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# Načrtovanje izdelovalnih sistemov, podprto s simulacijo

## Simulation-Aided Planning of Manufacturing Systems

**Tomaž Perme**

*Naraščajoča zapletenost sodobnih proizvodnih sistemov zahteva računalniško podprta orodja, s katerimi bo lahko načrtovalec bolje izkoristil svoje znanje, izkušnje, ustvarjalnost in intuicijo. Pomemben del teh orodij je simulacija, saj je le z njo mogoče pridobiti "dejanske" lastnosti izdelovalnih in montažnih sistemov že v fazi njihovega načrtovanja. Glavni del tega prispevka opisuje razvoj simulacijskega paketa (LASIMCO) za računalniško podprto načrtovanje izdelovalnih in montažnih sistemov, prikazana pa je tudi uporaba tega orodja na dejanskem primeru.*

**(Ključne besede: sistemi proizvodni, planiranje računalniško podprto, proizvodnja navidezna, mreže Petri)**

*The increasing complexity of modern manufacturing systems calls for computer-aided planning tools, which can help planners better use their knowledge, experience, creativity and intuition. Only by means of a simulation, which is a significant part of these tools, can the "real" properties of a manufacturing or assembly system be obtained during the planning phase. The main parts of this paper describe the development of a simulation package (LASIMCO) for the computer-aided planning of manufacturing and assembly systems, as well as the use of this tool in a case study.*

**(Keywords: manufacturing systems, computer-aided planning, virtual manufacturing, Petri nets)**

## 0 UVOD

Računalniško integrirana proizvodnja (RIP - CIM) brez ljudi je samo domišljija, prav tako pa tudi sistem za načrtovanje, ki bi načrtal izdelovalni sistem na podlagi podanih zahtev brez človeške sodelave. Kratica RIP pa ima tudi bolj dejanski pomen, kakor je na primer stalno izboljševanje izdelave. V tem pomenu je treba razmišljati tudi pri razvoju in re-inženiringu izdelovalnih in tudi montažnih sistemov.

Tako je pri načrtovanju proizvodnih sistemov v splošnem treba posebno pozornost posvetiti dvema stvarema: stalnemu izpopolnjevanju samih proizvodnih sistemov in orodjem, ki so v pomoč načrtovalcem, da lahko pri svojem delu izkoristijo vse svoje znanje, izkušnje, ustvarjalnost in intuicijo.

Tu seveda ni nobenega navodila za razvoj takih orodij, saj ima namreč vsak preizkus svoje dobre

## 0 INTRODUCTION

Computer-integrated manufacturing (CIM) without the need for workers and operators is a mere fiction, so too is a planning system that could design a manufacturing system on the basis of predefined requirements without only human interaction. But the abbreviation CIM can also have a more realistic meaning, like the continuous improvement of manufacturing; and in this sense the design and re-design of manufacturing as well as assembly systems need to be considered.

There are, therefore, two main points to focus on: the continuous improvement of manufacturing systems and the planning of tools to assist planners in using all their knowledge, experience, creativity and intuition to accomplish the first objective as successfully as possible.

There is no recipe for the development of such tools. Each attempt has its own potential and in slabe strani. Namen tega prispevka je predstaviti razvoj orodja, ki je zasnovano na zamisli navidezne izdelave in simulacije. Le ta temelji na razširjenih Petrijevih mrežah, ki omogočajo upoštevanje tako logičnih kakor tudi nekaj fizičnih lastnosti pri proučevanju načrtovanega sistema [1].

## 1 NAVIDEZNA IZDELAVA IN SIMULACIJA

Zamisel navidezne izdelave (NI), ki sta jo prva vpeljala Iwata in Onosato [2], rabi kot zapoved in osnovni okvir za razvoj orodij za načrtovanje izdelovalnih sistemov. Namen zamisli NI je integracija znanih modelov proizvodnje, tehnik analiziranja in oblik predstavitve v povezan, skladen in razumljiv sistem na način, ki omogoča, da se lahko preizkusijo in preverijo nove tehnike in metode načrtovanja in krmiljenja proizvodnje brez uporabe in motenj dejanskega proizvodnega sistema (DPS).

Da bi to lahko dosegli, je potrebno imeti napredno znanje o proizvodnji in uporabiti napredne računske tehnike. Interdisciplinarnost je že sama po sebi vsebovana v razvoju NI, ki mora biti prilagodljiv in odprt za simuliranje različnih vrst proizvodnih sistemov na način, ki omogoča izpopolnjevanje tako dejanskega kakor tudi navideznega proizvodnega sistema.

Beseda "navidezen" pomeni v bistvu to, da se aktivnosti v informacijskih in izdelovalnih procesih izvedejo v računalniku in z njim, pri čemer so sredstva in material objekti, ki so predstavljeni z informacijami. Glede na zamisel NI je lahko proizvodni sistem dejanski ali pa navidezen, predstavimo ga lahko v naslednji obliki (sl. 1) kot: dejanski fizični podsistem (DFP), dejanski informacijski podsistem (DIP), navidezni fizični podsistem (NFP) in navidezni informacijski podsistem (NIS).

Iz teh štirih osnovnih razlag izdelovalnega sistema se lahko sestavijo kombinacije, ki imajo praktični pomen v dejanskem okolju. Kombinacija NFP-DIP je na primer pomembna za postavitev navideznega izdelovalnega okolja (NIO). NFP-DIP dejansko pomeni navidezni izdelovalni sistem (fizično), kjer se izdeluje navidezni izdelek v računalniku na podlagi dejanskih informacij.

Pomemben del NI sta simulacija in prikaz rezultatov. Vernost navidezne izdelave je zelo odvisna od natančnosti rezultatov simulacije in privzetju dejanskosti njihove predstavitve. Rezultati simulacije morajo biti natančni in generirani v dejanskem času – načrtovalec mora najti ravnovesje med temi pogoji ob upoštevanju danih računalniških zmogljivosti. Problem je enak pri navidezni resničnosti (NR), ki jo lahko uporabimo tu kot obliko predstavitve. Privzetje dejanskosti pri uporabi NR je povezano z zmožnostjo opreme (računalnik, naglavni prikazovalnik,

drawbacks. The aim of this paper is to describe one such attempt, which is based on the concept of virtual manufacturing and a simulation using extended Petri nets, in such a way that the logical as well as some of the physical properties of the investigated system can be considered [1].

