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Kako zagotoviti konkurenčnost majhnega podjetja

How to Achieve a Competitive Position with a Small Company

Marko Starbek - Jože Duhovnik - Janez Grum - Janez Kušar

Osamosvojitev Slovenije v letu 1991 je za slovenska podjetja pomenila dramatično zmanjšanje domačega tržišča. Velika podjetja, ki se niso prilagodila na nove tržne razmere, so bila obsojena na propad. Ustanovljenih je bilo večje število manjših podjetij, ki so imela večjo možnost za prilagajanje novim tržnim razmeram. Pri vstopu na svetovni trg so se ta podjetja srečevala z različnimi problemi, največji problem pa so bili predolgi časi uvajanja izdelkov.

V prispevku je prikazano načelo istočasne izvedbe postopka uvajanja izdelkov. Ker trg sili majhna podjetja k prehodu iz zaporednega na istočasni inženiring in ker je temelj istočasnega inženiringa skupinsko delo, je posebna pozornost namenjena načrtovanju timov in delovnih skupin v zankah postopka istočasovnega uvajanja izdelkov v majhnih podjetjih.

Pregled objavljenih del s področja načrtovanja timov v velikih podjetjih ([1] in [2]) je pokazal, da se za velika podjetja priporoča tronivojska struktura timov in delovna skupina, sestavljena iz štirih osnovnih timov. Kritična ocena tronivojske strukture nas je pripeljala do sklepa, da predlagamo za majhna podjetja le dvonivojsko strukturo timov in delovno skupino, sestavljeno iz dveh osnovnih timov.

Prikazani so rezultati načrtovanja dvonivojske strukture timov in postopka izvedbe istočasovnega inženiringa v majhnem podjetju, ki izdeluje mini-nakladalnike.

(Ključne besede: inženiring simultani, zanke, delo skupinsko, timi projektni)

In 1991 the independence of Slovenia resulted in an enormous decrease in the domestic market for Slovenian companies. Big companies that did not adapt to the new conditions were destined to collapse. Several smaller companies were established, and they were more easily able to adapt to the new market conditions. When these companies entered the global market they encountered several difficulties, the most important of which was an excessively long time for product development.

This paper presents the principle of the concurrent product development process. The market forces small companies to switch from sequential to concurrent engineering, and as team work is the basic element of concurrent engineering, special attention has to be paid to forming workgroups in the loops of the concurrent product development process in small companies.

A survey of the published works in the field of planning teams in big companies ([1] and [2]) has revealed that in big companies a three-level team structure is recommended, as well as a workgroup consisting of four basic teams. An analysis of the three-level structure has led us to the conclusion that in small companies a two-level team structure and a workgroup consisting of two basic teams is to be preferred.

The results of planning a two-level team structure and the implementation of concurrent engineering in a small company that produces mini-loaders are presented.

(Keywords: concurrent engineering, loops, team work, project teams)

0 UVOD

Če analiziramo svetovni trg, lahko ugotovimo, da zahteve kupcev glede na funkcionalnost in kakovost izdelkov stalno naraščajo, hkrati pa se zmanjšuje pripravljenost kupcev, da bi za boljše izdelke plačali več in da bi

0 INTRODUCTION

An analysis of the global market has shown that customer requirements regarding the functionality and the quality of products are continuously increasing – but the customers are not willing to pay more for better products and neither do they accept dovolili podaljšanje rokov dobave izdelkov. Kupci postajajo čedalje bolj zahtevni in njihove zahteve se nenehno spreminjajo. Vse bolj se uveljavlja izrek »kupec je kralj« [3].

