MODELLING AND SIMULATION OF ALUMINIUM COILS PRODUCTION PROCESS USING COLOURED PETRI NETS

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Abstract

Production planning and scheduling are essential for achieving efficient resource allocation, in meeting end-customer demands and in determining the production-loading plan. Effective scheduling is a key issue for modern manufacturing production systems since it can improve throughput rates and machine utilisation. Manufacturing systems exhibit high complexity and are expected to manipulate huge amounts of data. Therefore, the need for appropriate models and efficient simulation tools to represent, analyse and evaluate such systems has long been acknowledged. This paper presents the modelling and simulation of a complete aluminium coils production plant, with the use of Hierarchical Coloured Petri Nets (HCPN). These nets provide an efficient representation for such production processes and can be used for their extensive analysis and performance evaluation with the aid of appropriate metrics. In particular, this work addresses the implementation of an overall model, capable of integrating the various aspects of the specific production processes. The proposed HCPN model provides information about throughput rates, makespans, machine occupancy and work in process inventory. The model was successfully validated using actual production data and it was found that CPN are suitable for the modelling, analysis and performance evaluation of the complex aluminium coils production process. With the aid of the model various scenarios were investigated via extensive simulation runs, such as installing additional machine centres, increasing buffer sizes and reducing pre-set times the products spend in intermediate storage areas. Results show that production managers can strongly benefit by the proposed model in gaining important knowledge about the system and performing better decision-making.

Keywords: Aluminium coils production system, Production scheduling, Coloured Petri nets, Performance analysis.

Presenting Author's biography

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1 Introduction

Production simulation especially in competitive markets has become a key factor, by which managers can determine the production loading plan, respond promptly to machine failures and improve productivity by creating different scenarios and decision making. Operating efficiency and manufacturing profitability need to be continuously improved, while managers must couple individual products with individual productive resources in shorter times. Manufacturing processes are often characterised by the presence of huge amounts of data and parameters. The efficient manipulation of all these data and parameters can be a cumbersome task and needs powerful tools with advanced capabilities.

This work is motivated by the problems faced by steel industries producing rolled aluminium lithographic coils. Production management in those industries involves the development of a weekly production loading plan -according to a list of products assigned by customers- by considering workforce level, manufacturing capacity, priority orders and other factors. These kinds of finished products are implemented in a make-to-order (MTO) industrial environment where a due date is agreed with the customer. End items are placed in the master weekly schedule, and production planning then specifies the necessary production [1]. While the main production schedule is based on orders in hand, the customer triggers the production and material withdrawal. This production system is known as pull production and it is very common in steel industries.

To describe, analyse and evaluate these industrial environments the need for models and simulation tools has long been recognised to be necessary and has been studied extensively. During the past few decades, many manufacturing companies have attempted to use various models and software tools in order to simulate their complex production environments and predict the future behaviour of the production process. By the manipulation of the model, it is also hoped that new knowledge about the production process can be obtained without the inconvenience or cost of manipulating the real process itself. Therefore, it becomes essential to understand the behaviour of production systems as well as the parameters that affect the performance of production lines.

This paper describes techniques for modelling and simulating a manufacturing process via Hierarchical Coloured Timed Petri Nets (HCTPN). The use of Petri nets in general has been extensively proposed in manufacturing literature. Dicesare et al. [2] provide the most important properties of Petri nets and their applications to the design and analysis of manufacturing systems. Xiaolan and Proth [3] and Silva and Valette [4] use Petri nets for specifying, modelling and evaluating the performances of manufacturing systems, while Proth and Xie [5] present the theory of Petri nets for the modelling and management of the future behaviour of production systems. Recalde et al. [6], present in a tutorial style, various examples in which Petri nets are used for modelling, analysis, synthesis and implementation of manufacturing systems.

Coloured Petri nets (CPN) are also widely used in industry. In [7] a single CPN model is created for the description and validation of control procedures in a chemical production system. The CPN model describes the process devices, their technical function and the allocation of process devices to control recipes. Zimmermann [8] uses CPN in order to facilitate the independent modelling of a manufacturing system structure and the production routes of the parts being processed. Chincholkar and Chetty [9] use Stochastic Coloured Petri nets for the scheduling of flexible manufacturing systems, considering stochastic behaviours such as failure and repair of machines and variations in processing times. Nandula and Dutta [10] study a push-type auction based manufacturing system embedded in a pull type production system with the aid of CPN and they propose various decision making rules for the entities to ensure the smooth flow of parts and improve the performance of the system. In [11], Tsinarakis et al. present Hybrid Timed Petri Nets for the modelling, analysis and performance evaluation of production systems, whereas Wu and Zhou in [12] analyse the issues of deadlock and starvation in automated manufacturing systems.

Coverability trees and reachability graphs have been proposed as valuable tools for analysis in Petri Nets [13]. However, they cannot easily be applied to complex systems mainly due to the state explosion problem, as reported in the literature [14] (the complexity increases exponentially with the size of the Petri Net). Even for a simple Kanban manufacturing system comprising of four components with N parts in the initial marking, complexities of the order of $O(N^{11})$ have been reported [14].

The design and software implementation proposed in this paper is based on CPN-Tools [15]. In our case, the state space in very large (1250 different tokens are used as initial marking and more than 34 transitions have to be executed) and, thus, it cannot be constructed. However, in our approach all different scenarios were investigated with the aid of appropriate monitors and auxiliary places gathering data implemented in CPN-Tools, allowing us to deal with all aspects of scheduling and production planning.

Prior to applying any methodology an extensive analysis of the production line in steel industry is needed. The description of all the set of activities and resources throughout the production process is given in next section. A careful study of the whole process can increase efficiency by allowing inventory only when it is needed, identifying bottlenecks, balancing capacity and generally coordinating the smooth flow of aluminium products. Moreover, analysing the production line as a whole to find out where most of the time delays occur allows the managers to focus attention on bottlenecks in order to shorten throughput time.