## 1 VIRTUAL MANUFACTURING AND SIMULATION

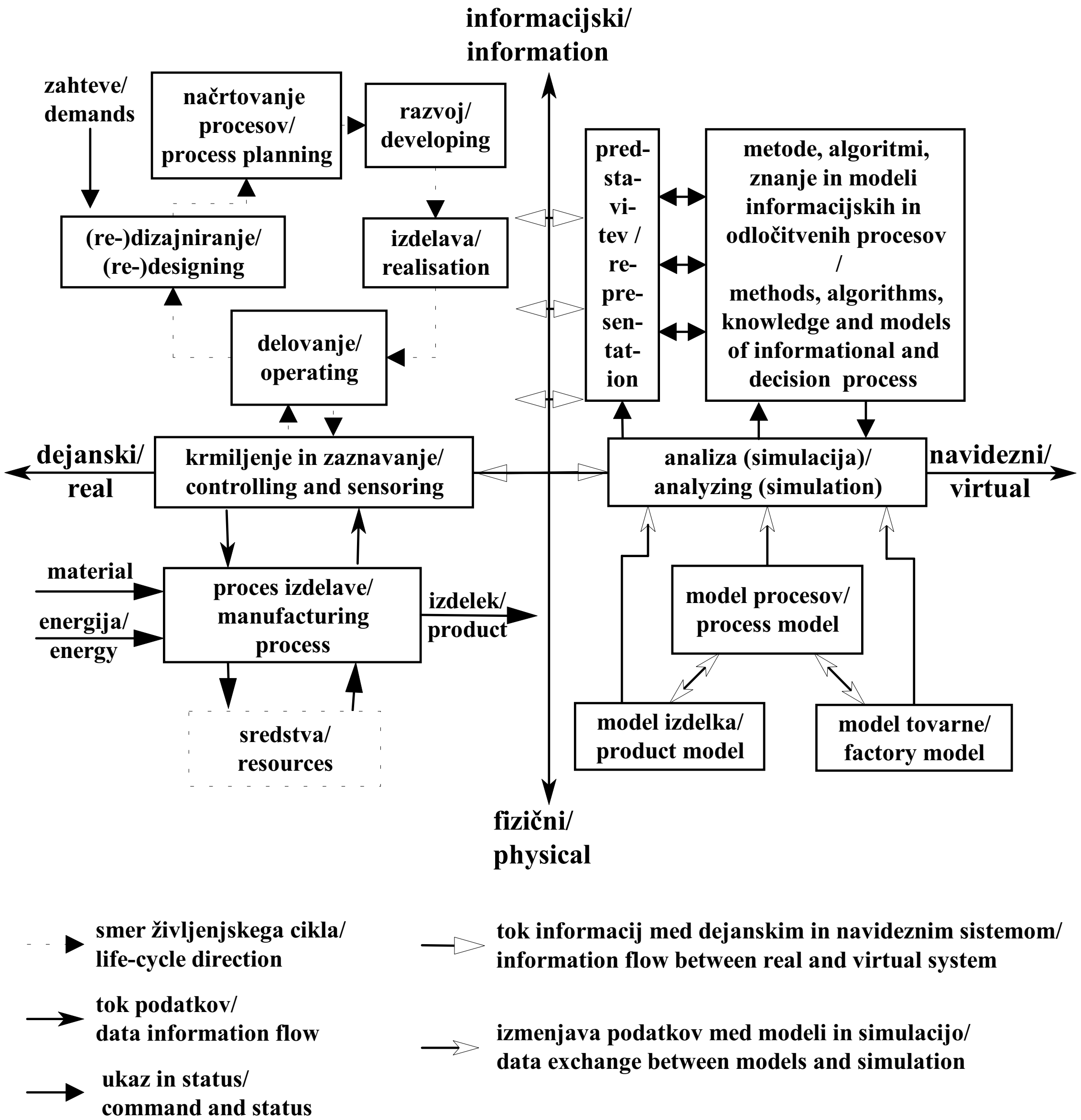
The concept of Virtual Manufacturing (VM), which was introduced by Iwata and Onosato [2], can serve as an imperative and as the basic framework for the development of planning tools for manufacturing systems. The purpose of a VM system is to integrate the existing manufacturing models, analytical techniques and presentation forms into a coherent system in such a way that new planning and control methods and techniques can be tested and verified without disturbing the real manufacturing system (RMS).

In order to achieve this, advanced knowledge of manufacturing is needed and advanced computational techniques have to be applied. Interdisciplinarity is inherent in the development of VM systems, which must be flexible and open enough to simulate different types of manufacturing systems in a way that enables the continuous improvement of real as well as virtual manufacturing processes.

The term "virtual" means that the activities within the information and manufacturing process are accomplished by and within a computer, and the resources and material are the objects described and represented by the information. According to the VM concept, the manufacturing system can be either real or virtual and can be presented in the form of a real physical subsystem (RPS), a real information subsystem (RIS), a virtual physical subsystem (VPS) and a virtual information subsystem (VIS) (Fig. 1).

From these four basic interpretations of manufacturing systems, combinations can be set up that have a practical significance in a real environment. The combination of a VPS and an RIS is sensible for establishing a virtual manufacturing environment (VME). In effect, VPS-RIS means a virtual manufacturing system (physically) where a virtual product is manufactured by a computer on the basis of real information.

Important elements of VM include the simulation and presentation of the results. The "reality" of the VM system is closely connected with the accuracy of the simulation results and the assumption of reality in the presentation. The results of the simulation must be accurate and generated in real time; the designer must find a balance between these conditions within the given computational capacity. The problem is the same in virtual reality (VR), which can be used as a form of presentation. The assumption of reality in the use of VR is connected to the capability of the equipment (computer, head-




Sl. 1. *Fizični in navidezni deli informacijskih in izdelovalnih procesov [3]*
Fig. 1. *Physical and virtual parts of the information and manufacturing processes [3]*

podatkovne rokavice in drugi vmesniki) za uglasitev uporabnika z navideznim okoljem.

Od možnih kombinacij se lahko postavi okolje za navidezno izdelavo, ki ga sestavljajo trije osnovni modeli dejanskega izdelovalnega sistema, in sicer model izdelka, model procesov in model tovarne. Ti modeli se lahko analizirajo s simulacijo, rezultati pa predstavijo v obliki, ki se približuje dejanskosti.

## 2 RAZŠIRJENE PETRIJEVE MREŽE IN NJIHOVA IZVEDBA

Dejanski izdelovalni ali montažni sistem (DIS) se lahko opazuje kot odprto množico osnovnih aktivnosti, ki se izvajajo posamično in ki potrebujejo za to določena sredstva, za katera se potegujejo, ter informacije, ki jih krmilijo. Te aktivnosti so potrebne za pretvorbo materiala z uporabo energije v končni

mounted display, data glove and other interface devices) to attune the user to the virtual environment.

From the various possible combinations, a VME can be set up containing three basic models of real manufacturing systems (RMS): the product, the process, and the factory model. These models can be analysed by simulation and the results can be presented in a form approaching reality.

## 2 EXTENDED PETRI NETS AND IMPLEMENTATION

The real manufacturing or assembly system (RPS) can be regarded as a bug of separately executed basic activities, which require certain resources that they compete for and information they are controlled by. These activities are needed to transform material, using energy, into the final product. The resources izdelek. Sredstva, ki omogočajo procese izdelave in montaže, vključujejo opremo, to so na primer obdelovalni stroji, orodja, transportne in strežne naprave, roboti, vpenjalni pripomočki in drugo, ter ljudi, ki delajo in upravljajo s to opremo.

Za modele procesov in tovarne, ki morajo opisati izvajanje osnovnih aktivnosti in sredstva, ki so za to potrebna, so na podlagi analogije in zahtev generičnega modela aktivnosti (GAM)[4] in njegovega matematičnega opisa[5], predlagane razširjene Petrijeve mreže (RPM).

## 2.1 Razširjene Petrijeve mreže

Petrijeve mreže so bile razvite v doktorski disertaciji, v kateri je Carl Adam Petri posebno pozornost posvetil opisu vzročnih zvez med dogodki [6]. Različni raziskovalci so glede na svoje zanimanje in uporabo na različne načine opredelili mnogo teoretičnih konceptov Petrijevih mrež. Formalna opredelitev Petijevih mrež [7] z omejeno kapaciteto (mreža stanj/prehodov) [8] in razširjena s prioritetami in časom je podana kot C=(P,T,F,K,W,M,R,Z) kjer:

$P = \{ p_1, p_2, ......p_m\}$ je končna množica mest,
$T = \{t_1, t_2, .....t_n\}$ je končna množica prehodov,
$P \cap T = 0$ in $P \cup T \neq 0$
$F \subseteq (P \times T) \cup (T \times P)$ je množica povezav,
$K: P \rightarrow \{1,2,3, ...\}$ vsakemu mestu opredeli kapaciteto,
$W: F \rightarrow \{\ldots -3,-2,-1, 1,2,3, ...\}$ je utežna funkcija,
$M_0: P \rightarrow \{1,2,3 ...\}$ je začetna označitev mest,
$R: T \rightarrow \{0,1,2,..,9\}$ vsakemu prehodu opredeli proriteta in
$Z: T \rightarrow \{0,1,2,3,..\}$ vsakemu prehodu opredeli čas.