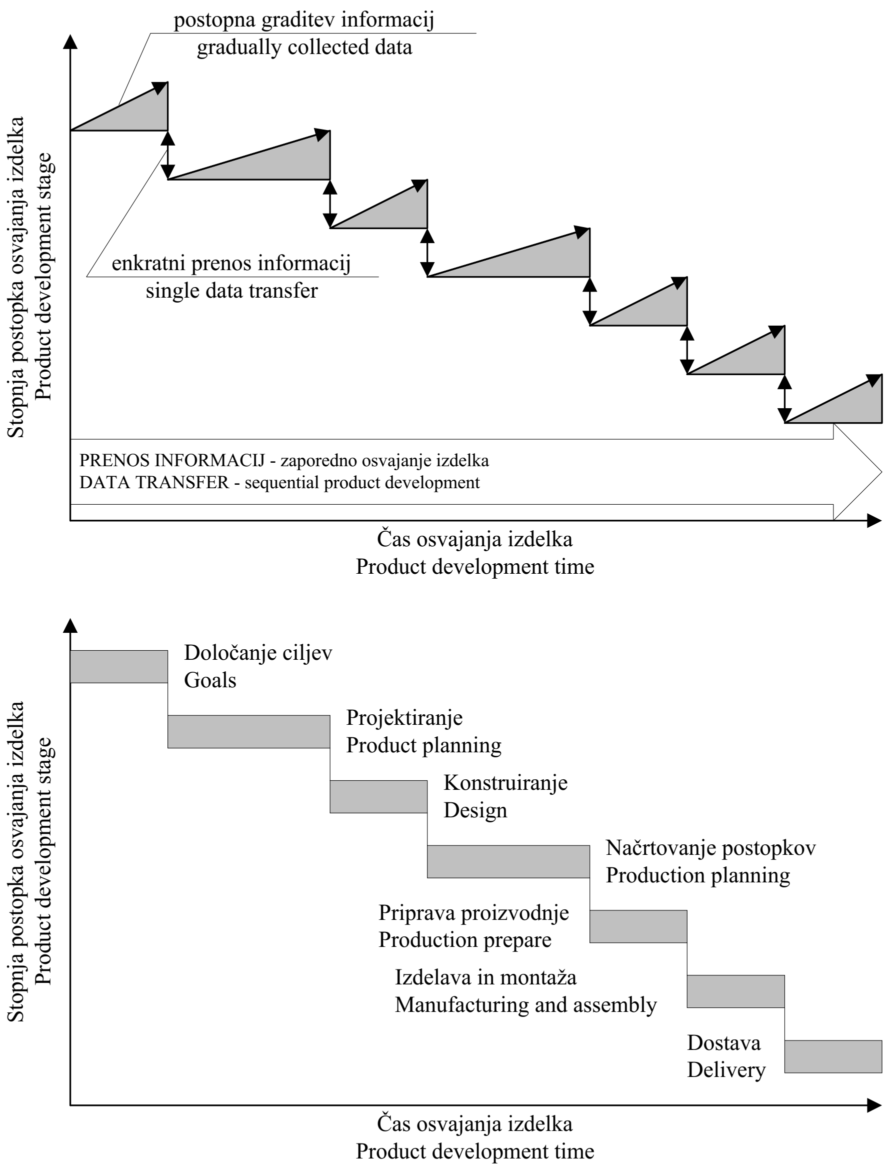
V tem položaju imajo možnost preživetja na trgu le tista podjetja, ki lahko ponudijo kupcem glede na zahtevano funkcionalnost in kakovost prave izdelke, ob pravem času, v pravi kakovosti in po pravi ceni.

Sodelavci *Labortorija za proizvodne sisteme* smo izvedli anketo, ki se je nanašala na problematiko neizpolnjevanja želja kupcev in predolgih časov uvajanja izdelkov, na katero je odgovorilo 23 majhnih podjetij z posamezno in maloserijsko proizvodnjo. Rezultati ankete so pokazali, da je v podjetjih zelo poudarjen problem neizpolnjevanja zahtev kupcev ter problem predolgih časov uvajanja izdelkov.

prolonged delivery terms. Customers are becoming more and more demanding and their requirements are changing all the time. “The customer is king” is becoming the motto of today [3].

In these circumstances only those companies that offer their customers the right products in terms of functionality and quality, and products that are produced at the right time, quality and price, can expect to succeed.

The members of the *Production Systems Laboratory* compiled a questionnaire about the unfulfilled wishes of customers and excessive product-development times. Responses were obtained from 23 small companies with individual and small-series production. The results of the questionnaire showed that these companies had definite problems with the unfulfilled requirements of customers and excessive product-development times.



Sl. 1. *Zaporedno uvajanje izdelka*
Fig. 1. *Sequential product development*

Izkazalo se je, da imajo v vseh podjetjih organizirano zaporedno uvajanje izdelkov, kar je vzrok dolgih, za trg nesprejemljivih časov uvajanja izdelkov.

Z rezultati ankete smo seznanili vsa v anketi sodelujoča podjetja in jih skušali zainteresirati za sodelovanje pri projektu postopnega prehoda iz zaporednega na istočasovno uvajanje izdelkov.

Od anketiranih podjetij se je za takojšnje sodelovanje pri projektu odločilo podjetje, ki je izdelovalec majhnih serij mini nakladalnikov, s katerimi se pojavlja na domačem in tujem trgu.

It became evident that all the companies were using a sequential product development process,which caused excessive and unacceptable times for product development.

The results of the questionnaire analysis were sent to all the participating companies and we tried to arouse their interest in cooperating in a project involving the gradual transition from the sequential to the concurrent development of products.