This paper focuses on presenting a simulation tool as accurate and flexible as possible for modelling the flow of intermediate aluminium products and manipulating efficiently the information (tokens) in each simulation step. CPN fulfil this requirement because they are capable to deal with coloured token attributes and, therefore, they can easily integrate different aspects such as control flow primitives, informational work objects or physical work objects.

2 Description of production process

The production process shown in Fig. 1 can be divided into three main individual work-stages according to the nature of the manufacturing process, time and layout of the plant's machinery. The first stage includes slabs' delivery, scalping, hot-rolling and tandem mill process. All these activities take place in the Hot-Line shop floor centre. The second stage, in the High-Bay area, integrates temporary storage, annealing and cold rolling processes and finally, the third stage includes levelling, stretching and degreasing treatment (LSDT), quality control and final storage. All parameters used (capacities, delay-times, material properties, etc.) are set to nominal values which can be easily modified between simulations.

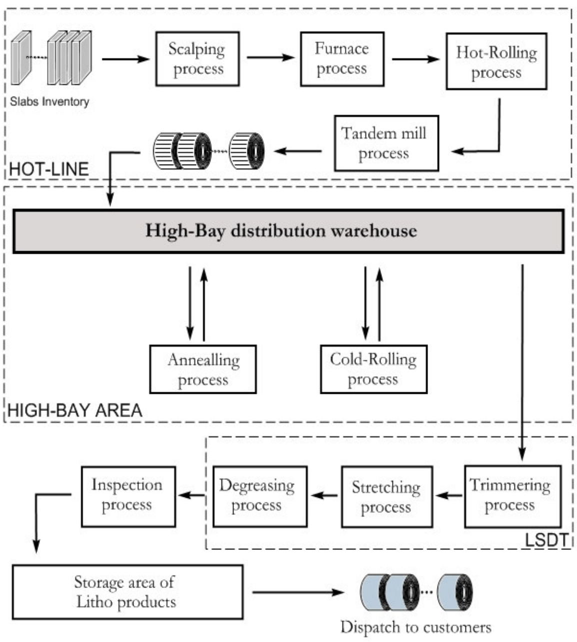

Fig. 1 Production line of lithographic coils

2.1 Stage 1: Hot-Line centre

In the first production stage, slabs are delivered to the manufacturing plant usually following a scheduled delivery date which is based on an annual order plan. In this work, since we focus more on the simulation of jobs in all production phases, we consider that slabs inventory is infinite. Although slabs differ in characteristics they have been grouped into nine different groups, for simulation purposes (Tab. 1).

A weekly process plan is proposed -according to the amount and type of customers' orders- and forwarded to the scalping process. The upper and lower surfaces are milled on a scalping machine, a process taking 15-25 minutes depending of the size and quality of each slab. The sequence of scalping follows the weekly schedule. After that, the slabs leaving the scalping machine are placed in a temporary storage area. The maximum capacity of this area is considered to be 110 slabs.

Tab. 1 The nine different coil types

Coil Type	Width	Gauge
1	Wide	Thick
2	Medium	Thick
3	Narrow	Thick
4	Wide	Standard
5	Medium	Standard
6	Narrow	Standard
7	Wide	Thin
8	Medium	Thin
9	Narrow	Thin

The next process involves hot rolling, where the rolling slabs are heated to the necessary rolling temperature in a furnace. Up to twenty-four slabs, each with a maximum weight of ten tons can be heated at the same time. The time taken for heating is 6 hours for the narrower slabs, 7.5 hours for the medium size slabs and 9 hours for the wider. The furnace sequencing follows a First-In-First-Out order and preheat recipes are used according to slab width. After the furnace process, the rolling slabs are taken directly from the furnace to the hot-rolling mill using special cranes. First, slabs are positioned on a roller table driven by electric motors. A single slab at a time is treated in the reversible mill, while the time taken for this process is approximately 15 minutes. There, the slabs are rolled down to their hot-rolling thickness in several phases. The finishing thickness of rolled plates is set approximately to 15mm. The resulting hot rolled plate is then sheared using a cropping shear with the aid of a camera. Sheared pieces of strips are destined for scrap.

The last continuing Hot-Line process involves the tandem mill which is used to achieve a desired thickness and surface quality. The output thickness is set to 2.6mm while the time needed is approximately 12 minutes for narrower slabs, 16 minutes for medium and 20 minutes for wider slabs. The tandem mill can also specify the width of the coil. During this process there are about 50-100mm width losses. As a result of the tandem mill processing, plates are wound into roll-form (coils) after a series of flat rolls. Coils are then stored temporarily in the Hot-Line building before being dispatched to the High-Bay area. Currently, the maximum capacity of the storage area is 50 coils and this is one of the parameters under consideration for simulation.

2.2 Stage 2: High-Bay area

In the next stage of production line coils are dispatched from the Hot-Line shop-floor to a column location (High-Bay). It is assumed that only one coil per specified time period can enter the High-Bay area. This time period is called *loading rate*. In the High-Bay distribution warehouse, initially assumed of 440 racks capacity, coils are stored using special automated handling equipment. Apart from those coils delivered from the Hot-Line shop-floor, High-Bay stores coils to be annealed and coils to be passed through the cold-rolling mill. Due to spacing limitations and several other restrictions, special computer software is used to manage all these progressions. This software keeps a list of all stored coils and makes a decision for the next process using a sophisticated communication protocol. Thus, the nature of the High-Bay design requires the manipulation of large amounts of data and it is often an iterative process that forces the production manager to go through the different decision making phases, several times before reaching the final decision. For modelling convenience, coils of the same characteristics are grouped together according to order types.