Petrijeve mreže so dejansko usmerjen, utežen, dvostranski graf, ki ga sestavljajo dve vrsti vozlišč, imenovana mesta in prehodi. Grafično se mesta prikazujejo z krogi, prehodi pa s črto oziroma s pravokotnikom. Mesta se povezujejo s prehodi in prehodi z mesti. Teža teh povezav je pozitivno celo število, kjer pomeni povezava med dvema vozliščema s težo *k* dejansko *k* povezav med tema dvema vozliščema. Vsako mesto ima opredeljeno tudi kapaciteto *K(p)*, ki pomeni največje število žetonov, ki so lahko v mestu *p* naenkrat. Označitev pripiše vsakemu mestu nenegativno celo število in je označena z *M*. *M* je stolpični vektor reda *m* x 1, kjer *m* pomeni število vseh mest. Če je ne negativno celo število *l,* pripisano mestu *p*, potem je mesto *p* označeno z *l* žetoni. Grafično so žetoni prikazani s pikami ali s številko.

Pravilo, ki pove, kdaj je neki prehod omogočen in se lahko izvede, je pravilo izvajanja in se opiše za RPM takole:

$\bullet p := \{t \mid (t,p) \in F\}$ je množica vhodnih prehodov mesta *p*,
$p\bullet := \{t \mid (p,t) \in F\}$ je množica izhodnih prehodov mesta *p*,
$\bullet t := \{p \mid (p,t) \in F\}$ je množica vhodnih mest prehoda *t* in
$t\bullet := \{p \mid (t,p) \in F\}$ je množica izhodnih mest prehoda *t*.

supporting the manufacturing process are composed of equipment, such as machine tools, tools, transport and handling devices, robots, auxiliary devices, etc., and people who operate and work with the equipment.

For the process and factory model, which have to model the execution of the basic activities and resources needed for these executions, Extended Petri Nets (EPNs) have been proposed following an analogy and the requirements of the Generic Activity Model (GAM) [4] and its mathematical description [5].

## 2.1 Extended Petri Nets

Petri nets have been developed in the doctoral thesis of Carl Adam Petri, which described the causal relationships between events [6]. Many of the fundamental concepts of Petri nets were defined by different researchers with different motivations in different ways. A formal definition of a Petri net [7] with a finite capacity (place/transition net) [8] and extended with priority and time is given by as an 8-tuple, C=(P, T, F, K, W, $M_0$, R, Z) where:

$P = \{ p_1, p_2, ......p_m\}$ is a finite set of places,
$T = \{t_1, t_2, .....t_n\}$ is a finite set of transitions,
$P \cap T = 0$ and $P \cup T \neq 0$
$F \subseteq (P \times T) \cup (T \times P)$ is a set of arcs,
$K: P \rightarrow \{1,2,3, ...\}$ defines the capacity for each place,
$W: F \rightarrow \{\ldots -3,-2,-1, 1,2,3, ...\}$ is a weight function,
$M_0: P \rightarrow \{1,2,3 ...\}$ is the initial marking,
$R: T \rightarrow \{0,1,2,..,9\}$ defines the priority for each transition,
$Z: T \rightarrow \{0,1,2,3,..\}$ defines the time for each transition.

The Petri net is a directed, weighted, bipartite graph consisting of two types of nodes, called places and transitions. In a graphical representation the places are represented by circles and the transitions by bars or rectangles. Places are connected with transitions, and transitions with places. The weight of the arcs is a positive integer, where a *k*-weighted arc means *k* parallel arcs. Each place *p* has an associate capacity *K*(*p*), which determines the maximum number of tokens that *p* can hold at any time. A marking assigns to each state a nonnegative integer, and is denoted by *M*. *M* is an $m \times 1$ column vector, where *m* is the number of places. If a nonnegative integer *l* is assigned to place *p*, the place *p* is marked with *l* tokens. In a graphical representation the tokens are represented by dots or a number.

The rule for transition enabling and firing is an execution rule, which can be described for an EPN in the following direction.

$\bullet p := \{t \mid (t,p) \in F\}$ is the set of input transitions of place *p*,
$p\bullet := \{t \mid (p,t) \in F\}$ is the set of output transitions of place *p*,
$\bullet t := \{p \mid (p,t) \in F\}$ is the set of input places of transition *t*,
$t\bullet := \{p \mid (t,p) \in F\}$ the set of output places of transition *t*.

Prehod $t$ je omogočen pri določeni označitvi $M$, če velja:

A transition $t$ is enabled under marking $M$ if:

$$\forall p \in \bullet t: \begin{cases} M(p) \geq W(p,t) & \forall \quad W(p,t) \geq 0 \\ M(p) < |W(p,t)| & \forall \quad W(p,t) < 0 \end{cases} \tag{1}$$

$$\forall p \in t\bullet: \begin{cases} M(p) \leq K(p) - W(t,p) & \forall \quad W(t,p) \geq 0 \\ M(p) > |W(t,p)| & \forall \quad W(t,p) < 0 \end{cases} \tag{2}$$

Enačba (1) pomeni, da označitev vsakega vhodnega mesta prehoda $t$ ne sme biti manjša, oziroma mora biti večja od $w(p, t)$, če $w(p, t)$ ni negativen, oziroma če je negativen. Enačba (2) pomeni, da število žetonov v vsakem izhodnem mestu $p$ od $t$ po izvedbi prehoda $t$ ne sme preseči, oziroma mora biti večje od njegove kapacitete $K(p)$, če $w(p, t)$ ni negativen, oziroma če je negativen. $w(p,t)$ je utež povezave mesta $p$ s prehodom $t$ in $w(t, p)$ utež povezave prehoda $t$ z mestom $p$.

Podmnožica prehodov $T' \subseteq T$ je omogočena pri $M$, če je $\forall\ t \in T'$ omogočen pri označitvi $M$.

Če je prehod omogočen, se lahko izvede ali pa tudi ne. To je odvisno od konfliktnih situacij in medsebojnega izključevanja prehodov. Prehod se lahko izvede, če je izpolnjen pogoj:

Equation (1) means that the marking of each input place should not be smaller, or have to be smaller, than $w(p, t)$ if $w(p, t)$ is not negative or it is negative, respectively. Equation (2) means that the number of tokens in each output place $p$ of $t$ cannot exceed or have to exceed its capacity $K(p)$ after the firing of $t$ when $w(p, t)$ is not negative or it is negative respectively. $w(p,t)$ is the weight of the arc from place $p$ to transition $t$ and $w(t, p)$ is the weight of the arc from transition $t$ to place $p$.

A sub-set of transitions $T' \subseteq T$ is enabled under $M$, when $\forall\ t \in T'$ is enabled under $M$.

