would have been four weeks long, 25% would have been eight weeks long, and only 13% would have been longer. In order for almost 87% of all MPS-MIX decisions to be deferred as long as the corresponding *PDTFs* would have permitted, therefore, it would have been sufficient to revise sales forecasts for $T_{\text{COMPLETION}}$ not only at time T= -8 weeks, but also at time T= -4 weeks. By leaving R unaltered, this change would not have excessively increased workload for the master production scheduler, who was responsible for planning production of all make-to-stock product families and for generating the related sales forecasts. This change would not have required more people in the production-planning department and, consequently, would have been completely free. At the same time, this change would have enabled the company to defer MPS-MIX decisions driving high value-added PDAs, such as final assembly and the making or sourcing of all final assembly components, by four weeks. This one-month delay would have

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allowed the master production scheduler to refine sales forecasts for $T_{\text{COMPLETION}}$ based on more recent actual sales data, as customer orders for the selected product family used to concentrate in the last week of each month. In turn, the increased forecast accuracy would have permitted the company to reduce safety stocks of both end-products and final assembly components without negatively affecting service levels. Therefore, the firm decided to implement this change–see Figure 4(b)–and a conservative estimate of the subsequent reduction in safety stock investment is around 60,000 euros.

The second case concerns a medium-sized company producing and selling a large variety of pumps for use in industry, construction, firefighting, and emergency duty. In this case, application of the measurement procedure involved a family of self-priming centrifugal pumps for industrial use, which includes both standard pumps made to stock and pumps produced to customer specification. Consequently, the measurement procedure was applied to the subset comprised of the standard pumps made to stock.

Application of the measurement procedure indicated that FP_{DM} potentials were substantial in this case ($\bar{U}$=9.8 weeks), similar to the previous one. On average, however, only 17% of these potentials could be pursued without redesigning the transformation process (O=0.17)–see Figure 4(c). Despite the relatively low re-planning frequency (R=1 month), the O value was low because sales forecasts for $T_{\text{COMPLETION}}$ were revised in each MPS cycle and the quantity of the jth outcome of PDA_i to be produced (i=1,…, I; j=1,…, M_i) was not frozen before the latest MPS cycle preceding initiation of the corresponding activity. In this case, therefore, application of the measurement procedure assisted the company to conclude that the timings of the MPS-MIX decisions virtually coincided with the timings of the corresponding PDAs and that the only avenue to substantially defer MPS-MIX decisions was to redesign the product architecture and/or the transformation process so as to delay the corresponding activities. Further, the curve of $(U_{\text{TRANSF}})_{i,\,j}$'s showed that many PDAs occurred early in the transformation process, at the component manufacturing stage, owing to low component commonality. Thus, the two curves of $(U_{\text{TRANSF}})_{i,\,j}$'s and $U_{i,\,j}$'s proved to be an effective means of making technical office personnel more aware of the need for increasing component commonality in order to implement FP_{DM}. The company also found the graphical outputs of the measurement procedure to be very helpful in making all managers conscious that there would have been little room for applying FP_{DM} unless the company had previously succeeded in reducing component sourcing and manufacturing lead-times, which accounted for 20 out of the 23 weeks of this product family *CTL*. As one senior executive of the company noted, "the two curves should be on the desktop of all of our managers in order to constantly remind each of them of the criticality of cutting lead-times and increasing standardisation".

Finally, the third case involves a medium-sized company producing and selling floats and tippers for commercial vehicles built by the main players in the automotive industry. In this case, the measurement procedure was applied to a family of anodised aluminium profiles that the company purchases on a to-forecast basis to subsequently make side and rear panels for its products. At the beginning of each month, the company used to give each of its two aluminium profile suppliers a time-phased material requirement's specification stated in product codes and covering the following month. Product codes univocally identify the aluminium profiles to be delivered. This means that the decisions as to how much of each possible profile to purchase were made at least one month before delivery, with negative effects on the amount of profile inventory needed to buffer against sales forecast inaccuracy.