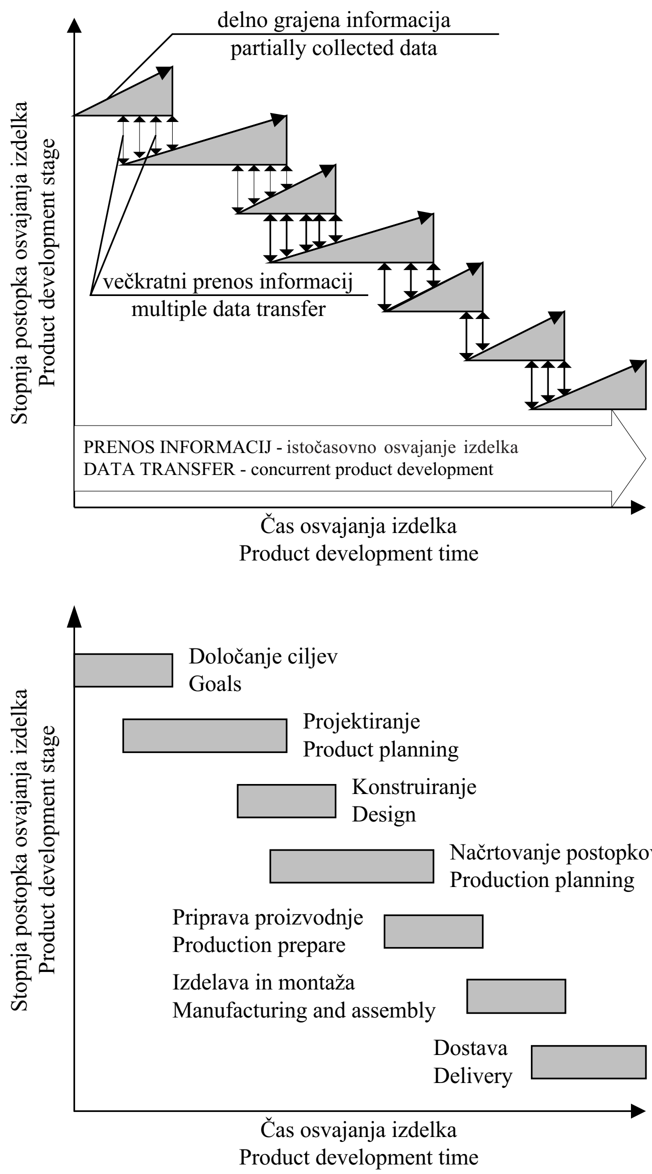
Of all the companies, a company that produces mini-loaders in small series for domestic and international markets immediately decided to participate in the project.

1 ZAPOREDNI IN ISTOČASOVNI INŽENIRING

1 SEQUENTIAL AND CONCURRENT ENGINEERING

Zaporedni inženiring karakterizira zaporedno izvajanje stopenj postopka uvajanja izdelka. Opazovana stopnja postopka se lahko prične, ko je

The main feature of sequential engineering is the sequential implementation of stages in the product development process. The treated process stage can



Sl. 2. *Istočasovno uvajanje izdelka*
Fig. 2. *Concurrent product development*

predhodna stopnja v celoti končana. Informacije o opazovani stopnji postopka se postopno gradijo in so ob koncu stopnje popolnoma zgrajene ter posredovane naslednji stopnji.

Slika 1 prikazuje načelo zaporednega uvajanja izdelka [1].

V nasprotju z zaporednim inženiringom pa istočasovni inženiring karakterizira vzporedno izvajanje stopenj postopka uvajanja izdelka. Tu se opazovana stopnja postopka lahko prične že pred končanjem njej predhodne stopnje.

Informacije o opazovani stopnji postopka se postopno gradijo in se že med gradnjo posredujejo naslednji stopnji. Serija medsebojnih prenosov informacij med opazovano in naslednjo stopnjo postopka se konča v trenutku, ko je graditev informacij opazovane stopnje končana.

Slika 2 prikazuje načelo istočasovnega uvajanja izdelka [1].

Pri istočasnem uvajanju izdelka obstajajo interakcije med posameznimi stopnjami postopka uvajanja izdelka in za izvedbo vplivov je bila razvita stezno zankasta tehnologija [1]. S tipom zanke je popisan tip sodelovanja med prekrivajočimi se stopnjami postopkov. Winner [4] predlaga uporabo 3-T zank, kjer obstaja medsebojni vpliv med tremi stopnjami postopka uvajanja izdelka.

V primeru uporabe 3-T zank (slika 3) se postopek uvajanja izdelka sestoji iz pet 3-T zank.

V vsaki zanki se na podlagi zahtev in omejitev izvede sprememba vstopkov v iztopke [2], kar prikazuje diagram toka informacij v stezno-zankastem postopku uvajanja izdelka (sl. 4).

Analiza na sliki 3 in 4 prikazanega stezno-zankastega postopka uvajanja izdelkov kaže, da istočasovnega inženiringa ni brez dobro organiziranega timskega dela.

begin after the preceding stage has been completed. Data on the treated process stage are collected gradually and they are completed when the stage is finished. After which the data are forwarded to the next stage.