If a transition is enabled, it may or may not fire. That depends on conflict situations and the mutual exclusion of enabled transitions. The transition may fire if:

$$\forall\ p \in \bullet t_i: p\bullet \cap T' = \{t_i\} \text{ in/and } \forall\ p \in t_i\bullet: \bullet p \cap T' = \{t_i\} \text{ ali/or} \tag{3}$$

$$\forall\ t \in T' \cap {**} \text{ in/and } \forall\ t \in T' \cap {**},\ t \neq t_i: R(t_i) > R(t) \tag{4}$$

Pogoj (3) pomeni, da $t_i$ ni v konfliktni situaciji oziroma nima skupnih vhodnih in izhodnih mest z nobenim prehodom, ki bi bil hkrati omogočen. Pravilo (4) pa pravi, če obstajata dva prehoda, ki sta hkrati omogočena in imata vsaj eno skupno vhodno oziroma izhodno mesto, potem se izvede najprej tisti prehod, ki ima večjo prioriteto $R(t)$.

Omogočen prehod se lahko izvede na dva načina, kar je odvisno od časa trajanja prehoda. Prehod s časom trajanja nič ($z(t) = 0$) se izvede takoj v celoti:

Condition (3) means that $t_i$ is not in a conflict situation, i.e. it has no common input or output places with any in the same time-enabled transition and (4) means that if two transitions are enabled and have some common input or output places, just the transition with the greater priority $R(t)$ can fire.

An enabled transition can fire in two ways, depending on the duration of the transition. Zero-time transitions ($z(t) = 0$) fire all at once:

$$M'(p) = \begin{cases} M(p) - W(p,t) & \forall \quad p \in \bullet t \setminus t\bullet \\ M(p) + W(t,p) & \forall \quad p \in t\bullet \setminus \bullet t \\ M(p) - W(p,t) + W(t,p) & \forall \quad p \in t\bullet \cap \bullet t \\ M(p) & \textit{sicer / else.} \end{cases} \tag{5}$$

Izvajanje omogočenega prehoda $t$ poteka tako, da se vzame $w(p,t)$ žetonov iz vsakega vhodnega mesta $p$ prehoda $t$, in da $w(t,p)$ žetonov vsakemu izhodnemu mestu $p$ prehoda $t$.

Prehodi, ki imajo določen čas trajanja ($z(t) > 0$), se izvedejo v dveh korakih: najprej se izvedejo delno nato pa še do konca. Delno izvajanje prehoda $t_i$:

The firing of an enabled transition removes $w(p,t)$ tokens from each input place $p$ of transition $t$, and adds $w(t,p)$ tokens to each output place $p$ of transition $t$.

Nonzero-time transitions ($z(t) > 0$) fire in two steps: first they fire partially and then they fire to the end. Partial firing of transition $t_i$

$$M'(p) = \begin{cases} M(p) - W(p,t_i) & \forall \quad p \in \bullet t_i \\ M(p) & \textit{sicer / else.} \end{cases} \tag{6}$$

$$T^{*\prime} = T^{*} \cup \{(t_i, z_i)\} \tag{7}$$

pomeni jemanje *w(p,t)* žetonov iz vhodnih mest prehoda $t_i$ in dodajanje novega elementa $(t_i, z_i)$ v $T^-$, kjer je $T^-$ množica delno izvedenih prehodov $\{(t_1, d_1)(t_2, d_2)....(t_n, d_n)\}$ z elementi $(t_k, d_k)$, $t_k \in T$ in $d_k \in \{1,2,3...\}$, kjer je $t_k$ delno izveden prehod in $d_k$ njen preostali čas do izvajanja do konca.

Izvajanje do konca prehoda $t_k$ se zgodi, ko je preostali čas nič ($d_k$=0) in če je za $t_k$ izpolnjen pogoj (2). Dejansko se izvedejo do konca prehodi z najmanjšim preostalim časom:

means removing the *w(p,t)* tokens from the input places of transition $t_i$ and adding one new element $(t_i, z_i)$ to the $T^-$, where $T^-$ is a set of partial firing transitions $\{(t_1, d_1)(t_2, d_2)....(t_n, d_n)\}$ with elements $(t_k, d_k)$, $t_k \in T$ and $d_k \in \{1,2,3...\}$, where $t_k$ are partially fired transitions and $d_k$ are their remaining times to end firing.

Firing to the end of transition $t_k$ happens when the remaining time $d_k$=0 and when for $t_k$ the condition (2) is fulfilled. Practically fires to the end of the transition with smallest remaining time:

$$\forall\ (t,d) \in T^- \mid t_k \neq t : d_k \leq d \tag{8}$$

Izvajanje do konca za to omogočenega (2) prehoda $t_i$ pri $M$:

Firing to the end of for the end firing enabled (2) transition $t_i$ under $M$:

$$M'(p) = \begin{cases} M(p) + W(t_i, p) & \forall \quad p \in t_i \bullet \\ M(p) & sicer\ /\ \ else. \end{cases} \tag{9}$$

kjer je:

where

$$t_i = t_k \mid (t_k, d_k) \in T^- \tag{10}$$

$$T^{-\prime} = T^- \backslash \{(t_k, d_k)\} \tag{11}$$

$$(t,d)' = (t,\ d - d_k) \text{ za/for } \forall\ (t,d) \in T^{-\prime} \tag{12}$$

kjer velja za $t$ da $\forall\ p \in \bullet t$: $M(p) < |W(p,t)|$ če je $W(p,t) < 0$

Izvajanje do konca prehoda $t_i$ pomeni dodajanje $w(t_i,p)$ žetonov vsakemu izhodnemu mestu $p$ prehoda $t_i$ (9), odvzem elementa $(t_k, d_k)$ iz $T^-$ (11) in odštevanje $d_k$ od $d$ vsem elementom v $T^-$, za katere je izpolnjen pogoj (12). Pogoj (12) pravi, če določen prehod $t$ ni omogočen glede na drugo vrstico pogoja (2), potem se preostali čas $d$ delno izvedenega prehoda $t$ ne more zmanjšati za čas $d_k$.

Petrijeve mreže so razširjene s objekti kot posebne vrste žetoni ter s atributivnimi in objektnimi mesti takole:

where for $t$ it holds that $\forall\ p \in \bullet t$: $M(p) < |W(p,t)|$ falls $W(p,t) < 0$

Firing to the end of transition $t_i$ means adding $w(t_i,p)$ tokens to each output place $p$ of transition $t_i$ (9), taking an element $(t_k, d_k)$ from $T^-$ (11) and subtracting $d_k$ from $d$ of all elements in $T^-$, which $t$ fulfils conditions (12). The condition (12) says that if a transition $t$ is not enabled by the second line of condition (2) then the remaining time $d$ of the partially firing transition $t$ cannot be decreased for the smallest remaining time $d_k$.

Petri nets are also extended with objects as a special type of tokens and attributive and object places in the following way:

$A = \{a_1, a_2, ...a_n\}$ je množica atributov,
$O = \{o_1, o_2, ...o_n\}$ je množica objektov,
$E{:}O \rightarrow A^n$ vsakemu objektu opredeljuje lastnosti,
$P_a \subseteq P$ je podmnožica atributivnih mest,
$P_o \subseteq P$ je podmnožica objektnih mest,
$P_a \cap P_o = \varnothing$
$O_s : O \rightarrow P_p \cup T$ vsakemu objektu opredeljuje natančno eno objektno mesto oziroma prehod,
$L{:}P_p \rightarrow N^{12}$ vsakemu objektnemu mestu opredeljuje položaj,
$E_a{:}S_a \rightarrow A$ vsakemu atributivnemu mestu opredeljuje atribut.

