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# Processing of Undesirable Business Events in Advanced Production Planning Systems

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**Abstract.** The paper proposes a novel predictive-reactive planning and scheduling framework in which both approaches are combined to complement each other in a reasonably balanced way. Neither original scheduling algorithms nor original techniques can be find in this paper. It also does not intend to invent new mechanisms or to propose some cardinally new ideas. The aim is to choose, adapt and test ideas, mechanisms and algorithms already proposed by other researchers. The focus of this research is set on make-to-order production environments. The proposed approach aims not only to absorb disruptions in shop floor level schedules but also to mitigate the impacts of potential exceptions, which disrupt mid-term level production plans. It is based on application of risk mitigation techniques and combines various simulation techniques extended by optimization procedures. The proposed approach is indented to be implemented in Advanced Planning and Scheduling system, which is an add-on for Enterprise Resources Planning system. To make it easier to understand the focus of the paper, at the beginning the position from which we start is clarified.

**Keywords:** ERP, exception handling, optimisation, production planning and scheduling, risk mitigation, simulation, what-if analysis.

## 1. Introduction

In the past industrial era, main focus of an enterprise was shared between the manufacturing and the relatively independently operating plant. In the present collaborative manufacturing era, main focus was shifted on enterprise performance. As a result, concerns were separated: the computer-based business systems became responsible for the development of plans and schedules and their optimization, while the computer-based manufacturing systems became responsible only for optimal responses. New kind of systems – product life-cycle management (PLM) systems emerged. In the majority of cases, PLM covers all the aspects of a product's life cycle and includes the following components: Client Relationship Management system, Supply Chain Management system, Enterprise Resource Planning (ERP) system, planning software, software supporting the development and description of products, and software for management and communication information about the products. In other words, PLM system is wider than ERP, and even wider than second generation ERP system (ERP II), because it also supports the plant floor activities. On the other hand, PLM is not a single software system and even not a software system at all. It is a system of systems or an umbrella, under which cooperation, coordination, interaction, and interoperability of people, data, processes, business and software systems, and working methods supporting all the aspects of a product's life cycle are organised into the coherent whole aiming "to address either single stages of the lifecycle or connect different tasks or manage the whole process" (Tomar, 2009). It is both a software technology and a business strategy through all stages of a product's life. Consequently, in the PLM context, ERP still remains one of the most important computer-based systems.

According to Bond *et al.* (2000) an ERP is "a business strategy and set of industry-domain-specific applications that build customer and shareholder communities' value network system by enabling and optimising enterprise and inter-enterprise collaborative operational and financial processes". Often the term ERP is used to address only this "set of industry-domain-specific applications" that is implemented as a single software system. On the other hand, the term ERP is rather an abstract term used to address the products of different providers that can differ in many particular aspects. Different ERP systems can vary in functionality, data representation schemes, operation modes and many other details. Besides, some ERP systems support only part of operational and financial processes. All such systems have only some essential architectural solutions in common.

The main focus of ERP systems is on resource planning and inventory accuracy. However, according to Jacobs and Bendoly (2003):

> *"The fundamental benefits of Enterprise Resource Planning systems do not in fact come from their inherent "planning" capabilities but rather from their abilities to process transactions efficiently and to provide organized record keeping structures for such transactions. Planning and decision support applications represent optional additions to the basic transaction processing, query and report capabilities included with a typical system."*

In the ERP industry, ERP systems are mainly addressed as a type of "back office" application where the "back office" is understood as a single database, which stores records about all company centred business activities, together with a set of applications that generate and process these records. The second generation of ERP systems, so called ERP II systems, integrates core ERP systems with supply chain applications – Supply Chain Management (SCM), Customer Relationship Management (CRM), and Data Warehouse – or, in other words, extends the system beyond the company boundaries. For this aim, ERP II systems provide not only supplier relationship management applications but also Advanced Planning and Optimization (APO) capabilities, which enable supply chain planning beyond the company boundaries. APO supports hierarchical planning that differentiates strategic, tactical and operational planning. For example, SAP® APO provides demand planning, supply network planning, master planning, delivery planning (in