Figure 1 presents the principle of sequential product development [1].

The main feature of concurrent engineering is the concurrent implementation of stages in the product development process. In this case the treated stage can begin before its preceding stage has been completed.

Data on the treated process stage are collected gradually and forwarded continuously to the next stage. The series of data exchange between the treated process stage and the next process stage ends when the data on the treated stage has been completed.

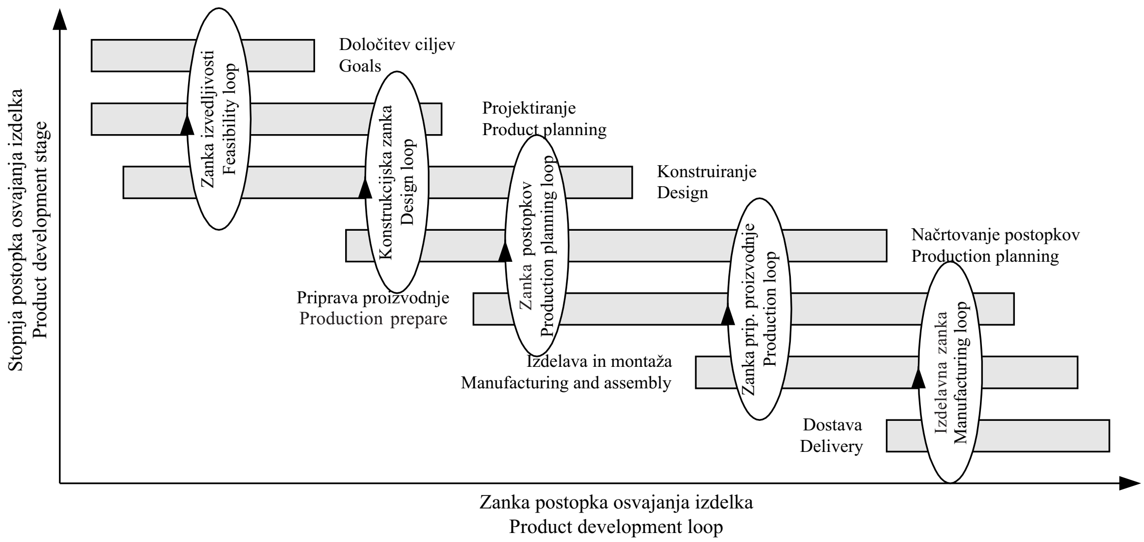
Figure 2 presents the principle of concurrent product development [1].

In concurrent product development there are interactions between the individual steps of the product-development process. Track-and-loop technology was developed for the implementation of interactions [1]. The type of loop defines the type of cooperation between overlapping process steps. Winner [4] proposes the use of 3-T loops, where interactions exist between three levels of the product-development process.