$A = \{a_1, a_2, ...a_n\}$ ...set of attributes.
$O = \{o_1, o_2, ...o_n\}$ ...set of objects
$E{:}O \rightarrow A^n$ defines a characteristic for each object
$P_a \subseteq P$ ...subset of attribute places
$P_o \subseteq P$ ... subset of object places
$P_a \cap P_o = \varnothing$
$O_s : O \rightarrow P_p \cup T$ define for each object one object place or transition
$L{:}\ P_p \rightarrow N^{12}$ define a position for each object place
$E_a{:}\ S_a \rightarrow A$ define an attribute on an attributive place

Prehod ima lahko največ eno objektno vhodno mesto in eno objektno izhodno mesto:

A transition may have a maximum of one object place as an input and one as an output place:

$$\forall\ t \in T\!:\ t\bullet \cap P_l = \{\varnothing\} \vee \{p\}\ \wedge \bullet t \cap P_l = \{\varnothing\} \vee \{p\} \tag{13}$$

Prehod z vhodnim ali izhodnim objektnim mestom je omogočen po definicijah (2), (3) in če velja:

A transition with object places is enabled by the definition (2), (3) and when:

$$\forall\, p \in t\bullet \cap P_a \wedge \exists i \in \{1,2,...n\}: E_a(p) = \mathrm{pr_i}(t) \qquad (14),$$

kjer

where

$$\mathrm{pr_i}: A^n \rightarrow A;\ (a_1, a_2, ..., a_n) \rightarrow a_i$$

Pogoj (14) pomeni, da ima posamezen objekt vse atribute, ki jih imajo vhodna atributivna mesta prehoda $t$.

Prehod, ki je omogočen, se izvede ter spremeni $M$ v $M'$ po definicijah (5) ali (6) in (9), pri čemer se spremenijo tudi atributi objekta $e_i$:

Condition (14) means that a particular object has, all by the attributive places of transition $t$, determined attributes.

The transition, which is enabled to fire under $M$ to $M'$ as in definitions (5) or (6) and (9), changes the attributes $e_i$ of the object:

$$\forall\, p \in \bullet t \cup Pa:\ E'(p) = E(p) \cup Ea(p) \qquad (15)$$

$$\forall\, p \in t\bullet \cup Pa:\ E'(p) = E(p) \setminus Ea(p) \qquad (16).$$

Dinamično obnašanje Petrijevih mrež – se pravi izvajanje prehodov – se lahko napiše tudi z enačbami v algebraični obliki. Jedro te metode je incidenčna matrika, ki je ustrezna standardni obliki predstavitve in omogoča, da se definicije izrazijo v vektorski in matrični obliki. Incidenčna matrika $C = [c_{ij}]$ je matrika velikosti $n \times m$ z elementi:

The dynamic behaviour of Petri nets – i.e. the firing of transitions – can also be described by some algebraic equations. The core of its method is an incidence matrix, which is equivalent to the standard representation form and allows the definition to be recast in vector and matrix terms. The incidence matrix $C = [c_{ij}]$ is an $n \times m$ matrix of integers given by:

$$c_{ij} = c_{ij}^{+} - c_{ij}^{-} \qquad (17),$$

kjer sta $c_{ij}$ teža povezave $w(t_i, p_j)$ prehoda $t_i$ z mestom $p_j$ in $c_{ij}^-$ teža povezave $w(p_j, t_i)$ mesta $p_j$ s prehodom $t_i$. Incidenčna matrika C se lahko zapiše tudi kot seštevek dveh matrik:

where $c_{ij}$ is the weight of the arc $w(t_i, p_j)$ from the transition $t_i$ to the output place $p_j$ and $c_{ij}^-$ is the weight of the arc $w(p_j, t_i)$ from the input place $p_j$ to the transition $t_i$. In the same way the incidence matrix C can be written as:

$$C = C^{+} - C^{-}, \qquad (18),$$

kjer sta $C^+$ matrika vseh vhodnih mest v prehode in $C^-$ matrika vseh izhodnih mest iz prehodov.

Izvajanje omogočenega prehoda $t_i$ se lahko napiše sedaj v matrični obliki:

where $C^+$ is the matrix of all the input arcs from places to transitions and $C^-$ is a matrix of all the output arcs from transitions to places.

The firing of the enabled transition $t_i$ can be written in a matrix equation as:

$$M' = M + C^{+\mathrm{T}}\, u(t_i) - C^{-\mathrm{T}}\, u(t_i) = M + C^{\mathrm{T}}\, u(t_i) \qquad (19),$$

kjer je $u(t_i)$ vektor z vsemi elementi 0, razen na i-tem mestu, kjer je 1.

Vseeno pa je v večini primerov matrična enačba uporabna samo za posebne podskupine Petrijevih mrež oziroma za posebne primere, saj je analitično reševanje enačb omejeno z nedoločenostjo, ki je lastna modelom Petrijevih mrež, in delno tudi s tem, da morajo biti rešitve ne negativna cela števila. Tako je za zapletene sisteme, ki se jih da popisati s hkratnimi, diskretnimi dogodki in ki jih je moč modelirati z RPM, tehnika simuliranja še vedno edina možnost, da se dobijo stvarne rezultate v primernem času.

where $u(t_i)$ means a vector with all the elements equal to 0, except on i-th place, which is equal to1.

However, in many cases the matrix equation is applicable only to special subclasses of Petri nets, or special situations, because the solvability of the equations is somehow limited by the nondeterministic nature inherent in the Petri-net model and partly because the solutions have to be found as non-negative integers. So, for the complex concurrent discrete event-driven systems, which can be modelled by the EPN class of Petri nets, a simulation technique is still considered as the only prospect for obtaing objective results in a reasonable time.

## 2.2 Izvedba

Izdelana teorija razširjenih Petrijevih mrež je bila jedro za razvoj simulacijskega paketa LASIMCO. Sestavljata ga programa PN_EDIT in PN_EXE, ki sta napisana v programskem jeziku AutoLISP in ArXDS, ter sta integrirana v program za konstruiranje AutoCAD 14.

Program PN_EDIT uporablja grafični in tekstovni vmesnik programa AutoCAD za vnos na RPM utemeljenega modela. Mesta in prehodi (v obliki blokov programa AutoCAD) se lahko postavijo na ustrezna mesta v prostoru tridimenzijskega modela in se povežejo s črtami. Določeni parametri modela RPM, na primer kapacitete, prioritete, časi, atributi, žetoni in druge, se vnesejo za posamezen element RPM prek vhodnih oblik in se dodajo ustreznemu bloku oziroma črti. Razdalja med objektnimi mesti se izračuna avtomatsko iz njihovih položajev. Tudi objekti, kot posebna oblika žetonov, so bloki in se lahko vstavijo v ustrezna objektna mesta.

Tako se izdela model RPM z vsemi parametri, ki so potrebni za simulacijo, in se shrani v isto datoteko kakor trodimenzijski model, se pravi v datoteko DWG programa AutoCAD. Tako shranjen model in parametri se lahko kadarkoli spreminjajo – tudi med izvajanjem simulacije.