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Application of the measurement procedure indicated that information on the specific profiles to be produced was needed by the two suppliers no earlier than two weeks prior to delivery. Two weeks was exactly the time span necessary for each supplier to plan and execute the extrusion process, which creates the different profiles, and the subsequent activities of stretching, cutting, superficial finishing, packing, and shipment. What the suppliers needed to know further in advance was just such aggregate information as was required to allocate production capacity. It was therefore agreed upon that at the beginning of each month, the company would have informed each supplier about the total profile volume (expressed in kilos) to be delivered in each of the following month's weeks. The mix of specific profiles, however, would have been specified only later, just two weeks before delivery. In other terms, application of the measurement procedure supported deferment of profile mix specification by at least two weeks through implementation of multi-level supply control, without any changes to the suppliers' transformation processes. This delay made it possible for the company to decide the profile mix based on sales forecasts that had an error margin of ±10%, instead of ±20%. As a consequence, this FP_{DM} application enabled the company to reduce safety stocks of aluminium profiles by around 130,000 euros without negatively affecting service levels and without any product and/or process redesign costs for the suppliers.

6. Discussion and conclusion

By formalising and operationalising FP as the deferment of production-planning decisions pertaining to product mix, this paper contributes to a better understanding of the changes in the sales forecasting and MPS process that enable FP and, at the same time, offers a mapping tool that assists companies in redesigning their decision-making routines to implement FP. The existing FP literature predominantly focuses on product and/or transformation process changes that enable the deferral of PDAs (Swaminathan and Lee 2003, Yang *et al.* 2004b). Only recently have Skipworth and Harrison (2004, 2006) and Harrison and Skipworth (2008) pointed out the role of the manufacturing planning and control system in FP implementation.

We show that in forecast-driven manufacturing environments in which product mix decisions are triggered by the MPS process, deferring PDAs may be insufficient to implement FP. In such contexts, to defer the MPS-MIX decisions driving PDAs, manufacturers may also have to improve the flexibility of the sales forecasting and MPS process. The proposed measurement procedure assists companies in this effort by enabling them to determine what time fence should be associated with each possible outcome of each forecast-driven PDA, how frequently the MPS should be re-planned, and at what time market demand for each possible outcome of each PDA should be forecasted in order for each MPS-MIX decision to be deferred until the corresponding activity is initiated. By doing this, the proposed measurement procedure helps manufacturers achieve the full potential benefits of remaining forecast-driven FP. This type of FP applies to forecast-driven PDAs and results in the carrying out of these activities still on a to-forecast basis, but closer to the time of customer order receipt (Forza *et al.* 2008). This type of FP is especially attractive in the situations where off-the-shelf availability of end-products is essential to get customer orders (Wong *et al.* 2008), such as in the grocery or apparel industry. Further, this FP type may be attractive to the machinery sector, where many manufacturers of long cumulative lead-time products are forced by customer pressures for faster deliveries to start building products on a to-forecast basis (Meredith and Akinc 2007). In all these contexts, more and more companies strive to redesign their products and/or their manufacturing and supply chain processes to defer PDAs, under the assumption that this will

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alleviate the negative effects of product variety on their performance. Opportunities for deferring product mix decisions, however, are sometimes lost by these firms in their administrative processes, so that only part of the potential benefits of FP are eventually realised.

We also show that FP and the related inventory risk reduction advantages may be achieved without necessarily redesigning the product family architecture and/or the transformation process to defer PDAs. This is because large time lags may exist between MPS-MIX decisions and initiation of the corresponding PDAs. This is hardly an issue for well-managed companies operating in market-responsive supply chains (Fisher 1997), who must not make MPS-MIX decisions in advance of the corresponding PDAs. Conversely, large time lags may exist in firms that for some reason (e.g., high interfunctional barriers or management focus only on the material flow) have failed to keep decision-making routines aligned with transformation processes. These time lags may also be substantial in well-managed companies that have traditionally faced high-volume predictable demand and have accordingly concentrated on achieving schedule stability, with the subsequent productivity and quality advantages (Harrison 1997), rather than schedule flexibility. A steep increase in demand volatility could prompt such firms to eliminate the time lags between MPS-MIX decisions and PDAs in order to lower overstock and stock-out costs. In all these contexts, the proposed measurement procedure assists companies in identifying the time lags between MPS-MIX decisions and PDAs as well as in revising the sales forecasting and MPS process so as to eliminate or at least reduce these lags.