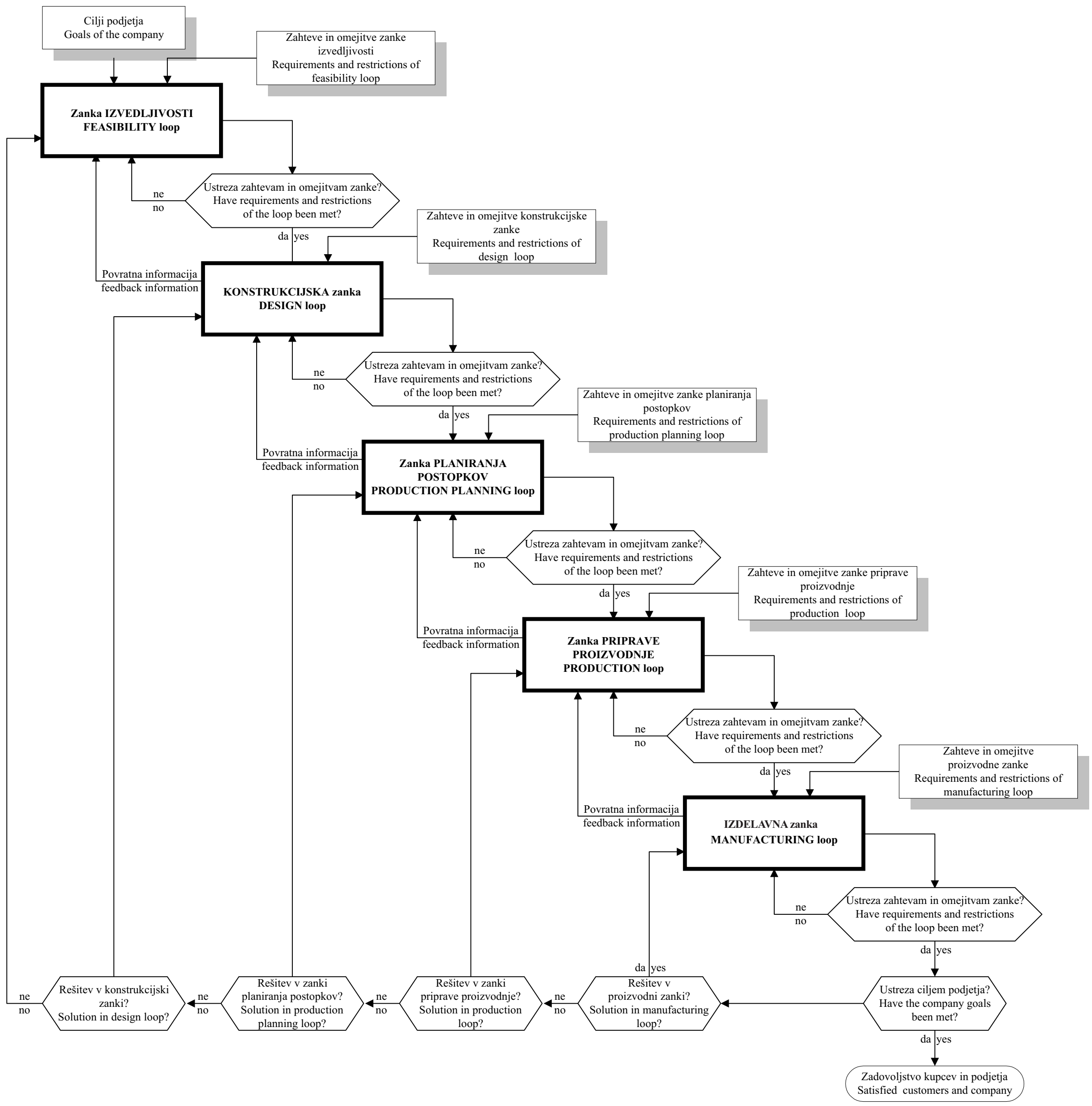
When 3-T loops are used (Figure 3) the product-development process consists of five 3-T loops.

On the basis of the requirements and the restrictions, the input is transformed into the output [2] in each loop, as shown in the diagram of information flow in the track-and-loop process of the product development (Fig. 4).

Analysis of the track-and-loop process of product development, as shown in Figures 3 and 4, reveals that concurrent engineering is not possible without well-organised team work.



Sl. 3. *Stezno-zankasti postopek uvajanja izdelka*
Fig. 3. *Track-and-loop process in product development*



Sl. 4. *Diagram toka informacij v stezno zankastem postopku uvajanja izdelka*
Fig. 4. *Diagram of information flow in the track-and-loop process of product development*

2 ISTOČASOVNI INŽENIRING IN TIMSKO DELO

O timskem delu oziroma timu govorimo takrat, ko je skupina ciljno usmerjena za reševanje skupne naloge [5].

Za timsko delo je potrebno [1]:
- sodelovanje, ki mora biti prilagodljivo, nenačrtovano in stalno,
- občutek obveze za dosego ciljev,
- komuniciranje, ki pomeni izmenjavo informacij,
- sposobnost sklepanja kompromisov,
- soglasnost kljub nestrinjanju,
- usklajevanje pri izvajanju medsebojno odvisnih dejavnosti,
- stalno izboljševanje z namenom večje produktivnosti in krajših časov.

2 CONCURRENT ENGINEERING AND TEAM WORK

Team work refers to a situation when a team is oriented towards the solution of a joint task [5].

The requirements for team work are [1]:
- a flexible, unplanned and continuous cooperation,
- a feeling of obligation regarding the achievement of goals,
- communication in the form of exchange of information,
- an ability to make compromises,
- a consensus in spite of disagreement,
- reconciliation when carrying out interdependent activities,
- continuous improvements in order to increase productivity and reduce process times.

2.1. Oblikovanje sestave timov v velikih podjetjih

Istočasovni inženiring sloni na večdisciplinarnem timu za uvajanje izdelka (TUI - PDT) ([6] in [7]), ki mora vključevati tako strokovnjake različnih služb podjetja, kakor tudi predstavnike strateških dobaviteljev in kupcev.

Člani tima za uvajanje izdelka so komunikacijsko povezani prek osrednjega informacijskega sistema (OIS - CIS), ki jim zagotavlja podatke o postopkih, orodjih, infrastrukturi, tehnologiji in znanih izdelkih podjetja. Predstavniki strateških dobaviteljev in kupcev zaradi oddaljenosti podjetja v timu sodelujejo le navidezno in to s uporabo medmrežne tehnologije (MT - IIS), ki jim omogoča uporabo istih orodij in tehnologij, kakršne uporabljajo člani tima podjetja [7].

