Journal of Enterprise Information Management

Analysis of production planning in a global manufacturing company with process mining

Mahendrawathi ER, Noval Arsad, Hanim Maria Astuti, Renny Pradina Kusumawardani, Rivia Atmajaningtyas Utami,

Analysis of production planning in a global manufacturing company with process mining

Mahendrawathi ER, Noval Arsad, Hanim Maria Astuti, Renny Pradina Kusumawardani and Rivia Atmajaningtyas Utami
Department of Information Systems, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

Received 6 January 2017
Revised 9 December 2017
Accepted 21 December 2017

Abstract

Purpose – The purpose of this paper is to present the result of using process mining to model the production planning (PP) process of a manufacturing company that is supported by enterprise resource planning (ERP) systems.

Design/methodology/approach – This paper uses event logs obtained from the case company's ERP database. The steps for this research are planning process mining implementation, extraction and construction of event log, discovering process model with Heuristic Miner and analysis.

Findings – Process model obtained from process mining shows how the PP is actually conducted. It shows the loop in materials requirement planning and create plan order process. Furthermore, the occurrences of changing plan order date and production line indicate the schedule instability in the case company. Further analysis of the material management (MM) event log shows the implication of production plan changes on MM. Continuous change in the plan affects material allocation priority and may result in a mismatch between production needs and the materials available.

Research limitations/implications – The study is only conducted in a single and specific case. Therefore, even though the findings provide good insight, the use of solitary case study does not imply a general result applied to other cases. Hence, there is a need to conduct similar studies on various cases so that a more generic conclusion can be drawn.

Practical implications – The result provides insights into how the current company's policy of adjusting the production plan to accommodate changing demand impacts their operation. It can help the company to consider a better balance between flexibility and efficiency to improve their process.

Originality/value – The paper demonstrates the use of process mining to capture the real progression of PP based on the data stored in the company's ERP database, which give an insight into how a real company conducts their PP process, the implication of schedule instability on MM and production. The novelty of this research lies in the use of process mining to attest to the schedule nervousness issue at a process level.

Keywords Process mining, SAP, Heuristic miner, Material management, Production planning

Paper type Research paper

1. Introduction

Today's highly competitive business environment forces companies to collaborate with trading partners in their supply chain to provide products and services at the right time, of the right quality and at acceptable cost. One of the key business processes towards succeeding in this highly volatile business environment is production planning (PP). PP is the process of ensuring that production occurs in a smooth and timely manner, satisfying a schedule made as a part of the business strategy of a company. The aim of this process is to maximise profits, fulfil demand, attract and retain customers.

The hierarchy of planning starts with a long-range aggregate plan that attempts to match the capacity with demand forecast and sales plans, followed by a medium-term plan that breaks the aggregate plan down into a detailed master production schedule and, finally, a short-term plan that determines what and how many products are to be made and when

This research is supported by funding from Directorate of Higher Education, Ministry of Research, Technology and Higher Education, Republic of Indonesia.

Journal of Enterprise Information Management
Vol. 31 No. 2, 2018
pp. 317-337

1741-0398
DOI 10.1108/JEIM-01-2017-0003

the production and procurement process must commence (Wisner *et al.*, 2015). PP involves making decisions about the type and quantity of items to be produced, the facilities that are necessary for the process, staffing the production process, etc.

The entire planning process requires information involving different functions of the company. PP is closely linked to material procurement, since the production process could not occur optimally if the material needed was unavailable. The challenge and complexity of PP processes have triggered the emergence of materials requirement planning (MRP), closed-loop MRP, manufacturing resource planning (MRPII) and ultimately enterprise resource planning (ERP). MRP logic provides an optimal just-in-time schedule for a deterministic environment (Dolgui and Prodon, 2007).

There is a great deal of literature addressing the PP process. Authors, including Yeung *et al.* (1998), Yucesan and De Groote (2000), Koh *et al.* (2002), Koh and Saad (2003), Mula *et al.* (2006) and Dolgui and Prodon (2007), provide extensive state-of-the-art reviews of different aspects of PP. One of the key issues receiving a great deal of attention in the literature is how to deal with uncertainties in the planning process.

A production plan provides guidelines for conducting activities including production and procurement to satisfy the demand of the end customers. A production schedule plays the important role of being a guide and evaluation baseline in the execution of the production process. It is, thus, desirable that the schedule is as stable as possible; however, the condition of the environment is rarely fully predictable. Allowing some planning flexibility should make the production system more robust to deviations in the assumptions, such as the arrival schedules of raw materials. Such flexibility would also enable the system to respond to changes in the dynamic planning process resulting from updated assumptions about the future (De Kok and Inderfurth, 1997).

In practice, this flexibility is obtained by periodic planning revision, considering new information about planning assumptions and forecasts of future conditions; however, since the business environment is inherently stochastic, this often leads to a continuous re-planning, which is associated with discontinuities in ordering decisions. Frequent changes to production schedules, also referred as "schedule instability" (Pujawan and Smart, 2012), may also lead to a phenomenon, known as the "nervousness syndrome" (Vollmann *et al.*, 1988). This phenomenon is disadvantageous, since it brings inefficiencies caused by the considerable efforts made for adjustments both in the short and medium term. The lack of planning stability potentially causes a negative perception of the personnel involved in the significance of decisions regarding planning and scheduling (De Kok and Inderfurth, 1997). Sivadasan *et al.* (2013) listed many researchers addressing the issues of schedules or "systems nervousness". The focus of the research are the consequences of schedule nervousness (Blackburn *et al.*, 1985, 1986; Koh and Saad, 2003; Ho, 1989, 1992, 2002; Ho and Ireland, 1998; Inman and Gonsalvez, 1997) and mitigation strategies (Blackburn *et al.*, 1985, 1986; Van Donselaar and Gubbels, 2002).

Mula *et al.* (2006) provided a literature review of PP under uncertainty and grouped the papers based on four modelling approaches: conceptual, analytical, artificial intelligence and simulation. It can be concluded that most of the studies in the literature to date address planning issues by modelling them from a system-level point of view. There are few studies that describe them in detail at the process level and follow the progression of the PP process as well as identifying the issues faced at each stage of the process. The fact that more and more companies automate their planning process using ERP means that the actual planning process can be traced from the data stored in the database.

One of the techniques used recently to analyse traces of user activities, i.e. event logs extracted from information systems such as ERP, is process mining. Process mining is a technique that combines different fields of computer science, business process re-engineering, etc. The technique is used as part of business process management initiative to evaluate the "as is" condition of business processes. It visualises the activities recorded in the event log into process model, which can be used to discover, assess conformance and identify potential improvements to the business process. The technique has been applied in various sectors, such as financial services (Weerdt *et al.*, 2013), healthcare (Rebuge and Ferreira, 2012) and telecommunication (ER *et al.*, 2015a). It has also been used for a specific purpose such as Jans *et al.*'s (2011) work that investigates internal fraud mitigation from procurement SAP ERP data. Our previous works model and analyse material movement (ER *et al.*, 2015b) and incoming raw materials for warehousing business process improvement (ER *et al.*,2015c).

Several studies apply process mining in a manufacturing context (Rozinat *et al.*, 2007, 2009; Paszkiewicz, 2013; Son *et al.*, 2014; Yahya, 2014; Park *et al.*, 2015). Rozinat *et al.* (2000, 2009) applied process mining to less structured test processes of a leading manufacturer of wafer scanners. They found that while process mining can be used to discover, measure compliance and propose improvement, there are several challenges for its application in a less structured event logs. Son *et al.* (2014) used process mining to analyse manufacturing processes based on event log obtained from manufacturing execution systems. Paszkiewicz (2013) applies process mining on inventory process event log obtained from warehouse management systems. Yahya (2014) demonstrates the use of process mining in manufacturing process using synthetic data. Finally, Park *et al.* (2015) used process mining to conduct performance analysis of manufacturing processes in make-to-order production. Despite previous works of process mining in a manufacturing context, there has not been any work that specifically addresses the PP process of manufacturing companies.