Similar to other value stream mapping tools discussed in literature (New 1974, Hines and Rich 1997), the measurement procedure proposed in this paper is not a prescriptive model expected to indicate some optimal course of action. The graphical and numerical outputs of the measurement procedure, however, are a very economical presentation of many interrelated characteristics of a product family, such as all planned lead-times, PDAs, forecast windows, etc. Consequently, these outputs are a relatively simple tool to convey complex but critical information to the upper management echelons of a manufacturing company and to help them focus attention on specific areas. These outputs can then be used as a basis for further, more detailed analysis aimed at assessing the benefits and costs associated with the identified opportunities for FP. These outputs may also be important in making top management more aware of the interdependencies between product design, manufacturing process design, supply chain design, and forecasting and MPS process design (Mather 1986, Forza *et al.* 2005). Such greater awareness will ultimately prompt coordinated redesign efforts intended to remove constraints and fully exploit opportunities for FP that may exist at the interfaces between different functional areas.

To overcome the limitations of the proposed measurement procedure, future research could focus on the development of prescriptive models aimed at determining the optimal positioning of product mix decisions in MPS-driven manufacturing environments, similar to the existing models for optimal positioning of PDAs triggered by *a priori*-defined inventory replenishment rules (e.g., Lee and Tang 1997, Hsu and Wang 2004). Another interesting opportunity for future research could be to perform an in-depth investigation of why some companies allow themselves to make product mix decisions so far in advance of when these decisions are required by the factory. Of course, this could be the result of a company's deliberate decision. The MPS literature, for instance, suggests that schedule instability and the associated costs incurred by both the manufacturer and its suppliers might outweigh the inventory risk reduction advantages resulting from elimination of the time lags between MPS-MIX decisions and initiation of the corresponding PDAs (e.g., Yeung *et al.* 2003; Robinson *et al.* 2007). Application of the

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proposed measurement procedure in the field, however, indicates that other factors than the completely rational agent's optimizing approach may explain such time lags. As some managers suggested, for example, the cognitive load of the master production scheduling task, including both complexity and workload (Fransoo and Wiers 2006), could play an important role. Postponing product mix decisions to the latest possible point in time prevents the master production scheduler from dealing with these decisions all at once, in a batch-like fashion, especially if she/he is responsible for scheduling different product families with different cumulative lead-times. The need for making product mix decisions at numerous points in time may conflict with other master production scheduler's tasks, or may subdue him/her to unduly cognitive load due to multiple "mental setups" (Pentland 2003), thus ultimately inhibiting the pursuit of FP. Investigating such possible behavioural explanations would contribute to a better understanding of organizational issues in FP implementation, which have been found as a high impediment to the application of FP (Matthews and Syed 2004) but have received little attention in the relevant literature (Yang *et al.* 2005).