Sestava tima za uvajanje izdelka v velikih podjetjih se skozi stopnje postopka uvajanja izdelka spreminja. Tim v določeni fazi uvajanja izdelka sestavljajo vsebinsko zaokrožene delovne skupine, vsaka delovna skupina tima je zgrajena iz štirih osnovnih timov [1], in to:

- logičnega tima, ki poskrbi, da se celotni postopek uvajanja izdelka razbije na logične enote (opravila, naloge) in se določijo vmesni členi in povezave med enotami postopka;
- kadrovskega tima, ki skrbi za potrebne kadre tima uvajanja izdelka, njihovo izobraževanje, motiviranje in nagrajevanje;
- tehnološkega tima, ki je odgovoren za stvaritev strategije in zamisli. Tim mora biti osredotočen na čim nižje stroške in kakovost izdelka,
- navideznega tima, ki deluje v obliki računalniških modulov in oskrbuje preostale člane tima za uvajanje izdelka s potrebnimi informacijami.

Slika 5 prikazuje sestavo delovne skupine v velikem podjetju.

Namen istočasovnega inženiringa je doseči čim boljše sodelovanje med omenjenimi štirimi osnovnimi timi določene delovne skupine.

Splošno velja, da naj bodo večdisciplinarni timi za uvajanje izdelka tako sestavljeni, da se doseže:

2.1. Workgroup structure in big companies

Concurrent engineering is based on a multidisciplinary product-development team (PDT) ([6] and [7]). PDT members are experts from various departments of a company and representatives of strategic suppliers and customers.

Product development team members communicate via a central information system (CIS), which provides them with data about processes, tools, infrastructure, technology, and the existing products of the company. The representatives of strategic suppliers and customers – because they are often remote from the company – participate in the team just virtually, using the internet information system (IIS), which allows them to use the same tools and technologies as the team members in the company [7].

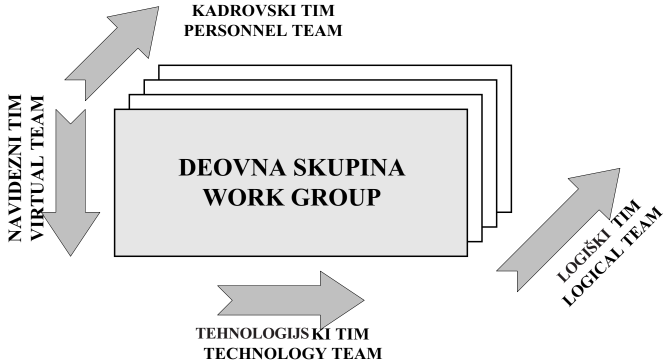
In big companies the composition of the PDT changes during the different phases of product development. The team consists of various workgroups in the various phases of product development, and each workgroup consists of four basic teams [1]:

- the logical team which ensures that the whole product-development process is split into logical units (operations, tasks) and defines the interfaces and connections between the individual process units.
- the personnel team which has to find the required personnel for the PDT, trains and motivates the personnel, and provides proper payment.
- the technology team which is responsible for creating a strategy and a concept. It has to concentrate on producing high-quality products at minimum costs.
- the virtual team which operates in the form of computer software and provides other PDT members with the data they required.

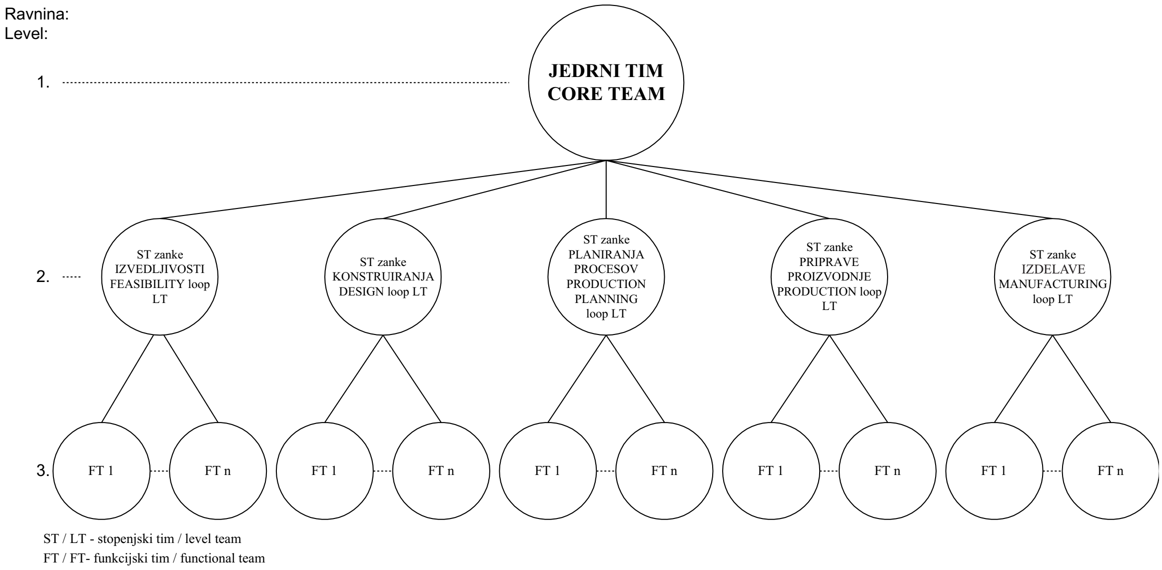
Figure 5 presents the composition of a workgroup in a big company.