The contribution of this paper is twofold. It attempts to enrich the literature by reporting the implementation of process mining to model PP process. In previous works, the process to be mined is either structured (administrative process) or less structured, e.g. test processes investigated by Rozinat *et al.* (2007). A PP process has a unique characteristic as it lays between structured process and standard process, yet there are many uncertainties that render it to deviate from the standards process. This paper attempts to demonstrate the use of process mining to discover the real PP process and how it progresses based on the data stored in the company's ERP database. This way, we also demonstrate how process mining and the tool available can be used to identify the implication of constant re-planning and trace the impact on material management (MM) and production. These issues are typically addressed from a system level with mathematical model in the previous studies and not in a process level. Therefore, the novelty of this research lies in the use of process mining to attest the impact of schedule instability at a process level.

2. Process mining

Process mining is a term describing the tools and techniques for extracting a structured process description from a series of real-life executions (van Der Aalst *et al.*, 2009). The basis of process mining is the analysis of event logs (van Der Aalst *et al.*, 2004), which are records of actual actions and their associated information, such as the time of execution. This analysis gives insight into real control-flow dependencies, data and resource utilisation, and various statistic measures. One of the end products of process mining is a description of the process in the form of a model.

Process mining is mainly done for three purposes: discovery, conformance and enhancement (van Der Aalst, 2011). The process mining algorithm can be used to produce a model based on event log without any a priori information. If an existing process model is compared with an event log of the same process, then the process can be used for conformance checking. In this case, process mining is useful for performing a Delta analysis, in which the information of interest is whether business process activities are actually performed according to the correct workflow as defined by company policy (van Der Aalst and Weijters, 2004). Process mining is useful for investigating whether there are variations or deviations from the expected workflow, and furthermore to quantify such variations or deviations. The third type of process mining is enhancement, i.e. extending or improving an existing process model using information about the actual process recorded in some event log.

Process mining can be viewed from several perspectives: control-flow, organisational, the case/data and time perspectives. Control-flow perspective focusses on the ordering of activities with a goal of finding a good characterisation of all possible paths. Organisational perspective focusses on information about resources in the event log, i.e. which actors and relation between them. The case/data perspective focusses on properties of cases, which can be characterised by the values of the corresponding data element. The time perspective focusses on the timing and frequency of events.

In fulfilling its aims, process mining uses techniques from the field of modelling and analysis, such as business process modelling and from computational intelligence and data mining for extracting the business process using various algorithms.

2.1 Process mining algorithm

There have been numerous studies on developing process mining algorithms to model the business process. One of the earliest algorithms was the α algorithm (van Der Aalst *et al.*, 2002). Medeiros *et al.* (2005, 2007) developed genetic process mining. Other algorithms include Fuzzy Miner (Bozkaya *et al.*, 2009; Günther and van der Aalst, 2007) and Heuristic Miner (Weijsters *et al.*, 2006). In this paper, we utilise Heuristic Miner as one of the most used algorithms (Rojas *et al.*, 2016) due to its robustness to deal with noises (Weijsters *et al.*, 2006). The Heuristic Miner algorithm is described in more detail in this section.

Heuristic miner is an algorithm that uses local approach to develop a process model. It considers frequency of relation orders in an event log (Weijters *et al.*, 2009). This characteristic enables heuristic miner to deal with "noise" and determine the main behaviour of the process found in the event log. Heuristic miner searches for information from the control-flow perspective that considers the order of events within a case, and not the order of events among cases. Take an example of activities A and B in an event log W. The higher the frequency of A followed directly by B, and the less the occurrence of B followed directly by A, the higher the chance that activity A is causally followed by B.

Weijters *et al.* (2006) explained that to discover a process model from the event log, the first step is to analyse causal dependencies. If an activity is always followed by another one, then it is likely that there is a dependency relation between the two activities. Several notations are defined first to analyse the relations. Let T be a set of activities, i is the activity identifier and t_i is activity number i in the trace. $\sigma \epsilon T^*$ is an event trace, i.e. an arbitrary sequence of activity identifiers. $W \subseteq T^*$ is an event log, i.e. a multiset (bag) of event traces. Let $a,b \in T$:

$$a >_w b \text{ iff there is a trace } \sigma = t_1, t_2, t_3, \ldots, t_n \text{ and } i \,\epsilon\, \{1, \ldots, n-1\},\ \sigma \,\epsilon\, W \text{ and } t_i = \text{ and } t_{i+1} = b \quad (1)$$

$$a \rightarrow b \text{ iff } a >_w b \text{ and } b \ngtr_w a \quad (2)$$

$$a\#w\ b \text{ iff } a \ngtr_w b \text{ and } b \ngtr_w a \quad (3)$$

$$a||b \text{ iff } a >_w b \text{ and } b >_w a \quad (4)$$

$$a >> w\ b \text{ iff there is a trace } \sigma = t_1, t_2, t_3, \ldots, t_n \text{ and } i \,\epsilon\, \{1, \ldots, n-2\} \text{ such that } \sigma \,\epsilon\, W \text{ and } t_i = a \text{ and } t_{i+1} = b \text{ and } t_{i+2} = a \quad (5)$$

$$a >>>_w b \text{ iff there is a trace } \sigma = t_1, t_2, t_3, \ldots, t_n \text{ and } i < j \text{ and } i, j \epsilon \{1, \ldots, n\} \text{ such that}$$
$$\sigma \epsilon W \text{ and } t_i = a \text{ and } t_j = b \tag{6}$$

Equation (1) describes the activities that directly follow one another (appear in sequence). Equation (2) is used to calculate direct dependency relation. Equation (3) indicates transitions that never follow each other directly, i.e. there is no direct dependency relation and parallelism is unlikely. Equation (4) captures parallelism, that is, when two activities can follow each other directly in any order. Equations (5) and (6) describe activities that are executed multiple time, i.e. loop. Equation (5) measures the loop of length one while Equation (6) measures the loop of length two.

The Heuristic Miner algorithm works in three steps: mining of the dependency graph, AND /XOR -split/join and non-observable tasks and mining long-distance dependency. The first step will be described here. However, readers are advised to read Weijters *et al.* (2009) for more detailed information for steps 2 and 3.

The first step of Heuristic Miner is to construct a dependency graph. A frequency-based metric is used to indicate how certain we are that there is truly a dependency relation between two events A and B (notation $A \Rightarrow wB$). The calculated $\Rightarrow w$ values between the events of an event log are used in a heuristic search for the correct dependency relations. Let W be an event log over T, and $a,b \in T$. Then, $|a >_w b|$ is the number of times $a >_w b$ occurs in W, and:

$$a \Rightarrow_w b = \frac{|a >_w b| - |b >_w a|}{|a >_w b| + |b >_w b| + 1} \tag{7}$$

The value of $a \Rightarrow_w b$ is always between −1 and 1. A high value close to 1 shows a strong positive dependency between a and b, i.e. *a* is often the cause of *b* but *a* hardly ever followed *b*. On the contrary, a value close to −1 means that there is a strong negative dependency between *a* and *b*. Using the above equation, the dependency graph is developed. The graph only shows dependency relation that meets certain thresholds (van Der Aalst, 2011).

3. Methodology

The methodology used in this study follows three out of five stages of the L* lifecycle model proposed by van Der Aalst (2011): plan and justify, extract and create control flow model. In the first phase, it is determined that the process mining is driven by the questions related to PP process in the case company. The case company experiences heavy re-scheduling in PP. The company has some ideas that constant adjustment to prognosis from the headquarters may influence other related process such as MM and production. However, they have not performed an in-depth analysis. Based on this, process mining is used to answer the following questions:

RQ1. Are there specific patterns in PP process that need to be investigated further?