The next step for a coil that has been transferred into the High-Bay is annealing. Coils are batch annealed in groups of four following the grouping decision made by the computer. Grouping is made according to their width. There are three different ranges for coils' widths. These are: (i) coils that have a width of less than 1150mm (narrow), (ii) those with width between 1150 and 1380mm (medium), and (iii) coils with a width greater than 1380mm (wide). Annealing times also vary according to the coils' width, as follows: 8 hours and 45 minutes for narrower coils, 9 hours and 45 minutes for medium and 10 hours and 45 minutes for wider. After the strip coils have acquired the required mechanical properties in annealing they return to High-Bay and remain there for about 72 hours. Initially, it is assumed that there are 3 annealing furnaces installed in the plant and operating in parallel.

The next process, after a coil has been cooled inside the High-Bay distribution warehouse following annealing, is cold-rolling. The cold-rolling mill allows the production of coils with low gauges and special tempers. Coils are also batch rolled in groups of four according to their characteristics. The cold-rolling process reduces the thickness of the coil by roughly 50%, each time. This means that after the first pass the thickness of the coil becomes 1.3mm, after the second 0.65mm, after the third 0.27-0.28mm or 0.38mm according to coil sizes and characteristics and finally, for special customer requirements, a fourth pass halves the thickness to 0.14mm. The time needed for each rolling depends on the speed of rolls and coil groups and can vary from 10 minutes to 30 minutes. After each cold-rolling pass, the coil is led back to High-Bay where it remains for 24 hours to be cooled to room temperature. When cold-rolling is completed the coil is finally assigned to a specific customer order. Tab. 2 depicts the cold-rolling times according to the four different coil groups (defined with different grey scales) and passes.

Tab. 2 Cold rolling and LSDT times (minutes). Groups are denoted with different grey shades

	Thick				Standard				Thin				
	Pass 1	Pass 2	Pass3	LSDT	Pass 1	Pass 2	Pass 3	LSDT	Pass 1	Pass 2	Pass 3	Pass 4	LSDT
Wide	10	15	20	35	10	15	20	40	10	15	20	30	70
Medium	10	15	20	35	NA	15	20	40	NA	15	20	30	70
Narrow	10	15	20	35	NA	15	20	40	NA	15	20	30	70

2.3 Stage 3: LSDT and quality control

The third stage is known as the LSDT and quality control stage. During this stage coils leave the High-Bay storage area and enter the tension levelling process in order to obtain the highest flatness and strip surface quality. The levelling process is divided into three main stages: side trimming, stretching and degreasing. All these stages take place in a single process line. Each coil is manually trimmed to the pre-specified width (ordered by the customer), gap and overlap setup (for tight width tolerances and minimum edge burr). Then the coil is flattened by the stretching machine, which bends up and down over the interrupting arcs of a long slender strip. Finally, each coil is degreased to remove residual rolling oils and lubricants. The LSDT process times vary according to coil characteristics. These times are also given in Tab. 2.

After tension levelling, each coil passes through surface inspection and quality control to ensure that its thickness gauge and width are accurate. Then, coils are placed in the final storage area and are ready to be dispatched to customers. In the case that a coil is rejected by the inspection process, it is stored temporarily for about four days and rechecked for its dimensional accuracy. If after the second inspection there are still deviations, rejection is the irrevocable decision. In addition to this, certain specific coil products are taken to relaxation before the inspection control.

3 Description of the HCTPN for aluminium coils production process

The description of the production process in the previous section suggests a production system consisting of many machine centres, buffers and cumbersome tasks. Thus it can be convenient to have a number of formally related small nets instead of a single large net. The implementation of these nets can be easily achieved with Hierarchical Petri nets. The structure of the HCPN model is then consisting of a top page and several sub-pages which are described in the next sections. The main concepts and semantics of HCPN's can be found in [13].

3.1 Top-page "*Production system*"

Fig. 2 depicts the HCTPN model of the aluminium coils production system. This abstract single top-page, called *Production System*, illustrates the highest network level and provides an overview of the entire production process described in the previous section. Fig. 2 also shows how the HCTPN has been hierarchically structured into seven modules (sub-pages represented by rectangles): The *Arrival of slabs (b1)*, the *Scalping and Furnace process (b2)*, the *Hot-rolling process (b3)*, the *Tandem mill process and transport into High-Bay area (b4)*, the *Annealing and cold-rolling process (b5)*, the *LSDT process (b6)* and finally, the *Inspection process and transport to final storage area (b7)*.

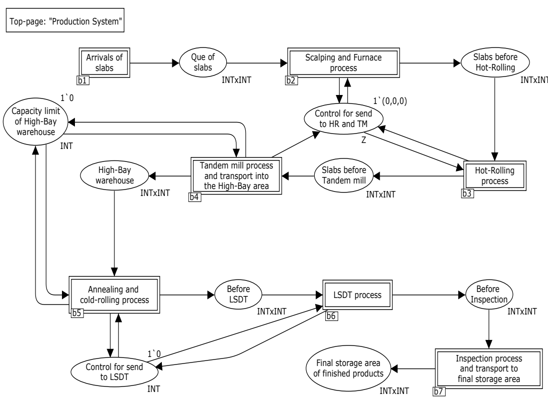

Fig. 2 Top Page "Production System" of the HCTPN

The Production System page has seven transitions which all are substitution transitions and contain all the sub-pages. There are also nine socket places which are similar to intermediate buffers and the final location in the production system. More specifically, place *Que of slabs* contains those slabs intended for the scalping and furnace process, place *Slabs before Hot-rolling* those slabs waiting to be hot rolled, while *Slabs before Tandem mill* holds the stripped slabs (strips) before entering the tandem mill machine. Place *High-Bay warehouse* stores all the coils that leave the Hot-Line and enter the High-Bay storage distribution warehouse. Place *Before LSDT* stores those coils destined for LSDT and place *Before Inspection* a list of coils before inspection control. Finally, place *Storage area of finished products* contains all the finished coils which are stored in the final warehouse and are ready to be dispatched to customers. The socket places *Capacity limit of High-Bay warehouse*, *Control for send to LSDT* and *Control for send to HR and TM* are used for monitoring the capacity constraints of buffers. For modelling purposes numerous declarations (functions, inscriptions etc.) have been used while the main code has been implemented in CPN ML which is an extended version of Standard ML.