The goal of concurrent engineering is to achieve the best possible cooperation among the four basic teams of a particular workgroup.

The multidisciplinary teams should generally have a structure that enables the following goals to be achieved:



Sl. 5. *Delovna skupina v velikem podjetju*
Fig. 5. *Workgroup in a big company*



Sl. 6. *Triravninska sestava timov v velikem podjetju*
Fig. 6. *Three-level team structure in a big company*

- jasna definiranost pristojnosti in odgovornosti,
- kratke odločitvene poti,
- razpoznavanje članov timov v izdelku, ki ga uvajajo.

Po pregledu objavljenih del s področja načrtovanja sestave timov v velikih podjetjih ([1] in [8]) smo ugotovili, da se za velika podjetja predlaga triravninska sestava timov uvajanja izdelka, kar prikazuje slika 6.

Jedrni tim, ki ga sestavljajo vodilni delavci podjetja in vodja opazovanega stopenjskega tima, ima nalogo, da podpira in nadzoruje projekt uvajanja izdelka.

Stopenjski tim, ki ga sestavljajo vodja stopenjskega tima in vodje v opazovani stopnji oziroma zanki udeleženih funkcijskih timov, ima nalogo, da koordinira in uglaša cilje in dejavnosti funkcijskih timov ter zagotavlja gladek prehod na naslednjo stopnjo osvajanja izdelka.

Funkcijski tim, ki ga sestavljajo vodja funkcijskega tima in strokovnjaki različnih področij dela podjetja ter predstavniki dobaviteljev in kupcev, ima nalogo, da izvaja zadane naloge v terminskem, finančnem in kadrovskem oziru.

2.2 Oblikovanje sestave timov v majhnih podjetjih

Analiza rezultatov oblikovanja delovnih skupin in sestave timov v velikih podjetjih je pokazala, da predlagani osnutek načrtovanja delovnih skupin in sestave timov za majhna podjetja ni sprejemljiv (preveliko število timov delovne skupine, preveč timskih ravni).

Pri oblikovanju osnutka delovnih skupin, sestave in organizacije majhnih podjetij bo torej treba paziti na predlaganje:
- čim manjšega števila timov delovne skupine,

- a clear definition of competence and responsibility,
- short decision paths,
- an identification of team members with the product being developed.

A survey of the published works in the field of team-structure planning in big companies ([1] and [8]) has revealed that a three-level PDT structure is recommended in big companies, as presented in Figure 6.

The core team consists of the company management and the manager of the treated stage team; its task is to support and control the product-development project.

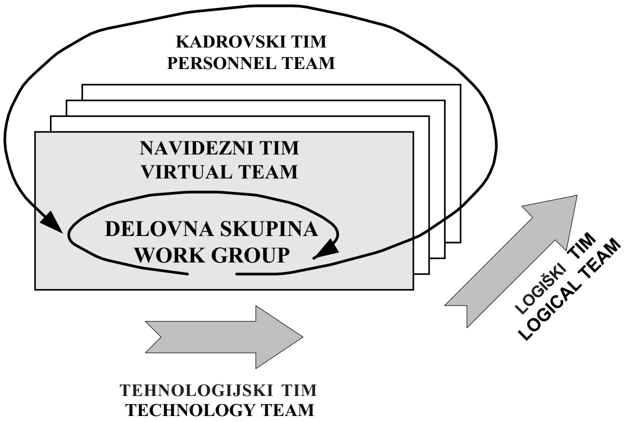
The level team consists of the level-team manager and the managers of the participating functional teams in the treated level (loop); its task is to coordinate the goals and tasks of the functional teams and to ensure a smooth transition to the next level of product development.

The functional team consists of the functional-team manager, experts from various fields in the company, and representatives of suppliers and customers; its task is to carry out the tasks given, taking into consideration terms, finance and personnel.

2.2. Team structure in small companies

An analysis of the results regarding the setup of workgroups and team structure in big companies has shown that the proposed concept for planning the workgroups and the structure of the teams cannot be used in small companies (there are too many teams in a workgroup and too many team levels).