Simulacija se izvaja s simulacijskim programom PN_EXE, utemeljenem kot simulator diskretnih dogodkov. Le ta simulira na RPM temelječ model opazovanega sistema tako, da izvaja omogočene prehode. Tako imenovani izvajalni algoritem (sl. 2) se odvija v dveh zankah:

– V notranji zanki, kjer se aktivirajo vsi omogočeni prehodi s časom nič, tisti z različnim časom od nič pa se izvedejo le delno. To poteka toliko časa, dokler niso izvedeni vsi omogočeni prehodi.
– V zunanji zanki, kjer se vsi delno izvedeni prehodi z najmanjšim preostalim časom izvedejo do konca. Za ta čas se poveča tudi čas simulacije. Simulacija se nadaljuje v notranji zanki toliko časa, dokler ni več omogočenih in delno izvedenih prehodov, ali pa simulacijski čas doseže končni čas.

Simulacija se lahko izvaja po korakih ali pa zvezno ter z animacijo in brez nje. Simulacija lahko teče v seriji ali pa tolikokrat, da je rezultat simulacije v 95-odstotni meji zaupanja. Za izbrana mesta in prehode se med simulacijo izračunava statistika, rezultati pa se lahko shranijo tudi v datoteko za nadaljnje statistične obdelave.

## 3 PRIMER

Simulacijski paket LASIMCO je bil uporabljen pri načrtovanju proge za preoblikovanje pločevine ([10] do [12]). Proga sestoji iz treh preoblikovalnih strojev in strežnega sistema. Za strego sta bila predlagana dva sistema: prvi s štirimi manipulatorji

## 2.2 Implementation

The elaborated theory of the extended Petri net was a core for the development of the LASIMCO simulation package. It consists of the PN_EDIT and PN_EXE programs, which are written in AutoLISP and ArXDS and integrated into a CAD system, AutoCAD 14.

The PN_EDIT program uses a graphical and textual interface of the AutoCAD system for the input of an EPN-based model. The places and transitions (in the form of AutoCAD blocks) can be put in the desired positions in a 3D model space and connected by poly-lines. Some parameters of the EPN model, such as capacity, priority, time, attributes, number of tokens and others can be added to a particular EPN element through input forms and attached to an appropriate block or poly-line. The length between the object places is calculated automatically from their positions. The objects (a special type of token) are also blocks and can be inserted into the appropriate object places.

In this way, an EPN model with all the parameters needed for a simulation is stored in the same file as the 3D model, i.e. in an AutoCAD drawing file. The model or the parameters can be changed any time before, or even during, the simulation.

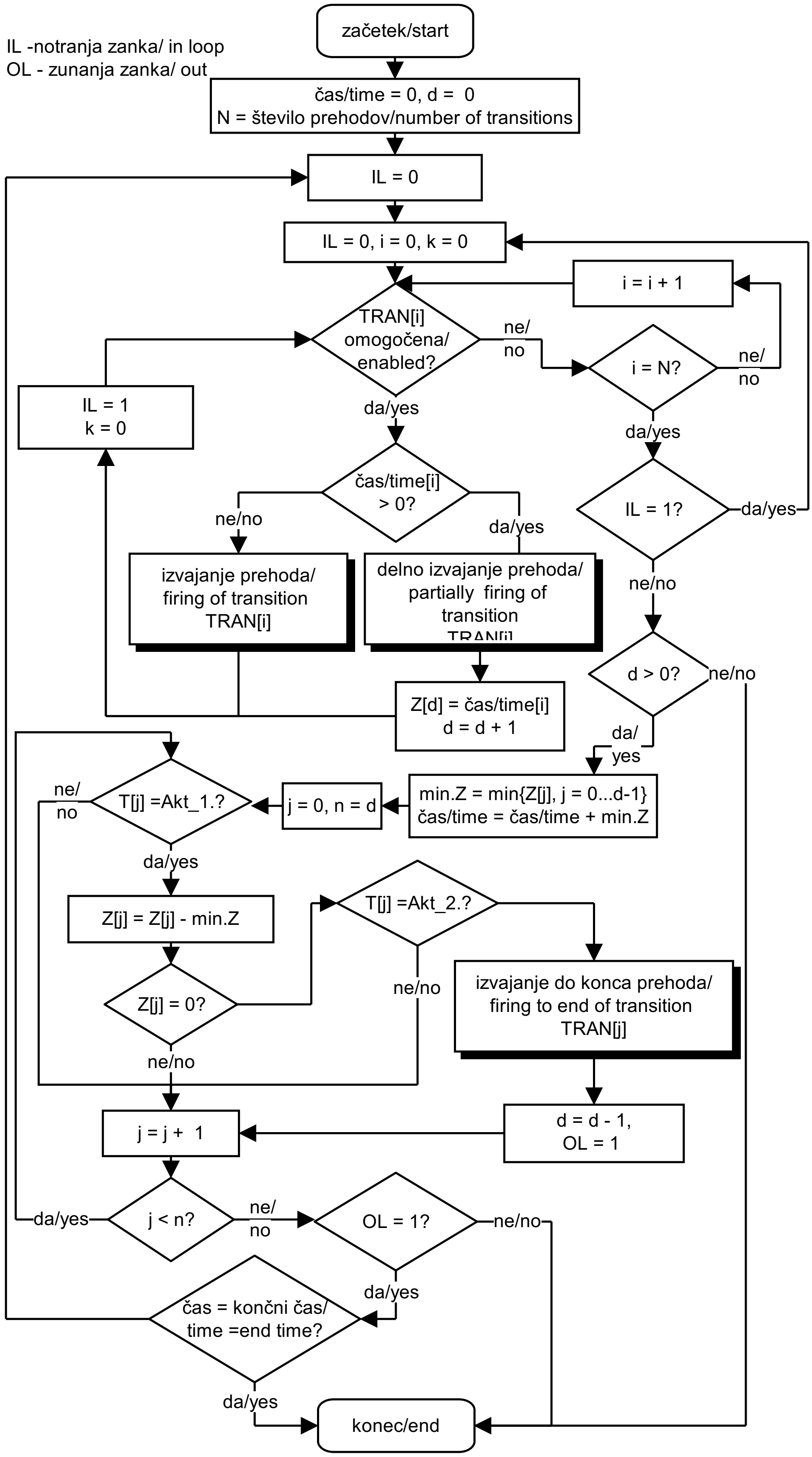
The simulation is executed by the PN_EXE simulation program. It is a discrete event-based simulator that executes the EPN-based model of the analysed system by firing the enabled transitions. The so-called playing algorithm (Fig. 2) is applied in two loops:

– The inner loop, where all the enabled transitions with zero time fire, and those with non-zero time fire only partially, until there are no more enabled transitions.
– The outer loop, where all the partially fired transitions with the least remaining time fire to the end. The simulation time increases by that time. The simulation proceeds with the inner loop, until there are no more enabled and partially fired transitions, or the simulation time reaches the end time.

The simulation can be executed in steps, or smoothly, with or without animation. The simulation can run in batches or as many times as is necessary for the result to pass the 95% confidence test. For the selected places and transitions, the statistics are calculated during the simulation and the results are stored in a file for further statistical processing.

## 3 EXAMPLE

The LASIMCO simulation package was used for planning a sheet-iron forming line. The line consists of three forming machines and a handling system. There were two alternatives proposed for the handling system: the first one with four




Sl. 2. *Izvajalni algoritem za simuliranje modela razširjenih Petrijevih mrež [1]*
Fig. 2. *The playing algorithm for the execution of the extended Petri net model [1]*

(sl. 4 a) in drugi s šestimi manipulatorji in dvema tekočima trakovoma (sl. 4 b). Prednost drugega sistema je v tem, da lahko stroji za preoblikovanje delujejo tudi samostojno, vendar pa je investicija nekoliko večja. Predpostavljeno je bilo, da bo z drugim sistemom proizvodnja večja, ker naj bi bili časi manipulacije krajši, in s tem naj bi se investicija tudi poplačala.