Appendix: notation overview

CLT	Cumulative lead-time for the MPS-driven activities within the transformation process of a product family.
F	Frozen interval in the MPS process. FP_{DM} is favoured by a reduction of the value of this parameter.
$PDTF_{i,j}$	Product differentiation time fence for the jth outcome of the ith PDA. FP_{DM} is favoured by adoption of $PDTF_{i,j}$'s.
I	Number of MPS-driven PDAs within the transformation process.
K	Number of MPS-driven activities within the transformation process.
l_k	Planned lead-time for the kth activity (assumed as independent of the activity outcome).
$l_{k,j}$	Planned lead-time for the kth activity when its outcome is j.
M_k	Number of possible different outcomes of the kth activity.
N	$=\sum_{i=1}^{i=I} M_i$
R	Re-planning interval in the MPS process. FP_{DM} is favoured by an increase of the value of this parameter.
$T_{\text{Actitity } k}$	Latest possible time at which the kth activity must start for production to be completed at time zero (assumed as independent of the activity outcome).
$T_{\text{Actitity } k,j}$	Latest possible time at which the kth activity must start when its outcome is j for production to be completed at time zero.
T_{CODP}	Customer order decoupling point
$T_{\text{COMPLETION}}$	Timing of production completion (set equal to zero).
T_{Frozen}	Latest point in time, relative to $T_{\text{COMPLETION}}$, at which the mix of product variants to be completed at $T_{\text{COMPLETION}}$ may be changed.
$T_{\text{PDA}_{i,j}}$	see $T_{\text{Activity } k,j}$, where activity k is the ith PDA_i.
T_{MPS}	Point in time at which additional MPS orders are appended to the schedule to satisfy market demand requirements at $T_{\text{COMPLETION}}$.

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$T_{\text{MPS-MIX}_{i,j}}$	Timing of the frozen decision specifying the quantity of the jth outcome of the ith PDA to be produced.
$U_{i,j}$	FP_{DM} potential for $\text{MPS-MIX}_{i,j}$.
$(U_{\text{MPS-MIX}})_{i,j}$	Maximum possible deferment of $\text{MPS-MIX}_{i,j}$ that can be achieved without having to defer $T_{\text{PDA}_{i,j}}$.
$(U_{\text{TRANSF}})_{i,j}$	$= U_{i,j} - (U_{\text{MPS-MIX}})_{i,j}$
$z_{i,j}$	Number of MPS cycles between the latest point in time at which new sales forecasts for the jth outcome of PDA_i are generated and $T_{\text{PDA}_{i,j}}$. FP_{DM} is favoured by a reduction of the value of this parameter.

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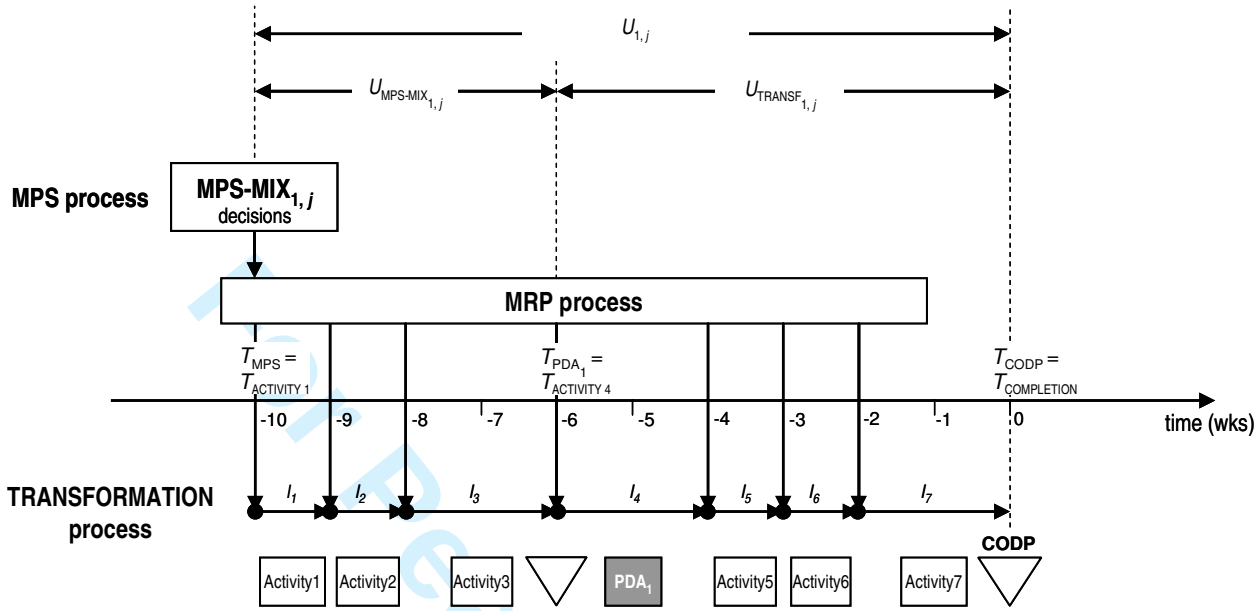

Figure 1. Potential for pursuing FP from a decision-making perspective in a hypothetical system configuration (see the Appendix for notations).