3.2 Sub-page "Arrival of slabs" (b1)

Sub-page *Arrival of slabs* models the slabs entry process into the production system. Place *list of slabs enter the plant* contains all the input slabs and can be modified by changing the initial marking *init*. In our model it is assumed that 1250 slabs of any of the different types given in Tab. 1 enter the production process. Each of these slabs carries valuable information which is encapsulated in tokens of type *INTxINT*. More specifically, the first integer represents the sequence order number of the slab (1 to 1250) entering the Hot-Line, in a simulation period of 5 weeks (up to 250 slabs in total, each week), while the second is a five-digit integer whose first digit indicates the coil type (1 to 9), the second indicates how many times the coil has been annealed, and the third digit how many times the coil has been cold rolled. The completion of the LSDT process is represented by the fourth digit (the value "0' is for no completion whereas "1" indicates end of the LSDT process) and finally, the fifth digit is used for future purposes (e.g., inspection, or completion of the processes taking place outside High-Bay area). Fig. 3 shows the sub-page *Arrival of slabs*, where transition *slabs input* and place *slabs counter* determine the entering sequence order of slabs and guarantee that only one slab at a time enters the process via output place *slabs*. Function *control(ss)* is used to secure that no more than 250 slabs enter the process in a period time of one week.

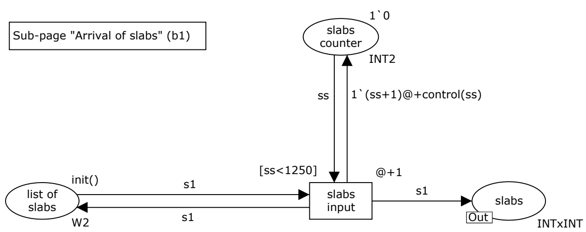

Fig. 3 Sub-page "Arrival of slabs" (b1)

3.3 Sub-page "Scalping and Furnace process" (b2)

This sub-page encompasses the design of the first two processes taking place in the production system i.e., the scalping and furnace stages. Fig. 4 depicts sub-page *Scalping and Furnace process* where input place *slabs* contains those slabs intended to pass through the scalping stage, something that takes place when transition *Start scalping process* fires. Function *scalptimes(b)* provides the scalping times (variable *b*) according to the slabs' size characteristics.

Place *sequence scalping*, function counter*(a,l)* and guard equality *a = l* on transition *Start scalping process* are used to ensure that new data (slabs) do not overtake older (sequencing order). Places *scalping limit*, *scalping busy* and transition *scalping stop* are used for single slab treatment (note that the initial marking in place *scalping limit*, *1'e*, determines the number of tokens (slabs) that transition *Start scalping process* can carry simultaneously).

Place *control sequence* checks whether the number of slabs in the buffer between scalping and furnace exceeds a pre-specified limit in capacity (initially set to 80 slabs). Places *sequence furnace* and *sequence delivery* have similar attributes with place *sequencing scalping* described previously. Places *furnace limit*, *furnace busy* and transition *furnace stop* are also used in order to determine the number of tokens (slabs) transition *Start furnace process* can process at the same time. Note that in this case up to 24 slabs can be placed inside the furnace simultaneously.

Function *furntimes(b)* specifies furnace times according to the slabs' size characteristics. In order to avoid the case of having slabs in the hot-rolling or in the tandem mill processes when the buffer between Hot-Line and High-Bay warehouse is full, the proposed CPN model uses place *Control for send to HR and TM* to communicate with all the processes which comprise the Hot-Line phase, as it can been seen in Fig. 2. Finally, place *End of furnace process* holds those slabs that have been heated and are due to enter the hot-rolling process.

3.4 Sub-page "Hot-Rolling process" (b3)

The sub-page of the CPN modelling the hot-rolling process is illustrated in Fig. 5 and it is very similar to the scalping process design described in the previous section. Places *sequence HR*, *HR limit* and *HR busy* and transition *HR stop* are used for sequencing order and to guarantee single slab treatment. Place *End of Hot-Rolling process* retains those slabs that are completed by the hot-Rolling process and are ready to be moved to the Tandem mill machine. The functionality of place *Control for send to HR and TM* was explained in the previous section.

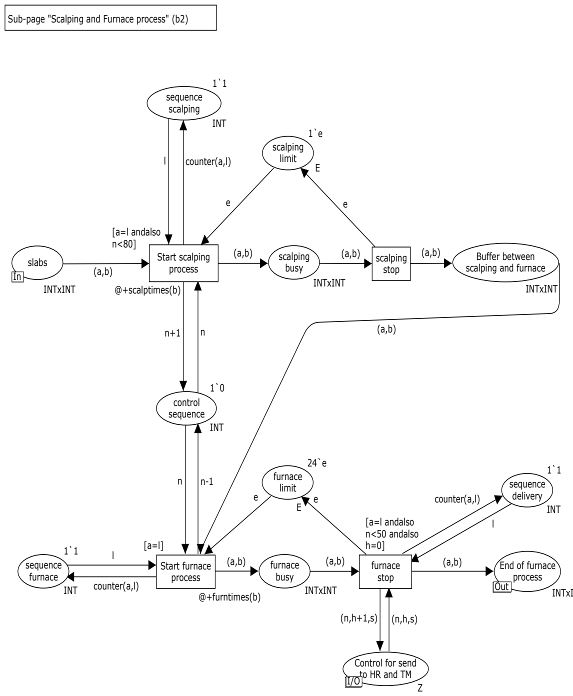

Fig. 4 Sub-page "Scalping and Furnace Process" (b2)