Nadalje je bila pozornost usmerjena tudi na vpliv napak na zastoje in s tem učinkovitost proge. Napake so bile razvrščene na tiste, ki se pojavijo na strojih med preoblikovanjem in napake, ki nastanejo pri stregi. Na tej stopnji načrtovanja so bili analizirani in upoštevani v modelu samo tisti zastoji, ki se pojavijo dovolj pogosto in so posledica napak v procesu preoblikovanja. To je bilo generirano tudi zato, da se prikaže zmožnost modeliranja z RPM.

LASIMCO je bil uporabljen za modeliranje in simulacijo obeh alternativ oziroma za ugotavljanje njihove dejanske zmogljivosti. Dodatno je bila generirana tudi 3D animacija proge, ki se razvija, predvsem za namene načrtovanja in tudi kot obvezno predstavitveno možnost za prikaz rešitve naročniku.

### 3.1 Modeliranje

Programa AutoCAD in PN_EDIT sta bila uporabljena za modeliranje, ki je bilo izvedeno v treh korakih[13]. Najprej so bili z ukazi za izdelavo trdnih teles programa AutoCAD izdelani 3D modeli materiala in vseh sredstev (stroji, manipulatorji, prijemala, tekoči trak). Vsi gibajoči se deli sredstev so bili modelirani kot objekti v modelu, deli sredstev, ki so stalno na istem mestu, pa so bili postavljeni v prostor tako, da so tvorili prostorsko ogrodje modela.

Modeliranje z RPM je bilo izvedeno v drugem koraku. Objektna mesta in časovni prehodi so bili vstavljeni v 3D prostor na svoja mesta in povezani med seboj tako, da so bili s tem modelirani posamezni gibi in transformacije objektov, ki dejansko pomenijo strežne in preoblikovalne procese. Z vstavitvijo normalnih mest in prehodov ter s pravilno izvedeno povezavo med njimi je bilo modelirano tudi zaporedje gibov in procesov. Potrebni podatki o časih, hitrostih, prioritetah, atributih ali pogojih so bili dodeljeni vsakemu posameznemu prehodu, mestu oziroma povezavi, s čimer je bilo modeliranje končano (sl. 3).

Tretji korak je bil identifikacija modela. Žetoni in objekti (objektni žetoni) z opredeljenimi atributi so bili vstavljeni v normalna ali atributivna mesta oziroma objektna mesta. S tem je bila izdelana tudi prostorska predstavitev (3D) modela (sl. 4 a in b).

Model preoblikovalne proge s štirimi manipulatorji (alternativa A1) je obsegal 241 mest, 163 prehodov, 583 povezav in 40 objektov, proga s

manipulators (Figure 6) and the second one with six manipulators and two conveyors (Figure 7). The advantage of the second one is that machines can also work on a stand-alone setting, but the required investment is greater. It was also assumed that production could be increased because of the possible shorter handling times, which would help repay the investment.

The next consideration was the impact of possible failures on production. Failures were classified as those occurring in machines during the forming processes and those caused by the handling system. Only failures which occur frequently and are caused by the forming processes have been investigated and were considered in the model at this stage. This was done largely to demonstrate the modelling ability of the EPN.

The LASIMCO was used for the modelling and the simulation of alternatives, and so gathering data on their actual capacity. In addition, the 3D animation of the developed line should be prepared for planning purposes and as an inevitable presentation possibility of the alternative developed for customers.

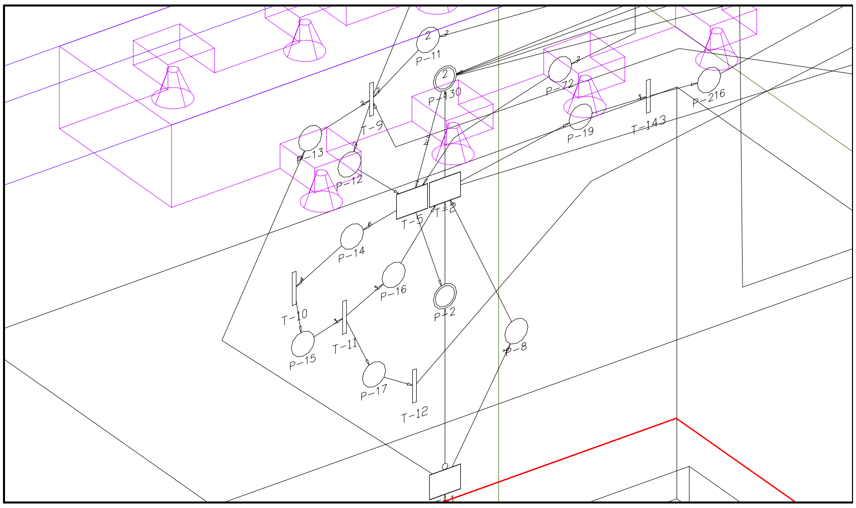
### 3.1 Modelling

The AutoCAD and PN_EDIT programs were used for modelling, which was accomplished in three steps. In the first step, 3D models of all resources (machines, manipulators, grippers, conveyors) and all materials were generated using AutoCAD solids. All the moving parts of the resources were modelled separately as objects in the model. The unmoving objects were placed into the space to build the 3D frame of the model.

Modelling with the EPN was carried out in the second step. The object places and time transitions were inserted into the 3D space in their positions and connected in such a manner that the particular movements and transformations of the objects representing the handling and forming processes could be modelled. With the insertion of the normal places and transitions and the making of appropriate connections, the sequence of the movements and processes was added to the model. Data such as time, velocity, priority, attribute and condition were assigned to each individual transition, place or connection, and the model was thus completed (Fig. 3).

The third step was the initialisation of the model. The tokens and objects (object tokens) with defined attributes were put into the normal or attributive places and the object places, respectively. The 3D representation of the model was thus completed as well (Fig. 4a and b)

The model of the line with four manipulators (alternative A1) contains 241 places, 163 transitions, 583 connections and 40 objects and the one with six




Sl. 3. *Del modela RPM*
Fig. 3. *A part of the EPN model*

šestimi mainpulatorji in dvema tekočima trakovoma (alternativa A2) pa 267 mest, 179 prehodov, 643 povezav in 44 objektov. Oba modela sta dokaj velika za sistema, ki nista tako zelo zapletena, toda to je posledica upoštevanja dobesedno vseh gibov in medsebojnih odnosov elementov sistema.

manipulators and two conveyors (alternative A2) has 267 places, 179 transitions, 643 connections and 44 objects. These two models are quite large for systems of lower complexity, but this is because every each movement and interrelation between the elements of the system was considered.

### 3.2 Simulacija

Za eksperimentiranje z modelom je bil uporabljen program PN_EXE. Obe alternativi sta bili simulirani pri dveh pogojih preoblikovanja: (I) z normalno hitrostjo preoblikovanja in 0,25 odstotnim izmetom ter (II) z 20-odstotno povečano hitrostjo preoblikovanja in izmetom 0,5 odstotka.

Ker ima vsak časovni prehod, s katerimi so popisani različni gibi in procesi, svojo nastavitev hitrosti oziroma trajanja, so za pojasnitev rezultatov prikazane samo njihove povprečne vrednosti. Tako je srednja hitrost manipulatorjev in tekočih trakov 0,6 m/s in normalno trajanje preoblikovalnih procesov prvega, drugega in tretjega stroja 12,6, 12,2 oziroma 6 s.