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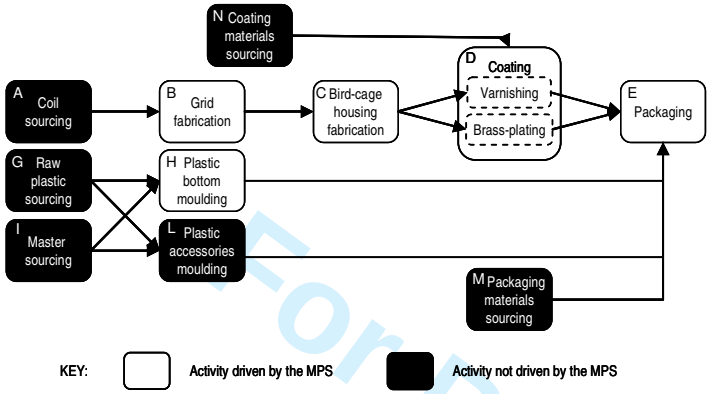

Figure 2(a): Sourcing and manufacturing process for a product family

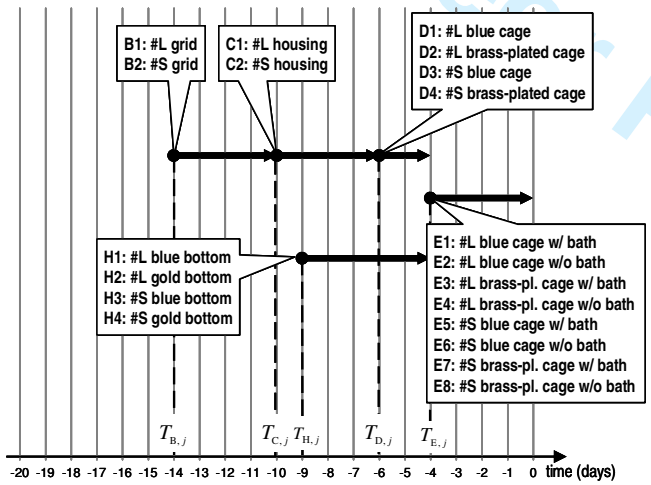

Figure 2(b): Product family operations setback chart and order release timings for the MPS-driven activities