SAP® APO this is supported by Available- and Capable-to-Promise (ACT/CTP) component), production planning and scheduling, and distribution and transportation planning capabilities (Kallrath and Maindl, 2006). Demand planning generates forecasted demand figures which are used for lower level planning. Demand planning can be used at all three levels because it can hold long-term data such as sales forecasts as well as short-term data such as customer orders (Kallrath and Maindl, 2006). The mathematical basis for demand planning consists of statistical methods and data analysis methods ("what-if-analysis", aggregation/disaggregation, etc.). The aim of supply network planning is to plan and coordinate strategic supply chain processes (suggestions for supply network design, co-operative supplier contracts, distribution structures, manufacturing programs, etc.). However, it is mainly used for tactical planning and performs mid-term supply chain planning on discrete time buckets (Kallrath and Maindl, 2006). The aim of master planning is to synchronize the material flow along the supply chain and to ensure efficient resource utilization in procurement, production, warehousing, and distribution. Mid-term production plans are generated at this level. ATC/CTP component determines delivery dates for each product and creates production orders, changes and adapts production plans according to incoming customer orders and available resource capacity. The aim of production planning and scheduling is to create short-term production plans for plants or other individual production areas. In other words, the dispatch lists (i.e., feasible production schedules) for the shop floor over a relatively short interval of time considering all modelled constraints and objectives are generated (Hamiton, 2003). It should be noted that, despite the fact that SAP® APO was designed for hierarchical planning, it can also be used for simultaneous planning. As pointed out by Kallrath and Maindl (2006), in some cases it is advisable to merge together mid term planning and short term scheduling. For small problems such a simultaneous optimization planning approach produces better results than a hierarchical approach. The same can be said about strategic and operative planning because border lines between those areas are often diffused or even artificial.

Linear programming (LP), mixed integer linear programming (MILP) algorithms as well as various heuristics and constraint propagation methods are used for planning in SAP® APO. In general, APO capabilities allow creating better plans than traditional ERP systems because they also implement various optimization and simulation methods. Commonly used scheduling heuristics in the production scheduling are versions of genetic algorithms and constraint-based programming (Stadtler and Kilger, 2005). In order to simplify the LP or MILP model, only constrained (or near-constrained) resources are modelled in detail (Ivert, 2009). Besides, to increase the solvability of the model, most APO tools distinguish between hard and soft constraints in the linear or mixed integer programming (Entrup, 2005). While hard constraints must be fulfilled, the violation of soft constraints only renders a penalty in the objective function. Despite the application of optimization and simulation methods, ERP II systems do not aim to produce optimal plans. In the best case, such systems are able to generate only near optimal plans (Jonsson *et al.*, 2007). ERP II systems cannot plan under uncertainty (Entrup, 2005). Besides, they provide only simple processing of undesirable business events and other exceptional situations. According to Bruccoleria and Pasek (2002):

*"An exception can be thought of as a difference between the actual and the expected state of the production system. Machine breakdowns, changes in job priorities, dynamic introduction of new jobs, order cancellations, increases in job arrival rates, changes in the mix of parts, and reworks due to quality problem, are all examples of exceptions. Exception occurrence is usually unpredictable. However, predictable events such as planned preventive maintenance can also be considered exceptions as they interrupt the production process."*

It should be noted that an exception occurrence may cause several different problems disrupting normal flow of production process. It can also generate a series of secondary exceptions that cause additional problems. Several exceptions of different kinds can occur simultaneously and additional problems can be caused by some compositions of exception occurrences. ERP II systems usually help to evaluate only several scenarios that describe what happens if demand changes (Ivert and Jonsson, 2010).

In summary, the focus of ERP II systems is on both enterprise centred and inter-enterprise business activities. ERP II systems usually also include Vendor Managed Inventory (VMI) processing, KANBAN type demand and supply signals to vendors for Just in Time (JIT) stock management. ERP II architectures are Web-centric, designed-to-integrate and significantly differ from the monolithic architectures of the traditional ERP systems. APO capabilities are typically implemented as an autonomous module that "extracts data from the ERP database and sends the resulting plans back for distribution and execution" (Jonsson *et al.*, 2007). However, ERP II systems up to date remain ill-suited to deal with undesirable business events and other exceptions.

ERP system integrates enterprise operations within and across an enterprise. ERP II extends supply functionality to external enterprises (vendors, suppliers). Finally, ERP III system moves to the next integration level and includes customers and the sales side of the marketplace in general. It should be noted that ERP III architecture is Service Oriented Architecture (SOA). Using SOA, Internet technologies, social media outlets, collaboration tools, and other advanced technologies, it creates the "borderless enterprise". However, ERP III systems do not provide any innovative means to deal with the exceptional situations.