RQ2. How is the PP process conducted in reality?

RQ3. What are the frequency and magnitude of production plan changes?

RQ4. How do production plan changes influence the MM process?

The scope of the process mining implementation is the progression of a plan from its initial development until the plan is realized and production is complete. This mainly involves the PP module of SAP ERP implemented in the case company. In order to realise the production, there is a need to procure materials, which is done through the MM module. Thus, there is also a need to extract and analyse data from the materials management module.

The results from the first phase are used as guidelines in the extraction phase. The first step in this phase is to interview managers and staff of PP and MM processes from the case company to obtain an overview of the standard process for PP and MM. This is followed by data preparation and extraction steps as proposed by Piessens (2011). Further interviews and observations are conducted with planners (staff of PP) to obtain more technical information with respect to the format of the data, database documents and tables in SAP and the relevant attributes. The results are raw data of the PP and MM process in the form of CSV. As suggested by van Der Aalst (2011), there are two main requirements for event logs, i.e. events must be ordered in time and events need to be correlated. Therefore, the raw data are processed to construct the event logs.

After the construction of PP and MM event logs, the next step is to conduct the analysis and answer the research questions. ProM, a prominent open-source software for process mining developed by researchers at TU/e (Eindhoven University of Technology), is chosen first to aid the process. ProM is developed in a "plug-able" environment for process mining. It consists of many plug-ins, and each plug-in typically provides a certain process mining functionality. First, dotted chart analysis is done with ProM to answer *RQ1*. A dotted chart provides a "helicopter-view" of the process (Song and van der Aalst, 2007), and is very useful to give a feeling of the process and the data in the event log. In a dotted chart, each event is depicted as a dot in a two-dimensional plane. The time of the event in absolute or relative form is represented by the horizontal axis. The vertical axis represents the class of the event. Each line corresponds to a class, e.g. a case, a resource or an activity.

The next step is creating a control-flow model to gain insights into how the real PP process is conducted in reality and answer *RQ2*. The most commonly used plug-ins in ProM are those that implement the discovery algorithms, such as Heuristic Miner, Fuzzy miner, etc. In this research, Heuristic Miner plug-in in ProM is used to discover the PP process model. The results from Heuristic Miner plug-in are dependency graphs that represent the PP process model. The PP process models discovered from ProM can show deviation from the standard procedure described by PP manager.

While the dependency graph shows the sequence and dependency of activities in PP, it did not provide an easy way to track the multiset of traces that follow the same path (sequence of activities). We are interested to see the frequency and magnitude of plan order changes and related activities occurrence within the multiset of traces. We particularly want to determine how many times sequence of run MRP and create plan order activity happen (loop between the two activities) and how many times change plan order date and change plan line activities occur. These are our way of giving indications on the severity of schedule changes and the schedule nervousness phenomena in the case companies. To achieve this, we used another tool called Disco to process the event log.

Disco is a tool developed by Fluxicon (Fluxicon, 2017) to provide an easy and fast tool to conduct process mining. The core functionality of process mining is the automated discovery of process maps by interpreting the sequences of activities in the imported log file. Disco uses an improved version of Fuzzy Miner to derive a process map. The resulting map can be zoomed in and zoomed out to provide more details or more generic process according to the need of the user.

In addition to discovering process models from the event log, Disco provides other features that allow more interactive and intuitive ways of conducting process mining. One of the features used in this research is variant analysis. A variant is a specific sequence of activities (Günther and Rozinat, 2012), which can be seen as one path from the beginning to the very end of the process. Disco also provides information regarding the number of cases that fall into certain variants (follow the sequence of activities). Usually, a large portion of cases in the data set are following just a few variants, and it is useful to know which are the most frequent ones, which are the infrequent or "strange" ones. By using Disco, we can see the frequency of activities occurrences and more specifically, we can see how many times certain activities are repeated (loop). Therefore, we can see how many times the production plan is changed. This is why we chose to use Disco in addition to ProM.

Finally, in order to answer *RQ4*, the MM process model is first obtained using Heuristic Miner plug-in in ProM. Then, Disco is used to gain more in-depth insights into the impact of schedule instability on MM. This is done by taking an example of a case that experiences production plan changes and considering how these changes impact the MM and production.

4. Results

4.1 Case description

PT. XYZ Indonesia is part of a global manufacturing network that has several manufacturing units and distribution centres all over the world. PT. XYZ Indonesia is a manufacturing unit that produces shoe uppers and finished shoes. The company has implemented SAP to support them in running their business process. The company's main business processes are PP and the procurement of materials, which are supported by SAP's PP module and material management module (MM).

All PP at PT. XYZ Indonesia is guided by forecasts provided by the company's headquarter, PT. XYZ International. The forecast becomes the main input used to conduct material requirement planning (MRP), and determines material requirements for the end products and components. Forecasts provided by the company's headquarters often change. PT. XYZ runs materials requirement planning (run MRP) periodically to anticipate the effect of forecast changes. The planner must peruse changes in plan orders created by the MRP process, and delete or change the production plan as necessary.

After the MRP process, the next step is to check material availability. If the material in stock can satisfy production requirements, then the production process can start. However, if the material in stock is not enough to satisfy production requirements, then additional material needs to be procured. Once the materials are available, the production process can continue.

The main priority of PT. XYZ Indonesia is to satisfy the production target given by the company's headquarters as quickly as possible. Time is an important element in a fashion-oriented industry. This is also the case for PT. XYZ because they sell for two seasons, i.e. spring-summer and winter-autumn. In reality, some production is delayed and fails to meet the planned date. Duration of the delay can reach up to 79 days from the planned date. When the production of a certain product is late, the company must expedite the shipment to the market, which can be very costly.

The interview results with representatives of the case company, including those in charge of the SAP PP and MM modules, are described below.

4.2 PP in PT. XYZ

Based on interviews with PT. XYZ PP manager, the general procedure of the PP process and the main activities are identified. The general procedure is depicted in Figure 1.

Each activity can be described as follows:

(1) Run MRP is an activity conducted to calculate material requirements for production based on a bill of material (BOM). In PT. XYZ Indonesia, this activity is performed automatically by the system every Wednesday night. Due to the sheer amount of data, the run MRP process can take up to eight hours.

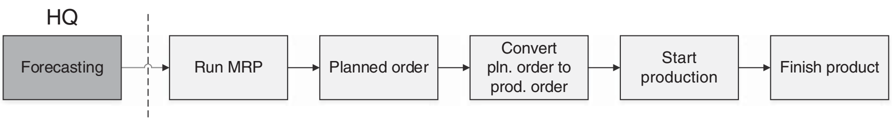

Figure 1. General procedure of production planning at PT. XYZ

(2) Plan order is the output obtained from run MRP. A plan order can be seen a proposal from the system suggesting that certain plans are required to satisfy the requirements of the product or material at a higher level in the BOM. A plan order contains information on which product to produce, materials used, and the expected production start and finished date. A plan order is created at a product level, but each plan order is expanded to material level so that the availability and lead time for each material can be considered. Planned order data can be downloaded from SAP in spreadsheet format. This file is called an ATP File. This feature enables the main planner to conduct alterations based on the latest situation, such as forecast change, material lateness, etc.

(3) Convert on is an activity to change the plan order status into production order. This is done on the assumption that the plan order is ready to be produced. The process is normally performed a week before the expected production start date. Interestingly, PT. XYZ conducts this process independent of material availability. This way a plan order can be converted into a production order, even when one or more of the materials are inadequate. This activity is performed once for each plan order.

(4) Start production is the activity to commence production process. It also marks the end of the PP process. A plan order must be converted into a production order before it can start. The production process itself can begin when all the materials required for the product are complete and released by the warehouse to the shop floor.