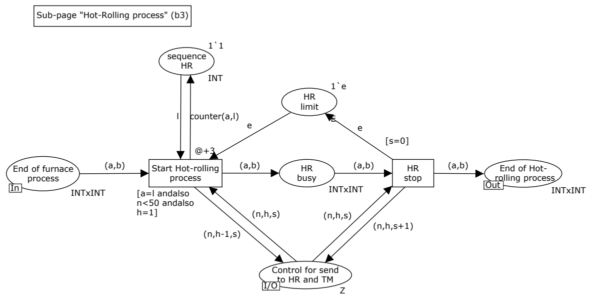

Fig. 5 Sub-page "Hot-Rolling process" (b3)

3.5 Sub-page "Tandem mill process & transport into the High-Bay area" (b4)

"Tandem mill process & transport into the High-Bay" sub-page shown in Fig. 6, has almost the same structure as the "Scalping and Furnace Process" sub-page with respect to the flow of both intermediate products (slabs) and information. The occurrence of transition *Start tandem mill process* signifies tandem mill action, while transition *Start transport into the High-Bay* models the transfer of coils from the buffer, which is located between Hot-Line and High-Bay (represented in Fig. 6 by place *buffer between Hot-Line and High-Bay*), into the High-Bay distribution warehouse. Place *Capacity limit of High-Bay warehouse* holds the capacity of the High-Bay storage area in each simulation step and returns this information to transition *Start transport into the High-Bay*, in order to avoid the event of sending a coil to the High-Bay when it reaches its maximum capacity. Places *sequencing tandem* and *sequencing transport* are used, again, for sequencing order, while function *tandemtimes(b)* gives the tandem mill process times.

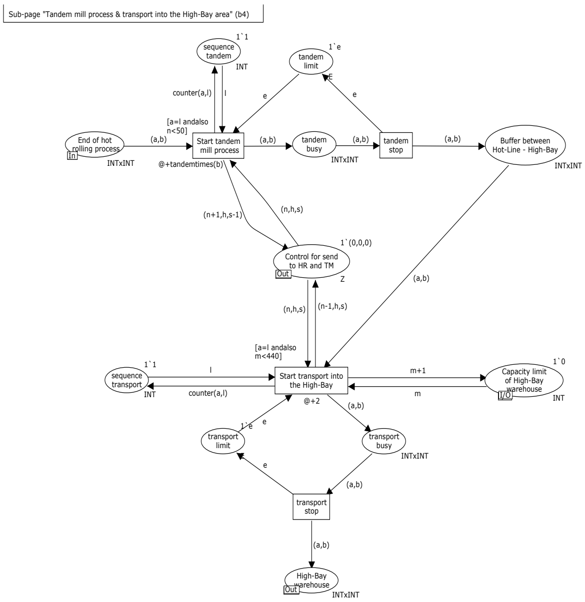

Fig. 6 Sub-page "Tandem mill process & transport into the High-Bay area" (b4)

3.6 Sub-page "Annealing and cold-rolling process" (b5)

The CPN sub-page for the annealing and cold-rolling process is shown in Fig. 7. Since the activities that take place inside the High-Bay area are the most complex processes of the overall production system, the corresponding compound CPN which models all these activities will be discussed in more detail. The CPN model can be divided into three individual networks as it can be seen in Fig. 7 and they are linked together through place *High-Bay warehouse*. This place contains all the coils that have been transferred to the High-Bay distribution warehouse from Hot-Line, those coils that have finished the annealing or cold-rolling processes and remain inside the High-Bay warehouse to be cooled and, moreover, those coils waiting to be dispatched to the LSDT process. The top network in Fig. 7 simulates the cold-rolling process. Each of the transitions *Make groupA for cold-rolling*, *Make groupB for cold-rolling*, *Make groupC for cold-rolling*, and *Make groupD for cold-rolling* is responsible to create the four coils grouping formation as it can be inferred from Tab. 2. This grouping formation is then achieved with the aid of guard functions *groupA*, *groupB*, *groupC*, and *groupD*. The corresponding places *GroupA for cold-rolling*, *GroupB for cold-rolling*, *GroupC for cold-rolling* and *GroupD for cold-rolling* hold the four different groups and when a list is ready, which is sensed by the guard function *activate*, transition *cold-rolling selection process* can be fired. Then the selected list (each list is assigned to variables *z1*, *z2*, *z3* and *z4*) is carried over to transition *Start cold-rolling process* which simulates the operation of the cold-rolling machine centre, via place *before cold-rolling*. Place *D2* updates the coil's data which is associated with the cold-rolling process (in fact, place *D2* increases by one the third digit of the coil's token through function *coilflag*) while function *p23* is used to control the number of coils that have been sent from the selected list. Place *D1* gathers information about the selected list and it distributes this information to transition *Start cold-rolling process*. Function *cdtimes* specifies the cold rolling times while nodes cd*limit*, cd*busy* and cd*stop* are used for single coil treatment during this process. After the cold-rolling process each coil is led back to place *High-Bay warehouse*.