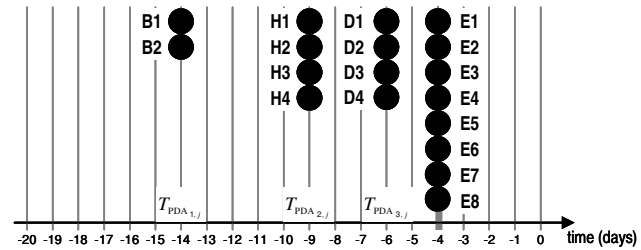

Figure 2(c): Order release timings for the PDAs

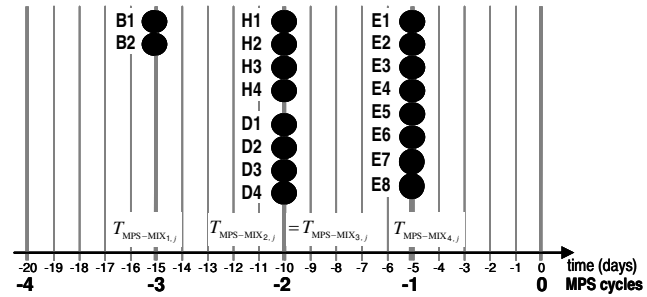

Figure 2(d): Timings of the MPS-MIX decisions

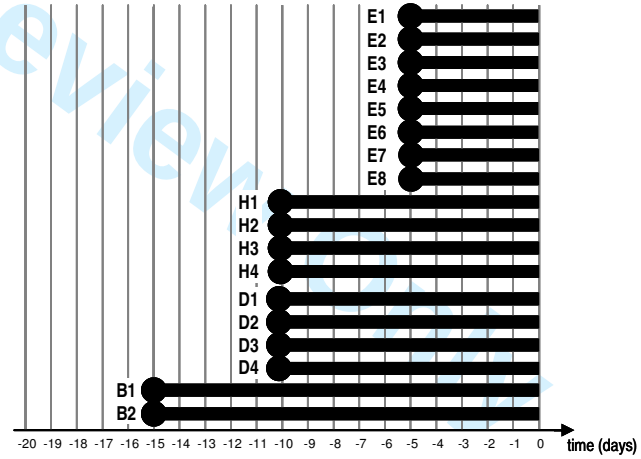

Figure 2(e): FP_{DM} potentials for the MPS-MIX decisions

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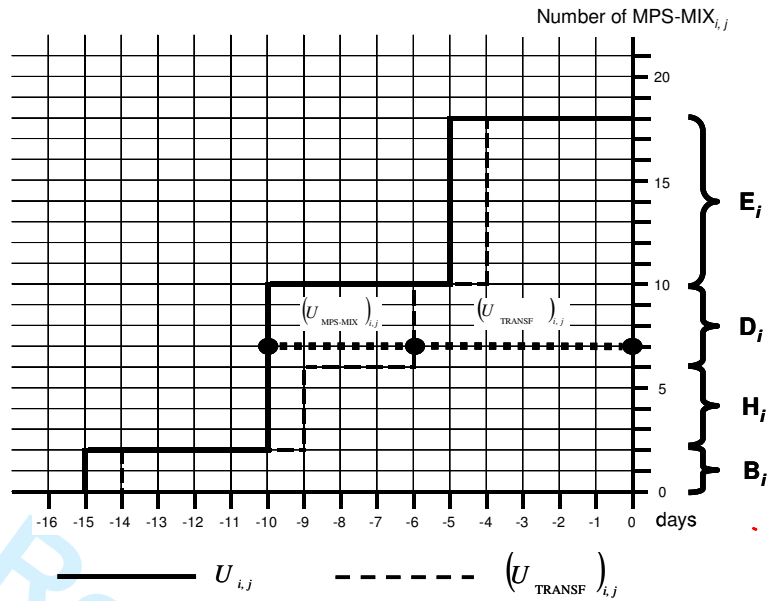
		T		U	
# MPS-MIX$_{i,j}$	ID MPS-MIX$_{i,j}$	$T_{\text{MPS-MIX}_{i,j}}$	$T_{\text{PDA}_{i,j}}$	$U_{i,j}$	$(U_{\text{TRANSF}})_{i,j}$
1	B1	-15	-14	15	14
2	B2	-15	-14	15	14
3	H1	-10	-9	10	9
4	H2	-10	-9	10	9
5	H3	-10	-9	10	9
6	H4	-10	-9	10	9
7	D1	-10	-6	10	6
8	D2	-10	-6	10	6
9	D3	-10	-6	10	6
10	D4	-10	-6	10	6
11	E1	-5	-4	5	4
12	E2	-5	-4	5	4
13	E3	-5	-4	5	4
14	E4	-5	-4	5	4
15	E5	-5	-4	5	4
16	E6	-5	-4	5	4
17	E7	-5	-4	5	4
18	E8	-5	-4	5	4

3(a)



3(b)

Figure 3. FP_{DM} potentials and their components for the bird-cage example in tabular form (3(a)) and diagram (3(b)).