(5) Finish production is the activity to mark the end of production process.

The planner also described additional activities that are not covered in the general procedure but are performed in practice including the following:

(1) An issued production order is an activity that determines whether the production is ready to commence. A plan order can be issued for a production order only when all the materials required for production are available.

(2) A change plan order date, or re-scheduling, is an activity to change the production schedule to accommodate changes in the demand forecast or material lateness.

(3) A change plan line is an activity to change the production line of a plan order. This activity is performed to balance production allocation for all production lines.

4.3 MM in PT. XYZ

As stated previously, the PP process with an MRP process is closely related to procurement of materials. In addition to the general PP standard processes described above, cross cheques are performed to relate PP to procurement. While planners only identify two types of changes, namely, change plan order date and change line, interviews with the procurement staff discovered that changes in the plan order made by the planner include several things, as follows:

(1) Change material status shows the different status of material for a certain product. Material requirements are compared with the material available in stock. Based on the comparison, the following four statuses are determined for the material:

- status A is when the inventory in stock is less than the requirements and the planner has issued a purchase requisition to buy the material;
- status B is when the inventory in stock is less than the requirements and the planner has sent a purchase order to the supplier but they have not received confirmation or a schedule of delivery from the supplier;

- status L is when the inventory in stock is less than the requirement, and the supplier has confirmed that they can fulfil the order or that the material is in transit; and
- status C is when the inventory in stock can be used to satisfy the requirements.

A change in material status is a natural event that occurs once a week. Materials issued is an activity that can be performed only when the material status is C. In this activity, the warehouse will get the materials out based on the requirements. There is no guarantee that a material is pegged to only one specific plan order. Material can be a component in other plan orders, so there is the possibility that a material initially allocated to plan order A is taken over for plan order B.

(2) Change the start date of production.

(3) Change the finish date of production.

(4) Change the expected schedule receipt of materials.

Changes type (b) and (c) are made when there are changes in the forecast/prognosis from the headquarters. The change includes the addition of production quantity or change of delivery time to the headquarters warehouse. PT. XYZ Indonesia must respond to this change by moving the production schedule forward, or later than in the initial plan. The consequences of the changes are a shift in plan order priorities. Higher priority is given to the plan order with the closest start date.

The plan order priority will determine the priority of obtaining materials. The higher the priority of a plan order, the higher its priority to acquire all the materials. This can be done by taking over the materials allocated for other non-priority plan orders. The shift in allocation is enabled because the materials are not pegged to a certain plan order. This is the policy defined by the company to accommodate changes in forecast/prognosis. If the materials are pegged to a specific order, then they must order materials every time there are changes in the forecast. The company tries to avoid this because they believe it will result in overstocking and eventually increase cost. The procurement staffs sometimes must change the expected scheduled receipt of materials (change type d).

4.4 Data preparation and extraction

As suggested in Section 3, in order to extract the data from the company's database, first the relationship of each activity with the SAP documents and database tables in SAP is mapped, then the relevant attributes are selected. The activity run MRP is not found in the SAP tables because run MRP is actually a function to renew the planned order file. Based on the interviews, this activity is performed once a week, i.e. each Wednesday evening. The related information is the timestamp of the activities.

Following data preparation, the actual data extraction is performed. Based on the mapping of activities to attributes from the preparation phase, the construction of event log data requires the 14 attributes listed in Table I. These are extracted from the SAP database.

4.5 Constructing the event logs

The next step is to construct the event logs. First, the workflow or data scenario to be analysed is defined. In order to obtain analysis results that can answer the research question, the scenario used must be the complete flow, from the beginning to the end of the process. The scenarios for both PP and MM module are presented in Table II.

Once the scenarios are defined, the next step is selecting case for the event log and structuring the event log. The case for PP is the plan order. The event logs are then structured into at least three different types of attributes: case identifiers, activity name and timestamp or

Table I. Extracted attributes from PP module

PP module			MM module		
Activity	Table name	Attribute name	Activity	Table name	Attribute name
Create plan order	PLAF	Start date Finish date Create plan order number	Planned order	PLAF	Order number Material Planned order qty Requirement qty Order finish date Production start date Production finish date Date of action (creation)
Convert on	AFKO	Order number Production order number Release date Finish date Start date Created by Create on Change by Change on	Material status	PLAF	Availability confirm
Start production	AFPO	Order number Create plan Order number	Materials issued	AUFM	Material order number Posting date
			Start production	AFKO	Order Number Actual start date Actual finish date Created on
Run MRP		Run MRP date	Run MRP		Run MRP date
Finish production	AFKO	Finish date			

Table II. Scenario to be analysed

Production planning scenario		Material management scenario	
No	Scenario	No	Scenario
1	Run MRP→plan order → convert on→issued production Order→start production	1	Run MRP → planned order → material status (A, B, L, C) → materials issued → start production
2	Run MRP→plan order →change plan line		
3	Run MRP→plan order→change plan order →run MRP→plan order→convert on→ issued production →start production		

the time attribute. Having defined these attributes, the final step is to compile the information into the MXML format.

With respect to the MM event log, the case is selected at the material level. This is because the focus of the process mining is to understand the flow of how a product is made from the forecast until it is ready to be produced, and the fact that each plan order can have more than one material. The case ID combines the order number with the material code. The MM event log constructed for this research has the following attributes:

(1) material + size, from the attribute material;

(2) order number, from the attribute order number;

(3) activity name; and

(4) activity date, from the attribute date of creation.

The MXML format of the event logs is then processed using ProM and Disco for further analysis as described below.

5. Analysis

This section describes results and the analysis of the study structured according to the research questions.

5.1 Dotted chart analysis

In order to answer *RQ1* related to general overview of the PP process, a dotted chart analysis is conducted using ProM. The PP event log consists of 642 cases, 7,126 events and 9 activities. The activities are represented in different colours of the dots. The *y*-axis depicts the cases (each case is represented in one row) and *x*-axis shows the time of the activities. The chart can be sorted based on different attributes. In this case, we chose to sort the chart based on the first events of each case. The result is shown in Figures 2 and 3.

Several things can be learned from the dotted chart. The first pattern marked in a red box in the top corner of Figure 2 shows that the first few cases took a long time to complete because there are long gaps between the first dots and the next. It can be seen from the chart that a case was actually originated on 15 October 2012. However, it took more than a month to proceed to the next activity. Finally, the case was finished on 3 December 2012 which required almost two months to complete the case.

Other lessons can be taken from the dotted chart, as seen in Figure 3, that consists of three patterns. Pattern 2 in Figure 3 shows that there are activities, i.e. create plan order, run MRP and issued production order that are conducted in batches. These activities are conducted at the same time regardless of when the previous activities took place. Pattern 3 shows that there are many change plan order date activities that gives early indication that the case company is facing a schedule nervousness issue.

Finally, the last pattern shows that activities that started at the same time may finish at different times. This pattern needs to be investigated further to understand whether it is something that is expected to happen or it is something caused by unexpected problems in the business process.

Figure 2.
Dotted chart showing longer time to complete an event

Figure 3.
Dotted chart showing batches activities, the most frequent activities and activities originated from the same time

5.2 PP process model

The dotted chart analysis indicates several potential issues in the PP process of PT. XYZ. In order to answer *RQ2* that relates to detailed PP process, the PP event log is processed using Heuristic Miner plug-in in ProM. The result is a dependency graph that shows the relation between activities (arc) and the number of activities occurrence. Several findings can be obtained from the model shown in Figure 4. Following the start of the process, the next activity is run MRP followed by create plan order. However, from create plan order, there are different ways the cases progress. The graph shows that the arc from create plan order to convert on is passed 469 times. However, out of 469 that flow to convert on, only 275 cases continue to the "standard" flow of issued production order. There are 194 cases that return to run MRP, showing a loop in the process.