So, summarizing all the above said, it can be concluded that advanced ERP systems are a powerful technology for production planning and scheduling, especially, in static environments. Static environments are those in which all jobs are present and ready to schedule at time $t = 0$ (Sabuncuoglu and Goren, 2009). However, the real production environment is highly dynamic and stochastic. If the environment is dynamic jobs continue to arrive dynamically throughout the scheduling horizon. It is deterministic if all job and machine parameters are constant and known in advance and stochastic otherwise (Sabuncuoglu and Goren, 2009). In dynamic and stochastic environment a lot of various exceptions (mostly random in nature) occur and bring up significant differences between the predetermined schedule and its realization at the shop floor level. Product changes, rush orders, unavailable materials, the need to rework the prototype and anything that changes the normal production process are potential source of risk (MacKay and Wiers, 2004). Although producing a schedule, it is difficult to predict in advance and take into account all exceptional situations, it is very desirable to produce such a schedule that mitigates risk and takes into account at least part of such situations. On the other hand, it is vital to react quickly to critical situations and revise plans and schedules in a cost effective manner (Vieira *et al.*, 2003). It is far not easy task, especially in the hierarchical planning systems.

Software solutions that in a reasonable way combine both predictive and reactive approaches to process exceptions are highly desirable. Although the big amount of research was done in this field (O'Donovan *et al.*, 1999; Pfeiffer, 2007; Kovács *et al.*, 2003), the problem is still far from being finally solved. This paper proposes a novel planning and scheduling framework in which both approaches are combined to complement each other in a reasonably balanced way. Neither original scheduling algorithms nor techniques are proposed in this paper. We also not intend to invent new mechanisms or propose new ideas. Our aim is to choose, adapt and test ideas, mechanisms and algorithms already proposed by other researchers. The focus of research is set on make-to-order production environments. Other basic assumptions are as follows:

- Manufacturing layout: product-oriented.
- Type of manufacturing: secondary.
- Automation level: fixed or programmable automation.
- Form of control: discrete.
- Form of manufacturing process monitoring: enterprise-wide.
- The annual product quantities produced: medium.
- Product variety: soft.

The reminder of the paper is organised as follows. The next section defines the problem more precisely and generally describes the proposed framework. Section 3 discusses the predictive approach used to mitigate the impact of undesirable events. Section 4 discusses the proposed approach to the reactive rescheduling. Finally, Section 5 concludes the paper.

## 2. Problem Definition

According to Herrmann (2006), the production scheduling problem can be considered from many different views and perspectives. The most important perspectives are the following:

- *Problem Solving Perspective.* From this perspective, the scheduling is an optimization problem. The most researchers formulated this problem as a combinatorial optimization problem and solved it as an isolated one, without taking into account its relations with the whole manufacturing planning and control system (Aiex *et al.*, 2003; Binato *et al.*, 2002; Wang and Zheng, 2001; Gonçalves *et al.*, 2002; Musikapun and Pongcharoen, 2012); a detailed survey can be find in Gupta and Stafford (2006), Pinedo (2012). Mainly this perspective is appropriate to produce schedules only at the shop floor level.
- *Decision Making Perspective*. The scheduling from this perspective is analyzed by MacKay and Wiers (2004). Authors see the scheduling as a decision that should

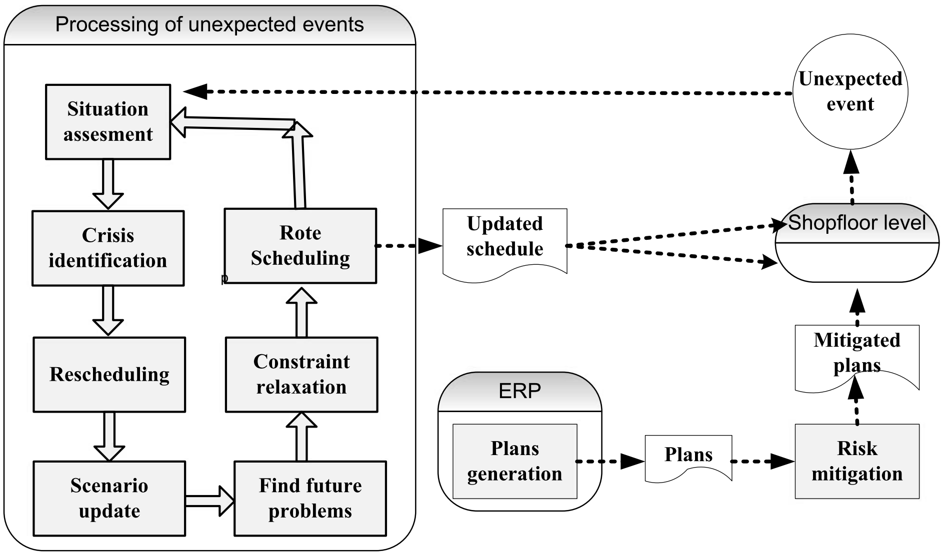


Fig. 1. The whole Manufacturing Planning and Control system.