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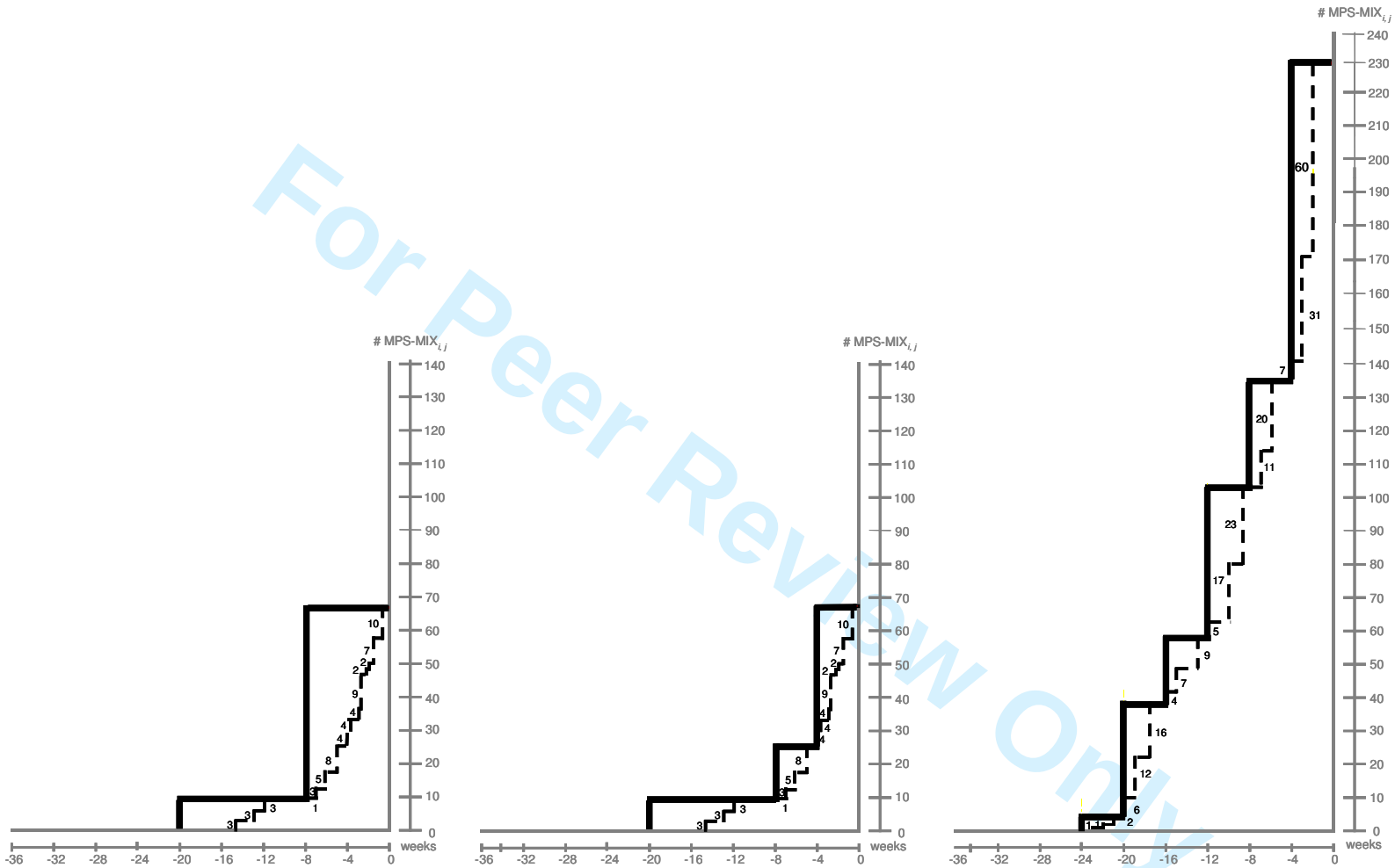

$O = 0.56$

$\overline{U} = 9.6$ weeks

4(a)

$O = 0.40$

$\overline{U} = 7.1$ weeks

4(b)

$O = 0.17$

$\overline{U} = 9.8$ weeks

4(c)

Figure 4. FP_{DM} potentials and their components (the numbers on the dashed curves are the numbers of MPS-MIX$_{i,j}$'s).

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