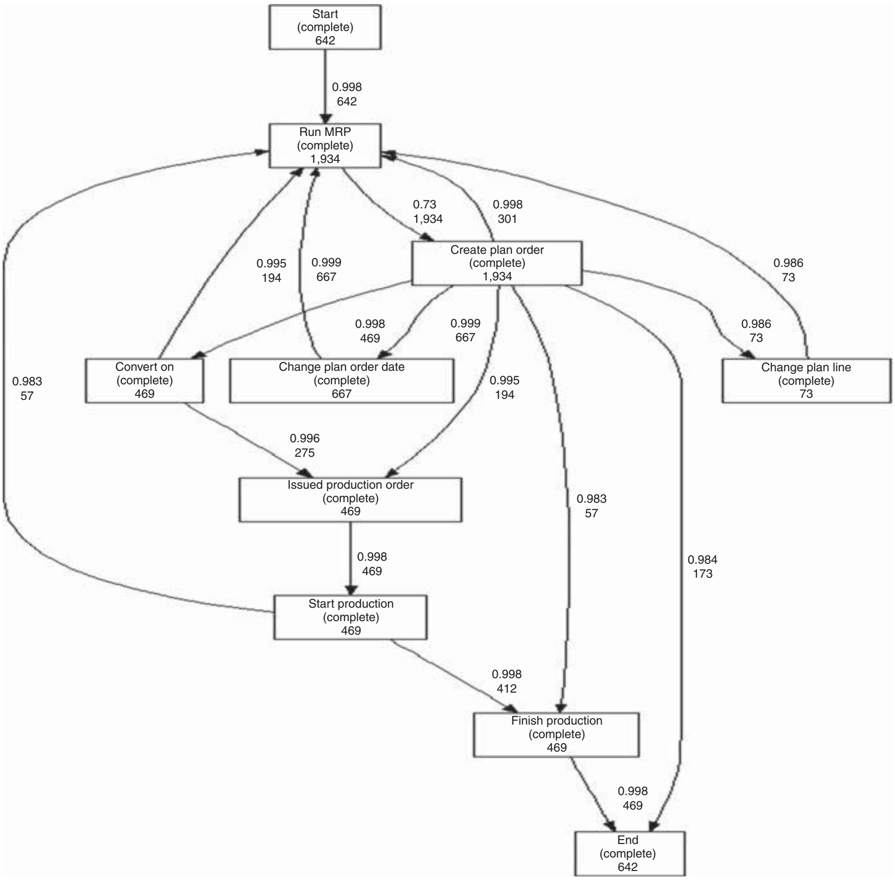

Figure 4.
Dependency graph of production planning process

There are also cases that deviate from the standard procedure stated by the planner. This can be seen by four different arcs from create plan order activities. Some cases flow to change plan order date (667) and return to run MRP and create plan order. This explains why the run MRP and create plan order are passed 1934 times (over three times the number of cases). There are also some cases that flow to change plan line (73 times) and return to run MRP. Another important finding is the presence of 57 cases that reach start production activity but then return to run MRP. Finally, 173 cases do not pass the finish production activity, which means that these cases are unfinished.

The process model uncovers the reality of PP process and enables us to identify several deviations from the standard process. However, the dependency graph only shows how the activities relate to one another. In this study, we also want to determine the frequency and magnitude of production plan changes (schedule nervousness/instability), as stated in *RQ3*.

In order to answer this question, several analyses with disco are conducted. First, the frequencies and magnitude of loop between run MRP and create plan order activities are determined. Second, the frequency of change plan order date and change plan line activities are determined. This is important because the occurrences of these activities represent implication of schedule instability and need to be traced down to identify the cause and effect. Finally, the frequency of cases that has not reached the issued to production also needs to be determined as this represents unfinished cases.

Disco is used to obtain these insights as it provides more intuitive details on the multiset of event log that follows the same sequences. This multiset is called variant in Disco. The PP event log is processed in Disco and results in 15 different multisets. Each multiset contains several cases with the same sequence of activities. An example taken from Disco shows that the order of activities for multiset (variant) number 1, with 101 cases (15.73 per cent of the total case), is (→ represents followed by):

Start→run MRP→create plan order→run MRP→create plan order→convert on→issued production order→start production.

Each of the 15 multisets obtained from Disco is perused, then grouped into another multiset based on: the frequency of run MRP and create plan order activities occurrences; the frequency of change planned order date activity occurrences; the frequency of change plan line activity occurrences; and the presence of finish production activity. The final multisets are summarised in Table III.

Multisets 1 and 2 are multisets of cases that closely resemble the standard process set by the case company. However, in all cases in these multisets, the run MRP and create plan order activities occurred more than once. Multiset 1 accounts for 31 per cent of the total cases, including cases where run MRP and create plan order activities occurred twice, while multiset 2 (3 per cent of the total cases) consists of cases where run MRP and create plan order activities occurred three times. This means that 34 per cent of the cases contain loop of run MRP and create plan order activities.

The rest of the multisets represent cases that deviate from the standard procedure set by the company in terms of change plan order date activity, change line and the last activity. In multisets 3 and 4, the change plan order date activity occurred once (10 per cent of total cases), and twice (21 per cent) while the run MRP and create plan order activities occurred three to four times. Thus, in total, over 31 per cent of the cases must experience re-scheduling of plan order date.

Multisets 5-7 represent unfinished cases where the last activity is create plan order and that have not reached the finish production activity. Multiset 5 consists of cases (11 per cent) that pass run MRP – create plan order twice and, eventually, the production line must be changed and they pass another loop of run MRP – create plan order. Multiset 6 contains cases (16 per cent) where run MRP and create plan order are done four times and the change plan order activities are conducted three times. Multiset 7 represents the cases, 9 per cent out of the total cases, that reached start production, but then must return to run MRP, create plan order and left unfinished.

The findings from process mining on the PP event log enable us to understand that there are a lot of loops in the process with 31 per cent of the total cases re-scheduled. This gave us the

Multiset	Number of run MRP and create plan order activity	Number of change plan order date activity	Number of change plan line activity	Last activity	Number of cases in the multiset	Percentage out of total cases (%)
1	2	0	0	Finish production	196	31
2	3	0	0	Finish Production	21	3
3	3	1	0	Finish production	61	10
4	3-4	2	0	Finish production	134	21
5	3	0	1	Create plan order	73	11
6	4	3	0	Create plan order	100	16
7	1-4	1	0	Create plan order	57	9

Table III.
Multiset of PP cases

magnitude of schedule instability in the case company. However, we want to gain deeper insights into the implication of the plan changes. Thus, further analysis is undertaken for the MM event logs. The MM event logs are constructed in a way that they can be related to the PP logs: the same plan order number and materials required to produce the orders are collected. This way we can track the changes in material status and how they affect the availability of materials.

5.3 *MM process model*

The MM event logs consist of 807 cases, 8 activities and 6897 events. Similar to PP process, the log is processed with ProM and Disco. ProM is used to obtain the general model on how the real process is executed but more intuitive tracing on the progression of each cases/multiset of cases are done with Disco. First, the log is processed using Heuristic Miner plug-in in ProM to obtain the dependency graph as shown in Figure 5.

Several points can be obtained about MM process based on Figure 5. The MM process model appears to be a "flower model" (van Der Aalst, 2011) with a "very loose" control flow. This model allows almost all combination of sequence of activities. This can be seen from feedback loop between run MRP with other activities including plan order, material status A, material status B, material status L and material status C. Only when run MRP flows to material issued, then it will be followed by start production. In all the cases, run MRP is followed by plan order, then it can be followed directly by either material status L, material status *C*, material status *A*, or material status *B* or any combination of these activities.