be made by human decision maker. To cope with his problem, the decision maker must perform a variety of tasks and use both formal and informal information. He must also address uncertainty, manage bottlenecks, and anticipate the problems that people cause.

- *Organisational Perspective*. From this perspective, the scheduling is part of the complex flow of information and decision-making that forms the manufacturing planning and control system (Chapman, 2005). Such systems consist of subsystems that perform aggregate planning, master scheduling, material requirements planning and other functions.

We consider the production scheduling problem mainly from the Decision Making Perspective in this paper. It means that the production scheduling system is part of larger, more complex manufacturing planning and control system (Fig. 1.) which involves ERP, shop floor level production scheduling subsystem, risk mitigation procedures, and exceptions processing mechanisms. This system combines manual and automated procedures or, in other words, it also involves human decision maker supported by modern software tools and technologies. We do not see the production scheduling system as the realization of optimization procedure and suppose that it combines optimisation and simulation methods, and aims, in the best case, to produce only near optimal schedule. In the worst case, only some acceptable from the management point of view solution can be produced.

## 3. Predictive Planning and Scheduling

According to Maravelias and Sung (2009) long-term (strategic) production planning determines the structure of the supply chain (e.g., facility location), medium-term (tactical) planning is concerned with decisions such as the assignment of production targets to facilities and the transportation from facilities to warehouses to distribution centres, and, finally, short-term planning is carried out on a daily or weekly basis to determine the assignment of tasks to units and the sequencing of tasks in each unit. At the production level, short-term planning is referred to as *scheduling*. As it is noted by Sabuncuoglu and Goren (2009), medium-term planning and shop floor level scheduling are strongly coupled. Master schedule sets the goals and constraints for the shop floor level scheduling that is responsible for keeping due dates and the efficient use of production resources. Master schedule provides activities for which neither processing times are fixed, nor their intensity is constant over time, however, the amount of work needed to process them is fixed. Each shop floor level schedule specifies what portions of which activities have to be done in each time unit, such that all precedence and capacity constraints are respected, and the schedule is optimal according to some optimization criterion (Kovács *et al.*, 2003). So, activities provided by master schedule in the shop floor level schedule are implemented as logical groups of atomic manufacturing operations, some of which are executed simultaneously, while the others sequentially, and remaining independently of each other. Consequently, any shop floor level schedule cannot improve much on an inadequate master schedule or other medium-term plan, whereas bad schedule may inhibit the fulfilment of a good plans, for example, wasting resources. The scheduling horizon is as long as the time unit used to plan activities in the medium-term plan. If an activity extends beyond several medium-term planning units, its operations that have to be scheduled during this period are determined proportional to the activity's intensities (Kovács *et al.*, 2003). According to Sabuncuoglu and Goren (2009), a schedule whose performance does not deteriorate much in the face of disruptions is called robust and a schedule whose realization does not deviate much from the initial schedule in the face of disruptions is called stable. Robustness and stability are the main schedule performance measures.

There are three main approaches in planning and scheduling to respond to disturbances raised by exceptions and to absorb or at least to mitigate their negative effects (Bruccoleria *et al.*, 2006; Herrmann, 2006): predictive, reactive, and predictive-reactive.

In the context of planning and scheduling the term *predictive* was coined to address plans that are structured around producing a pre-determined end results within a specific timeframe and schedules that have not only a good shop floor performance, but also take into account the stability. It should be noted that in this context the terms *predictive* and *proactive* are used as synonyms. In this paper, we use the terms *predictive planning* and *predictive scheduling* to address the approaches that, generating initial plans or schedules, also provide activities and procedures which help to avoid possible exceptions or, at least, to cope with them minimizing their effects on the performance measures. The resulting plan or schedule is not necessarily optimal but it should do well under uncertainty.