The middle CPN network in Fig. 7 models the annealing process. Transitions *Grouping wide coils*, *Grouping medium coils* and *Grouping narrow coils* are used to formulate the three groups of coils, according to their width, as given in Tab. 1. Guard functions *wide*, *medium* and *narrow* manipulate each coil's data and send the coil to the appropriate transition. Similarly to the cold-rolling grouping process described previously, each of these transitions creates lists of four coils of the same width (defined with variables *z1*, *z2* and *z3*). Once the groups are created, places *wide coils*, *medium coils* and *narrow coils* distribute them to transition *Annealing selection process*. This transition sends each of the selected group to two buffers which are located before the annealing machines and are denoted with places *buffer1* and *buffer2* in Fig. 7. Place *T* carries, at each time, the number of occupied buffers and sends this information to transition *Annealing selection process* through the variable *t*. In the case that any of the buffers is empty, transition *Annealing selection process* sends the selected group to the buffers. Transitions *Start Annealing machine1*, *Start Annealing machine2* and *Start Annealing machine3* represent the three annealing machine centres which are installed in the main High-Bay area. Functions *c17* are *c18* are used to load quartets of coils into machine centres, while function *annealtimes* computes annealing times according to the coil characteristics which are common for the three transitions *Start Annealing machine1*, *Start Annealing machine2* and *Start Annealing machine3*. Function *c19* verifies the end of the annealing cycle and updates the coil's information (it increases by one the second digit of the coil's token). Nodes *limit1*, *busy1*, *stop1*, *limit2*, *busy2*, *stop2 limit3*, *busy3* and *stop3* are used to ensure that one quartet of coils at a time exits the annealing machines before returning to place *High-Bay warehouse*.

The bottom CPN network in Fig. 7 simulates the dispatch process to the LSDT machine centre. Each time a coil has been cooled after the cold-rolling process, (specified by function *goLSDT*) transition *Going to LSDT* fires. If more coils can proceed to the LSDT stage, place *Before LSDT* updates a list of those coils in each simulation step. In the case that the LSDT machine centre is not busy (determined by place *Control for send to LSDT*) one coil at a time, specified by nodes *limit3*, *busy3* and *stop3*, goes over the LSDT treatment. Function *LSDTflag* updates the coil's information and sets the fourth digit of the coil's token to "1".

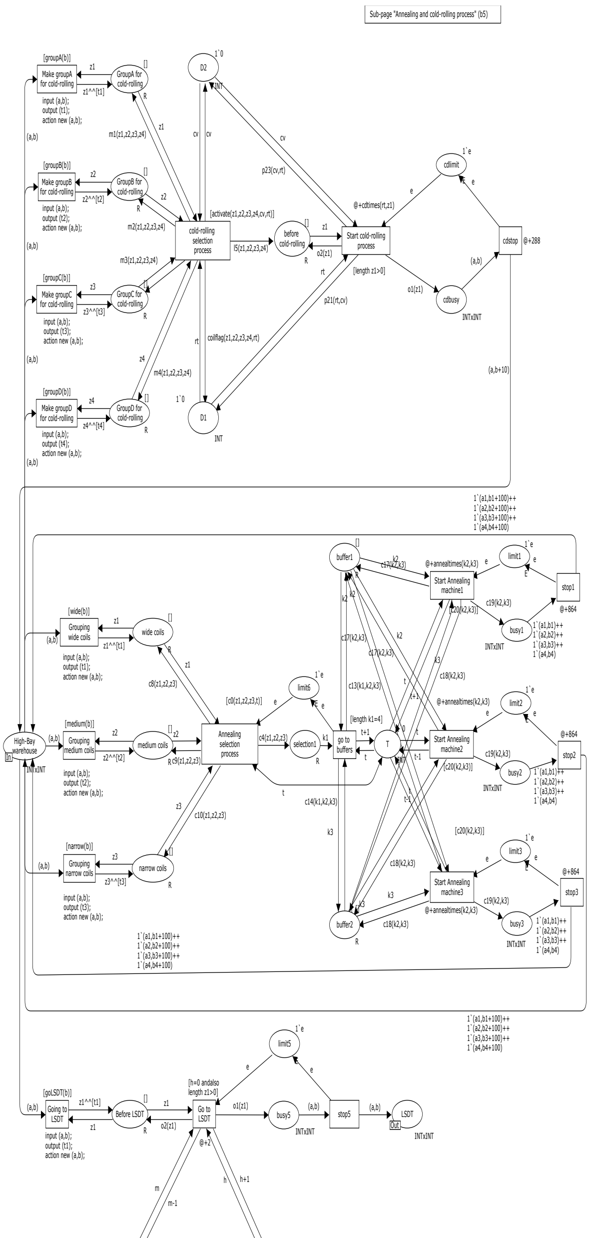

Fig. 7 Sub-page "Annealing and cold-rolling process" (b5)

3.7 Sub-page "LSDT process" (b6)

The LSDT process sub-page illustrated in Fig. 8 has many similarities with sub-page "Hot-Rolling process" described in section 3.4. Transition *Start LSDT process* models the operation of the LSDT machine centre while LSDT times are specified by function *lsdttimes(b).* Place *Control for send to LSDT* monitors the LSDT process state and interacts with the High-Bay distribution warehouse by sending information on whether the LSDT is busy or not.

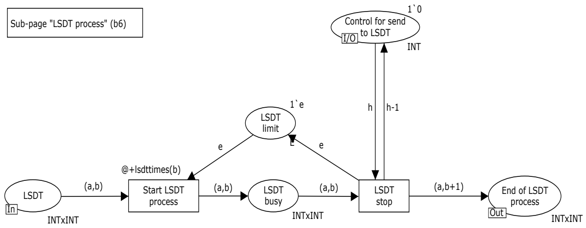

Fig. 8 Sub-page "LSDT process" (b6)

3.8 Sub-page "Inspection process and transport to the final storage area" (b7)

The final sub-page, which represents the CPN model design for the inspection process and delivery of finished coils to the final storage area, is shown in Fig. 9. Transition *Start Inspection process* corresponds to the inspection stage while transition *Inspection stop* and places I*nspection limit* and *Inspection busy* are used to indicate that, as a matter of fact, the inspection team tests a single finished coil at a time, before that coil is dispatched to the final storage area, represented in Fig. 2 and Fig. 9 by place *Final storage area of finished products*.