This finding offers a more realistic view of the process compared to the standard procedure explained by representatives from the case companies. According to them, the standard flow is that after run MRP and a planned order is created, the material status changes from A, B, L then C. After the material is complete (C), then it can be issued and production can start. But, the process model obtained from ProM suggests that there are different combinations of activity sequences.

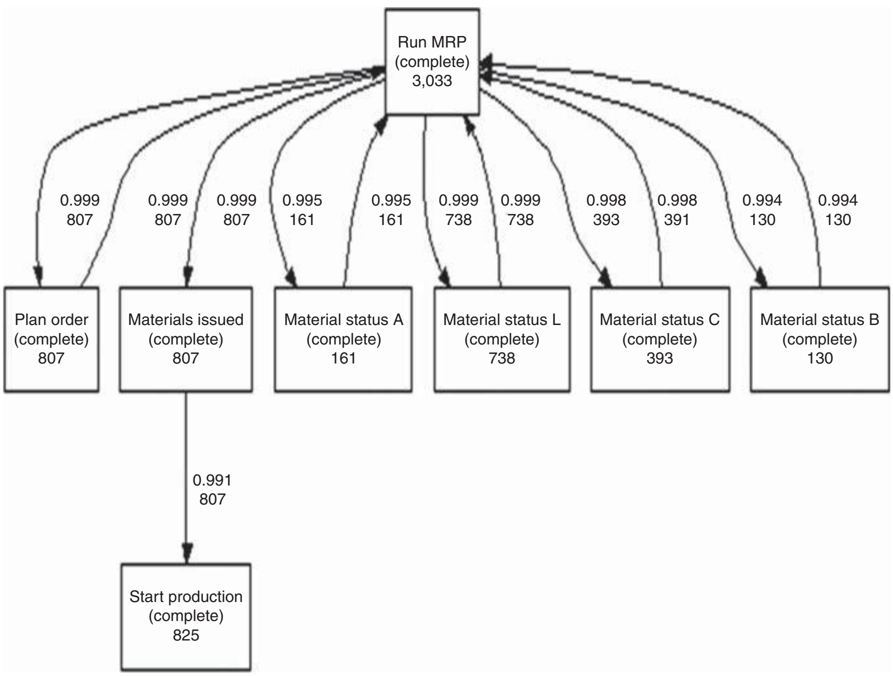

Figure 5.
Material management process model

To clarify this finding, the log is also processed using Disco. Unlike PP logs that originally can be grouped into 15 multisets, MM event logs have 106 different multisets. This result confirms the finding from ProM that there are a lot of different possible paths (sequence of activities) in the MM process. Most of the multisets contain less than 10 cases (less than 1 per cent of the total case). There are only 15 different variants that contain more than ten cases representing the most common path. These multisets are analysed further by perusing the sequence of activities and two measures: the average length of time to complete the cases in that multiset. The actual production start date is compared to the original planned production date to obtain the production lateness. Table IV summarises information from two multisets that contain over 50 per cent of the cases, and two multisets that experience 100 per cent production lateness.

As can be seen from Table IV, most of the cases in the event log move from run MRP, planned order, run MRP, material status *C*, run MRP, material issued, then start production. The rest of the cases also deviate from the standard A, B, L, C material status. Multisets numbered 7 and 8 are worth further investigation as all the cases in these multisets experienced production lateness. The cases in these variants are therefore investigated further and traced in the ATP data to understand why these variants experienced lateness. To illustrate the findings, one example is chosen and discussed further here.

As an example, we take case ID 00327835070091375000001, which falls in multiset number 8. From the ATP file, we can see that on 4 January 2013, the material status was L. Following another round of run MRP on 10 January 2013, the material status changed from L to B. Further perusal of the ATP data showed that there have been changes in the production plan date for material 00327835070091375000001 in the plan order 0032783507.

Plan order 0032783507 was originally planned to start production on 15 February 2013, but changed to 25 February 2013. This resulted in a priority change for the order. Because the production date was later, the production plan priority became lower. Originally, PT. XYZ Indonesia had allocated materials for the plan order, and on 4 January, the status was in transit (material status L). Once the production plan change, the status of material 00327835070091375000001 changed to B (waiting for supplier confirmation). This indicates that the materials originally allocated for the plan order were now allocated to another plan order with higher priority, i.e. the one with a closer production date.

This change had further impact as the material 00327835070091375000001 was imported from a supplier abroad, which means it had a long lead time. The material eventually arrived 20 days late. This result in the change from the original schedule released on 8 February 2013 but the material was released on 1 March 2013. The delay in the arrival of material 00327835070091375000001 delayed the production of plan order 0032783507. The plan production start date was 25 February 2013, but the actual production start date

Multiset number	Order of activities	Number of cases	Average length of time (day)	% Production lateness
1	Run MRP – planned order – run MRP – material status C – run MRP – materials issued – start production	313	41	3,5
2	Run MRP – planned order – run MRP – material status L – run MRP – materials issued – start production	122	40	33
7	run MRP – planned order – run MRP – material status L – run MRP – material status B – run MRP – material status B – run MRP – material status L – run MRP – materials issued – start production	10	51	100
8	Run MRP – planned order – run MRP – material status L – Run MRP – material status L – run MRP – Material status B – run MRP – materials issued – start production	12	41	100

Table IV.
Multiset of material management event log

was 1 March 2013, when material 003278350700913750001 was eventually released. This explanation is for one case only but it can show how changes in a plan indirectly affect the receipt of material and its release. It can cause the material to arrive later than expected and eventually delay production.

6. Discussion

Several findings from the research in the case company's PP process need to be discussed further. The discussion will focus on indication of schedule instability, the cause, implication and potential solutions to schedule instability problem found in the case company.

First, the results from interview, data extraction and process mining highlight the presence of change plan order date and change plan line, which give an indication of the schedule instability in the case company. Further exploration revealed the cause of the instability. As stated previously, PT. XYZ Indonesia obtains input for PP process from a prognosis provided by PT. XYZ International that is continuously updated. To accommodate any changes in the prognosis, PT. XYZ runs their MRP systems weekly. Planners must manually compare the plan orders obtained from the latest MRP run to the previous plan. They determine the changes, particularly change in production plan date or change in production quantity. These findings support previous studies by many researchers including Herrera *et al.*, (2016), Pujawan *et al.* (2014) and Sivadasan *et al.*, (2013) that point out demand uncertainty as one of the sources of schedule instability or nervousness.

The practice brings several implications to the case company. First, planners must conduct manual perusal of the MRP runs and identify any changes. Changes in the prognosis may lead to change plan order date or change plan order line. Changing plan line will affect the learning curve of that line, which according to the representative from the case company, normally, results in 70 per cent fall in the learning curve in the first week of the line change. It will take several weeks for the production line to reach 100 per cent productivity.

The schedule instability has further impact on MM. This is also something that has been mentioned previously in the literature (Sivadasan *et al.*, 2013). However, most literature focus on how schedule instability leads to systems nervousness in terms of lot-sizing decisions within MRP systems (Ho, 2002; Narayanan and Robinson, 2010), which cause a domino effect to other components within the same BOM, and to other products that use the same production facilities (Koh, 2004).

In the case company, however, the implication relates more to material allocation practices. The production plan date determines priorities to use materials. If the production plan date is pushed later than the original plan, then the plan order priority will decrease and material allocation will change too. In the case company, materials are not pegged to a certain production order. The procurement of materials is done in batches. This also means that the material can be switched from one plan order to another, depending on the production plan priority. As demonstrated in Section 5.3, when a plan order is pushed to later dates, the material originally allocated for a specific order can be given to higher priority plan orders.

Changes in the material allocation mean that the purchasing department must order the material to cover the original material that has been re-allocated to other priority plan orders. If these changes do not consider the lead time for ordering material, then there is a possibility that the material will arrive later than the material release date. The majority of materials used by PT. XYZ Indonesia come from vendors abroad. When the materials are late for the planned release date, then the production of the orders must be re-scheduled.