In ideal case, predictive scheduling produces the optimal schedule based on given requirements and constraints prior to the production process (Sun and Xue, 2001). Predictive scheduling is off-line scheduling that focuses on the development of such schedules that can absorb disruptions without affecting planned external activities while maintaining high shop floor performances. This can be obtained, for example, by inserting additional idle time into the schedule to absorb the impacts of breakdowns (O'Donovan *et al.*, 1999). The preventive off-line schedule should take into account also other production activities such as set-ups, maintenance, personnel management, material procurement, shipping, etc.

Many predictive scheduling methods use AI techniques trying to find optimal schedule through iterative constraints-guided search process (Sun *et al.*, 1999; Xue *et al.*, 2001; Szelke and Kerr, 1994; Gaspero, 2003). The schedule is produced on the basis of product constraints, manufacturing requirements, and resource constraints. However the schedules produced in this way usually are not true global optimal because of a large number of scheduled tasks (Sun and Xue, 2001). They can be improved using genetic algorithms, simulated annealing, tabu-search, and other stochastic computing methods that prevent from falling into local optimums (Szelke and Kerr, 1994). There are also proposed other techniques, including various probabilistic techniques and scenario planning ones. However, almost all proposed approaches are very specific, can be applied only in some particular situations. For example, some approaches (Wu *et al.*, 1999; Artigues *et al.*, 2005) deal with only one category of exceptions, namely, machine breakdowns, and using graph-theoretical approach generate family of schedules enabling decision maker, in case of exceptions, to switch from one schedule to another. Other approaches propose genetic algorithms (Leon *et al.*, 1994; Sevaux and Sörensen, 2004) tabu-search (Al-Fawzan and Haouari, 2005) or other techniques to generate robust schedules under specific assumptions about scheduling environment, available information, and robustness measures. Detail overview of above-mentioned approaches is presented in Sabuncuoglu and Goren (2009).

The approach proposed in this paper aims not only to absorb disruptions in shop floor level schedules but also to mitigate the impacts of potential exceptions disrupting mid-term level production plans. It is based on application of risk mitigation techniques (see, for exmple, USD (2003)) and combines various simulation techniques expanded by optimization procedures. The proposed approach is indented to be implemented in Advanced Planning and Scheduling (APS) system, namely PEN System, which is an add-on for some ERP system and intended to be used for the following aims:

- to evaluate the severity of potential impacts of predictable exceptions on medium-term level production plans and on short-time schedules generated by ERP system; and
- to rework these plans and schedules in such a way that the risk of predictable exceptions could be mitigated, i.e., either their likelihood can be minimized or the potential severity of their consequences (their impact) can be reduced.

By predictable exceptions we mean those exceptions (or series of exceptions), which took place in previous planning periods and resulted in significant financial losses or caused some other severe negative impact. The exceptions and data describing their impacts should be logged and stored in a historical data base. Predictable exceptions are regarded as risk that needs to be managed. It is assumed that data stored in the historical data base is sufficient to identify the likelihood of each predictable exception. By likelihood of an exception we mean its expected frequency (occurrences per planning horizon) with which this exception will occur. In our framework, risk management is seen as an integrated management approach. It means that all uncertainty minimizing activities – including administrative and quality management activities – are seen as risk treatment measures. Consequently, in order to mitigate risk, not only pre-planned activities can be changed but new activities may also be provided.

Let us now briefly sketch the functional features of the proposed APS system. Due to the limited space, this description is very general and highly-simplified.

The inputs for the system are as follows:

- master production scheduling and material requirement plan prepared by ERP;
- the list of predictable exceptions which potentially can negatively affect the execution of the plan; and
- relevant historical data base.

The search strategy constraints (e.g., search keeping the current deadline, search keeping the current budget, etc.) must be set invoking the system. In addition, enterprise map, decision matrix, models library, simulation and optimization procedures library, goals table, management focus, resources table, and thresholds table must be already stored in the system and accessible for its modules.