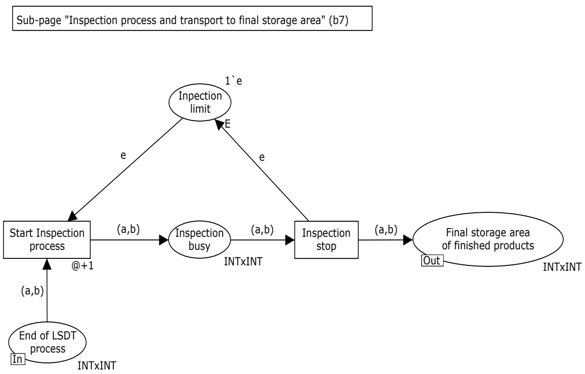

Fig. 9 Sub-page "Inspection process and transport to the final storage area" (b7)

4 Simulation Results and Performance Analysis

In order to evaluate the performance of the proposed production system a series of simulations were conducted with the aid of CPN-Tools. Simulation provided the means of testing the behaviour of the system, using specific metrics and by implementing a number of different scenarios. Since this is, essentially, a discrete event simulation it tracks the sequence of events in the production system in discrete time steps. Monitors were used in order to gather specific model information in places of interest (machines, intermediate buffers, queues) and reports were used to present quantitative information about the types of places, number of tokens, time stamps etc.

The proposed CPN model allows the investigation of the dynamic behaviour of the production system under study and it provides a significant insight of the system's characteristics. Since the overall design is hierarchical, the model can be easily modified as required in order to meet alternative design specifications. Apart from being flexible, the graphical interface of the CPN-Tools with the aid of marking schemes provides excellent representation of the current state of the production system, in contrast with other software simulation tools e.g. high level programming languages. Simulation runs allow the visualisation of the coils flow, grouping, and variations in intermediate buffer and queue sizes. The proposed CPN model depicts efficiently the interrelations between machine centres and related tasks as well as machine utilisation on each simulation step. Simulation times were also quite faster when compared with a corresponding model of the production system implemented in MatLab, mainly for verification purposes.

As stated in the previous section, coils are considered as coloured tokens whereas enabled transitions correspond to the possible events. Initial markings provide the option of setting alternative default parameters (e.g., buffer sizes, timing specifications) as required by the management decision-making. It must be noted that although 1250 slabs entered into the production system, 1178 finished coils were produced since the rest of the coils (72) were left inside the High-Bay area due to unmatched groupings (intermediate products).

The performance of the system was assessed using a number of common appropriate metrics such as:

- Throughput rate, defined as the number of finished coils in a specified time period (38,2 days).
- Makespan, defined as the time period (in days) a batch of 1178 coils spends in the production system.
- Utilisation, defined as the percentage of time each machine center (Annealing, cold-Rolling, LSDT, Hot-Line) is occupied in a simulation period.
- Work-In-Process (WIP) inventory, defined as the number of partially completed coils in processing at a given time.
- Decongestion, related to the number of times the buffer between the scalping and furnace processes (Buffer 1), the buffer between Hot-Line and High-Bay (Buffer 2), and the High-Bay storage area have reached their maximum capacities. The rate at which the coils leave the Hot-Line and enter the High-Bay area (input rate) is also used for measuring decongestion.

Multiple simulation runs were carried out in order to evaluate the proposed metrics for the production system under ordinary operation. Initially, the model was validated on actual system data, provided by an aluminium industry, with respect to buffer sizes, makespans, throughput rates and inventories. The proposed model was deadlock-free, as it was found after extensive simulations.

In order to gain further insight of the production system, various scenarios were investigated via extensive simulation runs. These scenarios include:

Scenario 1: Installing of an additional similar annealing machine, operating in parallel.

Scenario 2: Reducing by 50% the pre-set times that the coils remain in High-Bay during cooling and after annealing.

Scenario 3: Increasing buffer sizes between the Hot-Line and High-Bay area by 25%.

Scenario 4: Increasing the storage capacity of the High-Bay Distribution Warehouse by 25%.

The model incorporating these scenarios was analysed and assessed using the above metrics and detailed results are presented in Fig. 10-11 and Tab. 3-5.

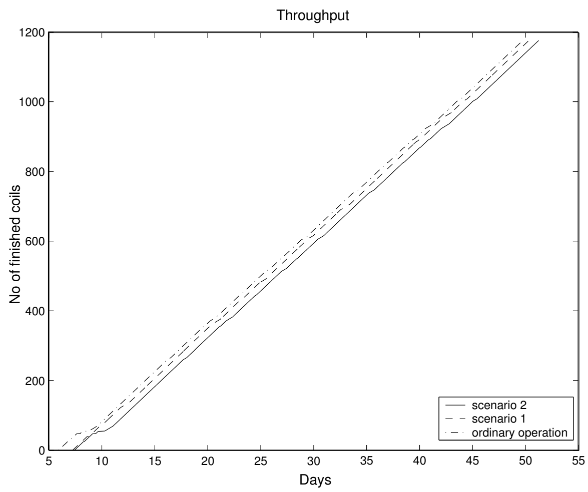

Fig. 10 Throughput variation

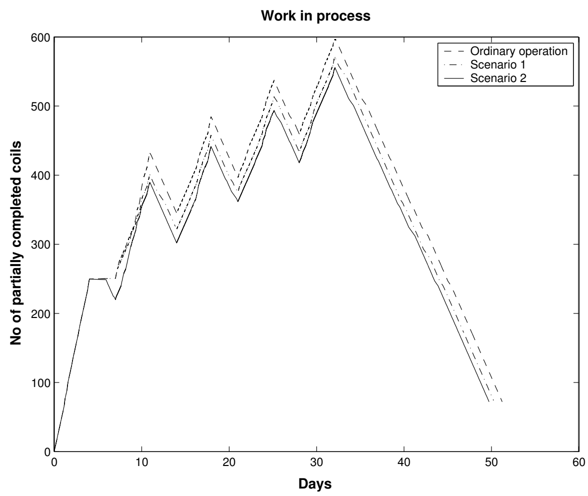

Fig. 11 Work in Process variation

Tab. 3 Throughput and Makespan metrics

	Throughput (in 38.2 days)	Makespan (days)	Duration (days)
Ordinary Operation	821	13.1	51.2
Scenario 1	846 (+3%)	12.5 (-4.4%)	50.2
Scenario 2	862 (+5%)	11.6 (-11.1%)	49.7
Scenario 3	821 (0%)	13.1 (0%)	51.2
Scenario 4	821 (0%)	13.1 (0%)	51.2