7. Practical and research implications

This research has several practical and research implications. For the case company, the results of this study demonstrate the implication of accommodating changing forecasts to the company's PP and MM, which may not have been investigated before.

Output of the process mining revealed that in general, PP process is more structured where the activities sequences follow several patterns compared to MM process. However, there are more possible activities and paths in both PP and MM processes than stated in the general guideline of the company. Thus, the process model can be used as inputs in defining a more detail procedure. This is necessary to ensure standard actions by various actors involved in the process, particularly with respect to exception handlings.

Further analysis suggests that the company experiences more than 30 per cent re-scheduling and around 11 per cent of change in production line. As explained in the previous section, these are implications of the company's policy to accommodate changes from the headquarters prognosis. This provides an opportunity for further study to examine the benefits and costs associated with providing such flexibility.

Many have been written in the literature about strategies to deal with schedule nervousness. Several researchers have proposed the use of frozen periods (Kadipasaoglu and Sridharan, 1995), choosing the appropriate frequency of re-scheduling (Hozak and Hill, 2009) and buffer stock for high-level item (Blackburn *et al.*, 1985). Other researchers have attempted to measure the impact of schedule nervousness on cost (Tunc *et al.*, 2013). There is a research opportunity to implement some of the proposed practice, such as imposing frozen periods, altering the frequency of re-scheduling and investigating the impact on the company's operation.

Finally, there is also an opportunity to explore the possibility for more advanced use of process mining in dealing with the situation. In this study, we demonstrate the use of process mining for process discovery on events that are mostly completed. van Der Aalst (2011) defined this type of process mining as offline. There is an opportunity to analyse events when they occur, which means using process mining as an online operational support. The progression of plan order can be captured in (near) real time, and some rules can be implemented. For example, planner can be notified when re-scheduling of certain case has been done for a certain number of times or when materials do not arrive before the scheduled production process. This way, more preventive efforts can be done to reduce the negative impact of schedule instability.

8. Conclusion

This paper demonstrates the use of process mining in modelling and analysing the event log from PP and MM of ERP systems in a real manufacturing company. The cases in the event log are at the material level in order to be able to tie the PP and MM processes. The results of process mining with Heuristic Miner show that there are many more activities and possible paths in the real PP process compared to the standard guideline determined by the case companies.

The PP model shows a lot of loops between run MRP and create plan order activities, which can occur twice (31 per cent) or three times (3 per cent). Further analysis reveals that 31 per cent of the cases experience change in plan order date, and 11 per cent of the plan entail change plan line. These represent the implication of schedule instability on the case companies. Further analysis of the MM found that changes in production plan affect the material allocation priority. As the material is not pegged to a certain order, then it can be allocated to production orders with a more imminent due date. The consequence is that material with a long lead time cannot arrive in time for production release and eventually delays production.

In more general view, it opens opportunity for further study. First, it will be interesting to assess the feasibility of utilising frozen periods and periodical re-planning in the case company and evaluate its impact on service level and the cost of flexibility. Another area for further study is to use process mining for operational support so the case company can detect, predict and recommend actions as the events in the process takes place. To achieve this, a mechanism to extract all related raw data and construct the event log for analysis is needed.

References

Blackburn, J.D., Kropp, D.H. and Millen, R.A. (1985), "System nervousness: causes and cures", *Engineering Costs and Production Economics*, Vol. 9 Nos 1-3, pp. 141-146.

Blackburn, J.D., Kropp, D.H. and Millen, R.A. (1986), "A comparison of strategies to dampen nervousness in MRP systems", *Management Science*, Vol. 32 No. 4, pp. 413-429.

Bozkaya, M., Gabriels, J. and Werf, J.M.E.M. (2009), "Process diagnostics: a method based on process mining", *International Conference on IEEE Information, Process, and Knowledge Management, February*, pp. 22-27.

De Kok, T. and Inderfurth, K. (1997), "Nervousness in inventory management: Comparison of basic control rules", *European Journal of Operational Research*, Vol. 103 No. 1, pp. 55-82.

Dolgui, A. and Prodon, C. (2007), "Supply planning under uncertainties in MRP environments: a state of the art", *Annual Reviews in Control*, Vol. 31 No. 2, pp. 269-279.

ER, M., Astuti, H.M. and Nastiti, A. (2015a), "Analysis of customer fulfilment business process in telco industry with process mining", *Procedia Computer Science*, Vol. 72, pp. 588-596.

ER, M., Astuti, H.M. and Wardhani, I.R.K. (2015b), "Material movement analysis for warehouse business process improvement with process mining. A case study", in Bae, J., Suriadi, S. and Wen, L. (Eds), *Asia Pacific Business Process Management*, Lecture Notes in Business Information Processing, Vol. 219, AP-BPM, Springer, Cham, pp. 115-127.

ER, M., Astuti, H.M., , Astuti, H.M. and Pramitasari, D. (2015c), "Modeling and analysis of incoming raw materials business process: a process mining approach", *International Journal of Computer and Communication Engineering*, Vol. 4 No. 3, pp. 196-203.

Fluxicon (2017), "Process mining for professionals", available at: https://fluxicon.com/disco/ (accessed 5 May 2017).

Günther, C.W. and Rozinat, A. (2012), "Disco: discover your processes", *BPM (Demos)*, Vol. 940, pp. 40-44.

Günther, C.W. and van der Aalst, W.M. (2007), "Fuzzy mining-adaptive process simplification based on multi-perspective metrics", *Business Process Management*, Springer, Berlin and Heidelberg, pp. 328-343.

Herrera, C., Berraf, S.B., Thomas, A. and Parada, V. (2016), "A reactive decision making approach to reduce instability in a master production schedule", *International Journal of Production Research*, Vol. 54 No. 8, pp. 2394-2404.

Ho, C.J. (1989), "Evaluating the impact of operating environments on MRP system nervousness", *International Journal of Production Research*, Vol. 27 No. 7, pp. 1115-1135.

Ho, C.J. (1992), "An examination of a distribution resource planning problem: DRP system nervousness", *Journal of Business Logistics*, Vol. 13 No. 2, pp. 125-152.

Ho, C.J. (2002), "Evaluating dampening effects of alternative lot-sizing rules to reduce MRP system nervousness", *International Journal of Production Research*, Vol. 40 No. 11, pp. 2633-2652.

Ho, C.J. and Ireland, T.C. (1998), "Correlating MRP system nervousness with forecast errors", *International Journal of Production Research*, Vol. 36 No. 8, pp. 2285-2299.

Hozak, K. and Hill, J.A. (2009), "Issues and opportunities regarding replanning and rescheduling frequencies", *International Journal of Production Research*, Vol. 47 No. 18, pp. 4955-4970.

Inman, R.R. and Gonsalvez, D.J.A. (1997), "Measuring and analysis supply chain stability: a case study in the automotive industry", *Production Planning & Control*, Vol. 8 No. 2, pp. 194-204.

Jans, M., van der Werf, J.M., Lybaert, N. and Vanhoof, K. (2011), "A business process mining application for internal transaction fraud mitigation", *Expert Systems with Applications*, Vol. 38 No. 10, pp. 13351-13359.

Kadipasaoglu, S. and Sridharan, V. (1995), "Alternative approaches for reducing schedule instability in multistage manufacturing under demand uncertainty", *Journal of Operations Management*, Vol. 13 No. 3, pp. 193-211.

Koh, S. and Saad, S. (2003), "MRP-controlled manufacturing environment disturbed by uncertainty", *Robotics and Computer-Integrated Manufacturing*, Vol. 19 Nos 1-2, pp. 157-171.