*Enterprise map* describes the workplaces (activities that can be provided at the given place, engines installed at the given place, workload storage capacity) and their locations. It also describes the physical distances among the workplaces measured by the transportation means together with the transportation time and costs. If a company is multi-located, enterprise map includes all the workplaces. In predictive scheduling, the map is used for routing. *Decision matrix* relates exceptions with a number of hypotheses, which are referred to as alternative scenarios for what-if analysis. Each alternative scenario corresponds to a class of scenarios that should be evaluated. A scenario is a statement of assumptions about the operating environment of a manufacturing system at a time when the exception occurs. It describes the decision variables and uncontrollable variables for a specific modelling situation. A class of scenarios includes worst possibly, best possibly and most likely scenarios for the alternative, and declares for which ones, from the decision variables appearing in the simulation model, the values must be specified in order to make the simulation model executable. The best possibly scenario aims to provide such countermeasures against the disruptions that avoid all these disruptions. However, it is possible only in rare cases. Most likely scenario provides such countermeasures that enable to avoid some exceptions, to reduce the likelihood of occurrences of other exceptions, and to mitigate the impact of the remaining ones. Finally, the worst possibly scenario is one that for most kinds of exceptions provides the countermeasures allowing to detect only the occurrences of these exceptions as early as possible. The decision matrix also defines models to be used for simulation and optimization, and composition(s) of simulation and optimisation procedures to be used to optimize the prepared plan. *Goals table* defines weighted goals to be used for the plan optimization. *Management focus* is a set of parameters that describe management preferences that, in turn, reflect the business policies regarding a particular supplier, customer, contract or some other business factors. *Resources table* describes locations, availability and usage costs of all given resources. *Thresholds table* describes the thresholds used to classify estimated impacts of exceptions. The estimate impact may be critical, high, moderate or low.

The outputs of the system are near optimal master production schedule, shop-floor level production schedule, and material requirement plan that mitigate the impacts of predicted exceptions.

The proposed approach provides the following procedures:

- to form a queue of occurrences of predictable exceptions;
- to assign weights and impact mitigation scenarios to occurrences of predictable exceptions;
- to perform what-if analysis of impact mitigation scenarios;
- to chose an impact mitigation scenario; and
- to optimise the predictive plans and schedules.

Since we are speaking about hierarchical planning and scheduling, the above-mentioned procedures are executed preparing both the medium-time plans as well as the detailed shop-floor level schedules.

To create a number of alternative preventive scenarios that should be evaluated and included to mid-term plans and to detailed shop floor level schedules in order to prevent the exceptions or, at least, mitigate their negative impact, it is necessary to predict the occurrences of these exceptions. Of course, the occurrences cannot be forecasted for all kinds of exceptions. For example, it is impossible to forecast when sudden machine breakdowns will happen (Aydt *et al.*, 2008). It means that predictive plans and schedules cannot help to avoid occurrences of unpredictable exceptions and, consequently, reactive approach has to be used to remove the effects of disruptions caused by such exceptions. Predictive planning can only prepare some contingency plans, for example, by planning additional time, facilities and financial reserves. However, such plans are cost-consuming and may be worthwhile only in cases when occurrences of unpredictable exceptions have high probability and losses caused by delay to remove the effects of disruptions are significantly higher than the costs to provide additional reserves. In case of predictable exceptions, the forecast-based preventive approach is more profitable than reactive approach because it can react earlier. On the other hand, the forecast is never perfectly accurate and there will always be some uncertainty regarding the occurrences of predictable exceptions (Aydt *et al.*, 2008). The aim of queue forming procedure is to forecast the occurrences of predictable exceptions and present it as a sequence of hypothetical occurrences assigning to each occurrence its likelihood and the time interval in which it is expected to be happening. For the exceptions caused by environment, this interval should not exceed the mid-term planning unit, and for the exceptions caused by shop floor events – the scheduling horizon. The likelihoods of occurrences are forecasted using historical data bases that register occurrences of exceptions in previous planning periods and describe their impacts. Time intervals are predicted assuming that occurrences of each exception are distributed over planning horizon according to normal, Poisson or some other standard or nonstandard distribution. As a result, a time-ordered sequence of occurrences is generated. If occurrences of different exceptions are forecasted to happen simultaneously, they are packed together and such packages are considered later as equivalent to other members of this sequence. After the time-ordered sequence of occurrences is formed, the impact analysis is performed. It is measured in both delay time units and potential financial loses. The *estimated impact* is calculated as a weighted production of impact(s) and *estimated likelihood* (Myung, 2003). The thresholds table is used to determine the category of the estimated impact of a particular occurrence. Occurrences with low and moderate impacts are deleted from the queue – it is not worthwhile to apply predictive planning because of the resource costs to eliminate such occurrences or to mitigate their impact. Thus, the procedure that forms the queue of occurrences of predictable exceptions implements quantitative risk assessment. However, the risk assessment methodology requires combining the quantitative risk assessment with qualitative one (see, for example, USD (2003)). Qualitative risk assessment means the application of a weighted factor based on a subjective analysis of the relative priority of a specific exception. It is implemented by the next procedure that assigns the weights and impact mitigation scenarios to occurrences of predictable exceptions.