It was found that installing an additional annealing machine resulted in a 3% increase in the overall throughput rate and a 4.4% makespan reduction, as shown in Tab. 3 and Fig. 10. Moreover, machine utilisation in the cold-rolling and LSDT processes was increased by 7.3% and 4.9% respectively, while Annealing and Hot-Line utilisation was reduced by 12.1% and 3.8% respectively, as shown in Tab. 5. Note that the reduction in the overall Annealing machines usage is a result of the installation of the fourth annealing machine. As it can also be inferred from Tab. 4 input rate for this scenario was increased by 2.3%. Furthermore, the addition of the fourth annealing machine had a significant reduction (73.3%) on the number of times the buffer between Hot-Line and High-Bay was full and also a notable reduction in the number of coils remaining in the High-Bay storage area (27.3%). Finally, as it can be seen in Fig. 11 the number of partially completed coils (WIP) was reduced after the 10th day.

Tab. 4 Buffer capacity changes and input rate

	Buffer 1 *no. of times full*	Buffer 2 *no. of times full*	High Bay *no. of times full*	Input Rate *days for 1250 coils*
Ordinary Operation	8	244	469	37.8
Scenario 1	0 (-100%)	65 (-73.3%)	341 (-27.3%)	36.9 (+2.3%)
Scenario 2	0 (-100%)	111 (-54.5%)	277 (-40.9%)	36.3 (+4%)
Scenario 3	0 (-100%)	201 (-17.6%)	469 (0%)	37.8 (0%)
Scenario 4	0 (-100%)	0 (-100%)	77 (-83.5%)	33.8 (+10.6%)

Scenario 2 resulted in a significant increase in throughput (5%) and a considerable decrease in makespan (11.1%), as shown in Tab. 3. Utilization of the machine centres in High-Bay area was raised by about 3%, as it can be seen in Tab. 5. Additionally, the decrease of pre-set cooling times after annealing by 50% has led to the decongestion of the Hot-Line machine centres by 6.3%. Another important outcome is that the High-Bay storage area was full 277 times (a 40.9% reduction with respect to ordinary operation) while this scenario also halved the number of times the buffer between Hot-Line and High-Bay reached its maximum capacity (50 coils). Finally, the input rate has been increased by 4%, as it is also shown in Tab. 4.

Tab. 5 Machine centres utilization (percentage of *machine busy/simulation period*)

	Annealing	Cold-Rolling	LSDT	Hot-Line
Ordinary Operation	77.4	60.4	52.7	49.3
Scenario 1	68 (-12.1%)	64.8 (+7.3%)	55.3 (+4.9%)	47.4 (-3.8%)
Scenario 2	79.8 (+3.1%)	62.3 (+3.1%)	54.3 (+3%)	46.2 (-6.3%)
Scenario 3	77.4 (0%)	60.4 (0%)	52.7 (0%)	48.2 (-2.2%)
Scenario 4	77.4 (0%)	60.4 (0%)	52.7 (0%)	43.3 (-12.2%)

No significant changes were noted as far as throughput, makespan, machine centre usage in High-Bay area, input rate and changes in High Bay distribution warehouse capacity are concerned for the third scenario (as shown in Tab. 3 and Tab. 5). However, Hot-Line utilization has been decreased by 2.2% while the buffer between Hot-Line and High-Bay (Buffer 2) was decongested by 17.6% as shown in Tab. 4.

Although the performance of the system, after the increase in storage capacity of the High-Bay Distribution Warehouse under the fourth scenario, resembles that of scenario 3, with respect to throughput, makespan and machine centre usage in High-Bay area, important improvement resulted to the input rate (10.6%). Furthermore, the overall Hot-Line stage was decongested as shown in Tab. 4 and Tab. 5. More specifically, the Hot-Line machine centres usage has been decreased by 12.2% whereas Buffer 2 never reached its maximum capacity. As it was expected, the installation of new racks in the High-Bay Distribution Warehouse area led to an important reduction (by 83.5%) on the number of times the maximum capacity of 550 racks was reached.

It should be noted that Buffer 1 was never full, under all four scenarios, as it can be inferred from Tab. 4.

In summary, notable changes in throughput, makespan, WIP and machine utilization were observed for the first two scenarios (with scenario 2 providing better results for throughput, makespan, and WIP and scenario 1 for machine utilization), whereas best decongestion results were observed for the fourth scenario. Although Scenario 3 has not provided best results for any metric, it is the cheapest to implement.

It is clear that the assessment all alternative scenarios provided by the extended simulations of the proposed model will significantly aid decision-making management procedures, especially when cost over benefit investment considerations are taken into account.

5 Conclusions

This paper presented a technique for the modelling and simulation of an aluminium coils production system by means of Hierarchical Coloured Timed Petri Nets (HCTPN). The effects of physical and capacity constraints (e.g., installing new machinery, storage constraints of intermediate inventory buffers, pre-set time changes) were analysed. Different scenarios were assessed and analysed by measuring some common metrics such as throughput, makespan, WIP, buffers capacity and machine utilisation.

The proposed model encapsulates in detail the behaviour of the production system, it is flexible in the sense that it can accommodate alternative system configurations and its reliability was assessed on actual production data.

Hence, the proposed model can aid the production management process in such complex manufacturing environments by providing important knowledge about the system and thus, resulting to better decision-making.

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