Pri izvajanju simulacije je bil upoštevan tudi čas “ogrevanja”, vsak preizkus pa se je ponavljal toliko časa, da so bili rezultati v 95 odstotnem območju zaupanja. Rezultati so prikazani v preglednici 1.

### 3.2 Simulation

The PN_EXE program was used for experimentation with the model. Two alternatives of the system were simulated, with two different forming conditions: (I) with a normal forming velocity and 0.25% low-quality products, and (II) with velocity increased by 20% resulting in an increase in the amount of low-quality products to 0.5%.

Since each time transition that models different movements and processes has its own settings for velocity and duration, only the mean values are reported here for an illustration of the simulation results. The mean velocity of the manipulators and the conveyor is 0.6 m/s, and the normal durations of the forming process for the first, second and third machines are 12.6, 12.2 and 6 s, respectively.

The warm-up period was considered as well, and each experiment was run until the result was within the 95% confidence interval. The results are shown in Table 1.

Preglednica 1. *Takt preoblikovalne proge (rezultati simulacije)*
Table 1. *Frequency of the forming line (results of simulation)*

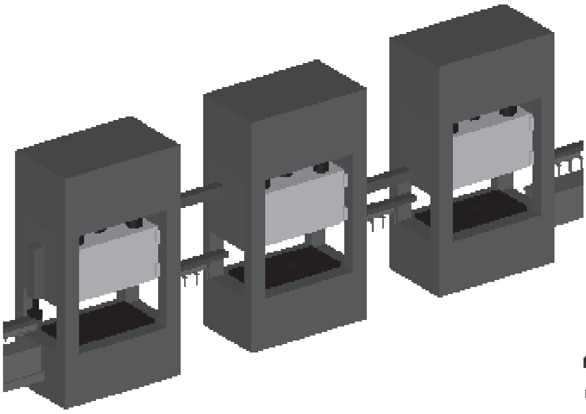
| | Model A1 | Model A2 |
|---|---|---|
| pogoj I / condition I | 40,0 s | 37,8 s |
| pogoj II / condition II | 38,5 s | 36,3 s |

### 3.3. Rezultati in komentarji

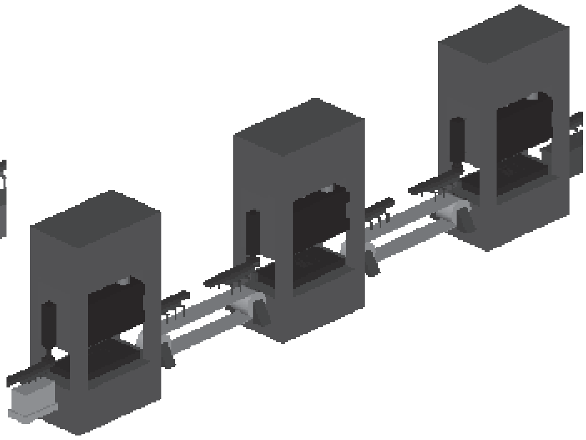
Ob upoštevanju rezultatov simulacije in stroškov komponent je bil izračunan strošek preoblikovanja za en izdelek, in je bil namenjen kot osnova za primerjavo obeh alternativ. Kalkulacija je pokazala, da je kljub 4-odstotnim večjim stroškom alternative A2 v primerjavi z A1, strošek izdelave na en izdelke manjši, saj je produktivnost alternative A2 večja od A1 za 5.8 %. Tako je alternativa A2 boljša rešitev od A1.

### 3.3 Results and comments

Taking into account the simulation results and the costs of the components, the costs of a single part were calculated in order to compare the different variants of the forming line. The calculation showed that although the investment for alternative A2 is 4% greater than that required for alternative A1, the costs of the finished product are lower because production is 5.8% greater. Therefore, alternative A2 is a better solution than A1.



a)



b)

Sl. 4. *Preoblikovalna proga s štirimi manipulatorji (a) in proga s šestimi manipulatorji ter dvema tekočima trakovoma (b)*

Fig. 4. *A forming line (a) with six manipulators and two conveyors and (b) with four manipulators*

Modeliranje je bilo časovno zelo zamudno opravilo in je zahtevalo od načrtovalca temeljito poznavanje modeliranja in simulacije z RPM. Da bo simulacijski paket bolj uporabniško prijazen, ga bo treba dograditi z avtomatsko izdelavo simulacijskega modela iz načrta prostorske postavitve preoblikovalne proge, kakor je to generirano za načrtovanje montažnih prog in sistemov s programom LASIMCO, kjer načrtovalec brez predznanja o modeliranju in simulaciji lahko izvaja eksperimente z modelom in tako dobi podatke o »dejanskih« lastnostih načrtovanega sistema na »navidezni« način že v fazi načrtovanja.

Zmogljivosti sistema AutoCAD niso dovolj za "stvarno" grafično predstavitev navidezne izdelave. Načrtovalec lahko opazuje med simulacijo samo animacijo žičnega grafičnega modela, ki pa je za načrtovanje zadostna. Stvarna prostorska animacija, ki je že nujno potrebna oblika predstavitve še zlasti v fazi razpisov in pridobivanja naročil, pa se lahko prikazuje samo po končani simulaciji.

The modelling was a very time-consuming task and it required a thorough knowledge from the planner of the modelling and the simulation with EPN. To make the simulation package more userfriendly, it will be extended with an automatic generation of the simulation model from the layout of the forming line in the same way as the LASIMCO planning of assembly systems was carried out [4], so that planners without any previous experience in simulations will be able to perform experiments with the simulation model and obtain the "real" properties of a planned system in a "virtual" way, already during the planning phase.

For a "realistic" graphical presentation of "virtual" manufacturing, the capabilities of AutoCAD systems are not sufficient. Planners can now observe, online, only the wire-frame graphic animation, which is reasonable enough for planning purposes. A realistic 3D animation can be generated offline and used as an indispensable presentation form, especially in the tender-preparation phase.

## 4 SKLEP

Razširitve Petrijevih mrež so bile razvite in že tudi uporabljene za načrtovanje montažnih sistemov ([4]

## 4 CONCLUSION

Extensions of Petri nets have been developed and used in the planning of assembly systems ([4]

in [11]). V prispevku je zgoščeno predstavljen koncept navidezne izdelave, izpeljane so razširitve Petrijevih mrež in prikazana je njihova uporaba. Na primeru je bilo pokazano, da se jih lahko splošno uporabi tudi pri načrtovanju izdelovalnih sistemov, kot na primer preoblikovalnih prog. Ta primer še enkrat demonstrira prednosti integracije modeliranja in simulacije v okolju računalniško podprtega načrtovanja [15]. Sistem je še daleč od želja in potreb načrtovanja, zato bo potrebno v smislu stalnega izpopolnjevanje še nadalje razvijati RPM v povezavi s prostorsko (3D) grafiko in simulacijo, tako da ga bo mogoče uporabiti tudi v drugih fazah življenjskega cikla izdelovalnih sistemov.

and [11]). This paper briefly describes the concept of "virtual" manufacturing, the derived extensions of PNs and the implementation of the EPN. It was shown in an example that they can also be used in planning other manufacturing systems, e.g. forming lines. This implementation shows once more the benefits of the integration of modelling and simulation into the CAD environment [12]. This is still far from the desired and required planning system, but in the sense of continuous improvement, EPN, together with 3D graphics and simulation, will need to be further developed in order to also provide support for other phases of the manufacturing system's life-cycle.

## 5 LITERATURA
## 5 REFERENCES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