Management focus is used to assign weights to the predictable exceptions. In result, the occurrences in the queue are prioritized and the time-ordered sequence is transformed into priority-ordered sequence. Using decision matrix the occurrences are related with a number of alternative scenarios for what-if analysis.

What-if analysis and optimization procedures are executed sequentially. What-if analysis is used as a tool to evaluate each occurrence, which remained in the queue after occurrences with moderate and low impacts were deleted, in all risk mitigation scenarios for each alternative. The evaluation of different scenarios is performed in parallel. During the scenario evaluation, the occurrences are processed iterative, in the decreasing order of priorities. In each iteration decision maker tests and evaluates scenarios for all alternative scenarios and decides which alternative, if any, is acceptable. After, specifying alternative values of decision variables and, possibly, changing constrains, the decision maker, using what-if analysis procedure in an interactive mode, produces the required results. The main aim is to calculate for all alternatives the *estimated mitigated impacts* of worst possibly, best possibly and most likely scenarios for the occurrence under evaluation. What-if analysis procedure uses the data downloaded from ERP system (i. e. preliminary plans and schedules that does not provide any countermeasures against the disruptions caused by exceptions). The used simulation models and procedures depend on planning level and on specifics of a particular situation (what kinds of exceptions must be handled, what kinds of countermeasures is planned, etc.). Models library and simulation and optimization procedures library support what-if analysis and optimization of the plans under consideration. Simulation models and methods that are used to perform what-if analysis as well as kinds of planned countermeasures and their identification strategies are out of the scope of this paper. A description of most popular simulation models can be find in Mula *et al.* (2006). Kinds of most popular countermeasures are discussed in Graves (2011) and their identification strategies in Asnar and Giorgini (2006).

It is important to note that countermeasures superpose each other and sometimes conflicts can arise because the queue of exceptions occurrences is processed in iterative manner. After an occurrence with higher priority is processed and countermeasures against it are provided the procedure starts to process next occurrence and attempts to modify the already provided countermeasures or add additional ones. If countermeasures contradict each other, the conflict must be solved by decision maker.

When the processing of the queue of occurrences is finished, the optimization procedure may be invoked. To invoke this procedure or not, decides the decision maker after the examination of the results of what-if analysis procedure. What composition of simulation and optimization methods to use to optimize the plan under consideration, the system decides automatically using decisions matrix. The choice depends on the level of plan under consideration as well as on kinds of countermeasures and on particular optimization problem. The underlying optimization problem will vary due to differences in the manufacturing and production context. An exhaustive overview of applicable model formulations can be found in Graves (2002). An up-to-date survey of important theoretical scheduling models as well as significant real-world scheduling problems are presented in Pinedo (2012). This survey describes methods to create a schedule that is robust with respect to disruptions and that are used in our approach proposed in this paper.

## 4. Reactive Planning and Scheduling

As is noted by Sun and Xue (2001), any predictive plan and schedule should be changed during the production process in order to reflect the changes in environment and manufacturing conditions. *Inter al*, manufacturing conditions can also be changed by resource disturbances caused by exceptions. A reactive scheduling or rescheduling is a process that aims to modify the predictive schedule in order to adapt this schedule to the changes of manufacturing conditions (Kempf *et al.*, 2000; Sun and Xue, 2001). Most approaches to reactive scheduling revise only part of initial schedule to respond to the exceptions without rescheduling all the required tasks.

Pure reactive scheduling does not require any preventive schedule that should be generated in advance. All the decisions are made locally in real-time to deploy corrective mechanisms in order to maintain the stability of existing schedules and provide quick solutions in response to the dynamic and uncertain exception described above. Dynamic dispatching rules' selection, based on jobs, machines and system status is a frequently used pure reactive approach.

In this paper, a predictive-reactive scheduling approach is proposed. It combines both predictive medium-term planning and scheduling, and replanning and rescheduling. The functional features of predictive planning and scheduling were described in the previous section. Let us now briefly sketch the functional features of the proposed replanning and rescheduling approach.

The inputs of the APS system working in replanning and rescheduling mode are description of the detected exception, actual state of running plan or schedule that should be repaired, and search strategy constraints. Data about the actual state of the plan or schedule under the consideration must be downloaded from the ERP. Constraints of search strategy (e.g., search keeping the current deadline, search keeping the current budget, etc.) must be set invoking the system. In addition, enterprise map, decision matrix, models library, simulation and optimization procedures library, goals table, management focus, resources and materials tables, and thresholds table must be already stored in the system and accessible for its modules. Materials table describes the acceptable substitutions of the materials that were planned in the material requirements plan.