Koh, S., Saad, S. and Jones, M. (2002), "Uncertainty under MRP-planned manufacture: review and categorization", *International Journal of Production Research*, Vol. 40 No. 10, pp. 2399-2421.

Koh, S.C.L. (2004), "MRP-controlled batch-manufacturing environment under uncertainty", *Journal of the Operational Research Society*, Vol. 55 No. 3, pp. 219-232.

Medeiros, A.K.A. de, Weijters, A.J.M.M. and van der Aalst, W.M.P. (2007), "Genetic process mining: an experimental evaluation", *Data Mining and Knowledge Discovery*, Vol. 14 No. Issue 2, pp. 245-304.

Mula, J., Poler, R., Garcia-Sabater, J.P. and Lario, F.C. (2006), "Models for production planning under uncertainty: a review", *International Journal of Production Economics*, Vol. 103 No. 1, pp. 271-285.

Narayanan, A. and Robinson, P. (2010), "Evaluation of joint replenishment lot-sizing procedures in rolling horizon planning systems", *International Journal of Production Economics*, Vol. 127 No. 1, pp. 85-94.

Park, M., Song, M., Baek, T.H., Son, S., Ha, S.J. and Cho, S.W. (2015), "Workload and delay analysis in manufacturing process using process mining", in Bae, J., Suriadi, S. and Wen, L. (Eds), *Asia Pacific Business Process Management*, Vol. 219, AP-BPM, Springer, Cham, pp. 138-151.

Paszkiewicz, Z. (2013), "Process mining techniques in conformance testing of inventory processes: an industrial application", in Abramowicz, W. (Ed.), *Business Information Systems Workshops. Lecture Notes in Business Information Processing*, Vol. 160, BIS, Springer, Berlin and Heidelberg, pp. 302-313.

Piessens, D. (2011), "Event log extraction from SAP ECC 6.0.unpublished master thesis, Technische Universiteit Eindhoven, Eindhoven.

Pujawan, I.N., ER, M., Kritchanchai, D. and Somboonwiwat, T. (2014), "Uncertainty and schedule instability in supply chain: insights from case studies", *International Journal of Services and Operations Management*, Vol. 19 No. 4, pp. 468-490.

Pujawan, N. and Smart, A.U. (2012), "Factors affecting schedule instability in manufacturing companies", *International Journal of Production Research*, Vol. 50 No. 8, pp. 2252-2266.

Rebuge, Á. and Ferreira, D.R. (2012), "Business process analysis in healthcare environments: a methodology based on process mining", *Information Systems*, Vol. 37 No. 2, pp. 99-116.

Rojas, E., Munoz-Gama, J., Sepúlveda, M. and Capurro, D. (2016), "Process mining in healthcare: a literature review", *Journal of Biomedical Informatics*, Vol. 61, June, pp. 224-236.

Rozinat, A., Jong, I.S.M. de, Günther, C.W. and van Der Aalst, W.M.P. (2007), "Process mining of test processes: a case study", Technical report Working Papers No. 220, Technische Universiteit Eindhoven, Eindhoven.

Rozinat, A., Jong, I.S.M. de, Günther, C.W. and van der Aalst, W.M.P. (2009), "Process mining applied to the test process of wafer scanners in ASML", *IEEE Transactions on Systems, Man, and Cybernetics*, Part C, Vol. 39 No. 4, pp. 1-6.

Sivadasan, S., Smart, J., Huatuco, L.H. and Calinescu, A. (2013), "Reducing schedule instability by identifying and omitting complexity-adding information flows at the supplier-customer Interface", *International Journal of Production Economics*, Vol. 145 No. 1, pp. 253-262.

Son, S., Yahya, B., Song, M., Choi, S., Hyeon, J., Lee, B., Jang, Y. and Sung, N. (2014), "Process mining for manufacturing process analysis: a case study", *Proceeding of 2nd Asia Pacific Conference on Business Process Management*, *Brisbane*, *3-4 July*.

Song, M. and van der Aalst, W.M.P (2007), "Supporting process mining by showing events at a glance", Proceedings of the 17th Annual Workshop on Information Technologies and Systems.

Tunc, H., Kilic, O.A., Tarim, S.A. and Eksioglu, B. (2013), "A simple approach for assessing the cost of system nervousness", *International Journal of Production Economics*, Vol. 141 No. 2, pp. 619-625.

van Der Aalst, W.M.P. and Weijters, A.J.M.M. (2004), "Process mining: a research agenda", *Computers in Industry*, Vol. 53 No. 3, pp. 231-244.

van Der Aalst, W.M.P., Weijters, A.J.M.M. and Maruste, L. (2004), "Workflow mining discovering process models from event logs", *IEEE Transactions on Knowledge and Data Engineering*, Vol. 16 No. 9, pp. 1128-1142.

van Der Aalst, W.M.P., Adriansyah, A. and Karla Alves, A. (2009), *Process Mining Manifesto*, Eindhoven University of Technology, Eindhoven.

van Der Aalst, W.M.P. (2011), *Process Mining: Discovery, Conformance and Enhancement of Business Processes*, Springer-Verlag, Berlin and Heidelberg.

Van Donselaar, K.H. and Gubbels, B.J. (2002), "How to release orders in order to minimise system inventory and system nervousness?", *International Journal of Production Economics*, Vol. 78 No. 3, pp. 335-343.

Vollmann, T.E., Berry, W.L. and Whybark, D.C. (1988), *Manufacturing Planning and Control System*, 2nd ed., Irwin, Homewood, IL.

Weijsters, A.J.M.M., van Der Aalst, W.M.P. and Medeiros, A.K. Alves de (2006), "Process mining with the heuristics miner algorithm", BETA Working Paper Series No. 166, Eindhoven University of Technology, Eindhoven.

Weerdt, J. De, Schupp, A., Vanderloock, A. and Baesens, B. (2013), "Process mining for the multi-faceted analysis of business processes – a case study in a financial services organisation", *Computers in Industry*, Vol. 64 No. 1, pp. 57-67.

Wisner, J., Tan, K.C. and Leong, G. (2015), *Principles of Supply Chain Management: A Balanced Approach*, Cengage Learning, Boston, MA,.

Yahya, B.N. (2014), "The development of manufacturing process analysis: lesson learned from process mining", *Jurnal Teknik Industri*, Vol. 12 No. 2, pp. 95-106.

Yeung, J., Wong, W. and Ma, L. (1998), "Parameters affecting the effectiveness of MRP systems: a review", *International Journal of Production Research*, Vol. 36 No. 2, pp. 313-331.

Yucesan, E. and De Groote, X. (2000), "Lead times, order release mechanisms, and customer service", *European Journal of Operational Research*, Vol. 120 No. 1, pp. 118-130.

Further reading

Medeiros, A.K.A. de and Weijters, A.J.M.M. (2005), "Genetic process mining", Applications and Theory of Petri Nets 2005, Volume 3536 of Lecture Notes in Computer Science.

Rozinat, A. and van der Aalst, W.M.P. (2008), "Conformance checking of processes based on monitoring real behaviour", *Information Systems*, Vol. 33 No. Issue 1, pp. 64-95.

van Der Aalst, W.M.P., Adriansyah, A., de Medeiros, A., Arcieri, F., Baier, T., Blickle, T. *et al.* (2012), "Process mining manifesto", in Daniel, F., Barkaoui, K. and Dustdar, S. (Eds), *Business Process Management Workshops*, Vol. 99, Springer , Berlin and Heidelberg, pp. 169-194.

Van Donselaar, K., Van Den Nieuwenhof, J. and Visschers, J.W.C.H. (2000), "The impact of material coordination concepts on planning stability in supply chains", *International Journal of Production Economics*, Vol. 68 No. 2, pp. 169-176.

Corresponding author
Mahendrawathi ER can be contacted at: mahendra_w@is.its.ac.id