The outputs of the APS system are a set of repaired plans/schedules (one for each alternative) and their summaries. The repaired plans/schedules can be optimal or near optimal. In some cases, the system is not able to absorb the negative impact caused by the occurrence of exception and to repair the plan or schedule. In such cases, it generates the empty set of results. It means that full replanning from the scratch must be done using ERP system. The summary of a plan/schedule includes numerical estimate of solution taking into account multiple criteria nature of the problem caused by the stated optimization goals.

The proposed approach provides following procedures:

- to mark the plan or schedule under consideration;
- to identify problems caused by the occurrence of exception;
- to identify alternatives how to repair plan or schedule that was disrupted;
- to generate a set of repaired plans or schedules and their summaries; and
- to choose one from alternative plans or schedules.

The actual running plan/schedule is an input for marking procedure. Two kinds of marks are used in this procedure. It marks all the activities or jobs, which are affected by the occurrence of exception, and all the activities or jobs, which are out of replanning/rescheduling time window, require no changes and can be automatically moved to the new plan/schedule. In such way, the search space is significantly reduced.

The problems caused by the occurrence of exception and plan/schedule repairing strategies (i.e., methods to solve identified problems) are identified using the decision matrix.

The set of plans/schedules – one for each alternative and their summaries – are generated using a composition of optimization and simulation procedures defined by decision matrix. Enterprise map is used to reroute the jobs or, if it is necessary, to relocate jobs moving them to another plant and to calculate the relocation costs, as well as the delay in delivery time. This map, if it is necessary, can also be used to outsource activities/jobs and to calculate the outsourcing costs and the delay in delivery time. Substitution of materials, if it is required, is done on the basis of the materials table. The weighted goals are stated in goals table, the search constraints are determined by the search strategy.

Decision maker choose the acceptable variant, if any, of the plan/schedule on the basis of summaries.

## 5. Conclusions

The paper proposes a novel predictive-reactive planning and scheduling framework. The focus of this research is set on make-to-order production environments. The proposed approach aims not only to absorb disruptions in shop floor level schedules but also to mitigate the impacts of potential exceptions disrupting mid-term level production plans. It is based on application of risk mitigation techniques and combines various simulation techniques expanded by optimization procedures. The proposed approach is indented to be implemented in Advanced Planning and Scheduling system, which is an add-on for Enterprise Resources Planning system.

The system implementing the proposed framework is different from the other similar products by the following aspects: (a) it provides specific rule-based mechanisms in the production re-scheduling process to take into account the knowledge about the specifics of the production system of a particular target enterprise; (b) it provides integrated handling of business goals defined in the goals table and management focuses during the optimization of new schedules.

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## Neplanuotų verslo įvykių apdorojimas šiuolaikinėse gamybos planavimo sistemose

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Straipsnyje pasiūlytas naujas įmonės planavimo ir gamybos tvarkaraščių sudarymo sistemos, harmoningai derinančios prediktyviąją ir reaktyviąją planavimo metodikas, modelis. Straipsnyje nėra pateikta jokių naujų planavimo ir tvarkaraščių sudarymo metodų, algoritmų ar mechanizmų. Jo tikslas parinkti, pritaikyti ir panaudoti kitų autorių pasiūlytas idėjas, požiūrius bei mechanizmus, visa tai jungiant į vieną organišką visumą. Modelis pritaikytas pagal užsakymus vykdomai gamybai planuoti ir numato ne tik kaip keisti planus bei tvarkaraščius, siekiant pašalinti neplanuotų įvykių sukeltas nepageidautinas pasekmes, bet ir kaip sudaryti tokius pirminius planus, kurie leistų maksimaliai apsisaugoti nuo tokių pasekmių arba bent jau jas maksimaliai sušvelninti. Modelis sudarytas panaudojant rizikos švelninimo metodus bei gamybos proceso modeliavimo procedūras praplėstas optimizavimo metodais. Pasiūlytas modelis skirtas kurti tokias vadinamąsias didesnio sudėtingumo planavimo ir tvarkaraščių sistemas, kurios išplečia įmonių išteklių planavimo sistemas ir veikia kaip tų sistemų priedėliai.