When developing the workgroup concept, structure and organisation in small companies it will therefore be necessary to propose:
- as few workgroup teams as possible,



Sl. 7. *Delovna skupina v majhnem podjetju*
Fig. 7. *Workgroup in a small company*

- čim manjšega števila timskih ravni in
- ustrezne organizacije podjetja.

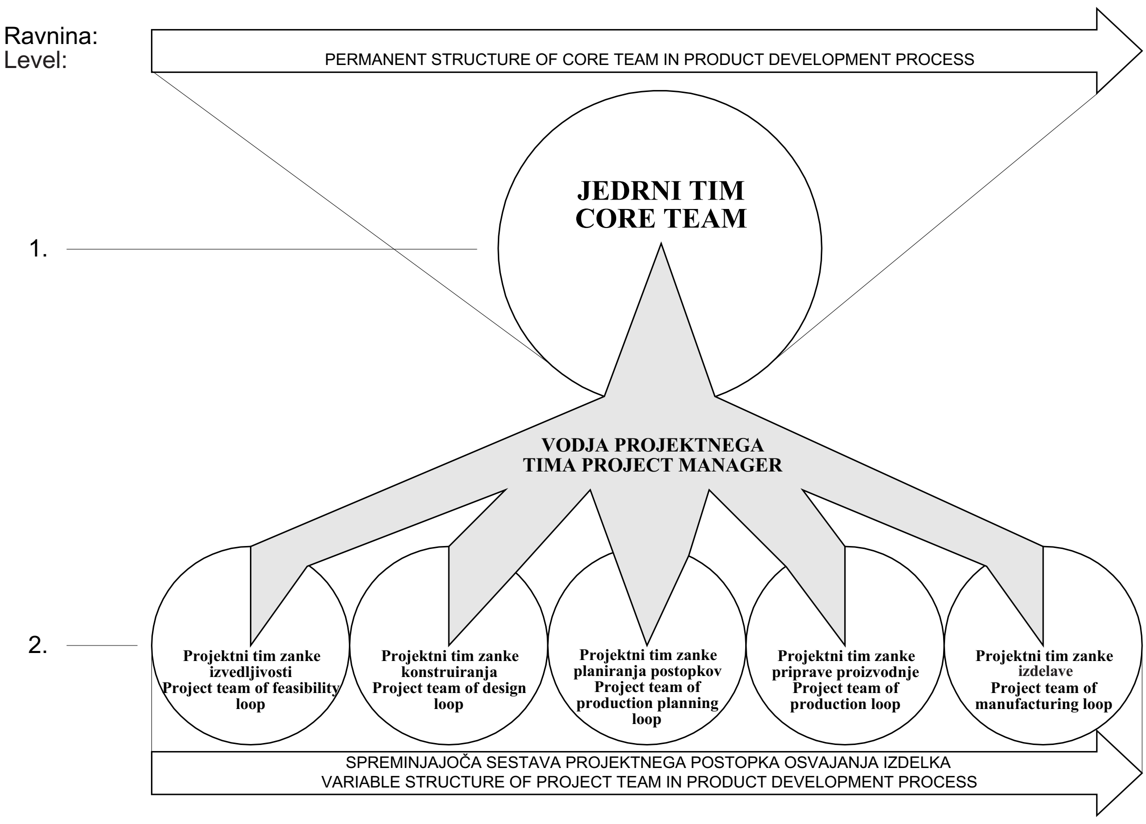
Sodelavci *Laboratorija za proizvodne sisteme* smo izdelali nekaj variant sestave delovnih skupin in sestave timov ter se po vrednotenju predlaganih variant odločili, da za majhna podjetja predlagamo:

- prehod iz štirih timov delovne skupine (kadrovski, logiški, tehnologijski, navidezni tim) na dva tima (logiški in tehnologijski tim),
- prehod iz triravninske na dvoravninsko sestavo timov.

- as few team levels as possible,
- an appropriate organisation of the company.

The members of the *Production Systems Laboratory* made several versions of the workgroup composition and team structure, and decided, after an evaluation of the proposed versions, that the following was advisable for small companies:

– a switch from four workgroup teams (personnel, logical, technology, and virtual team) to two workgroup teams (logical and technology team);
- a switch from a three-level to a two-level team structure.



Sl. 8. *Dvoravninska sestava timov v majhnem podjetju*
Fig. 8. *Two-level team structure in a small company*

V majhnem podjetju bo torej delovna skupina sestavljena le iz dveh osnovnih timov (slika 7) in to:
- logiškega tima, ki naj poskrbi, da se celotni postopek uvajanja izdelka razdeli na logične enote in da se določijo vmesni členi ter povezave med enotami postopka in
- tehnologijskega tima, ki naj odgovarja za stvaritev strategije in zamisli.

Naloge navideznega tima bo v majhnem podjetju prevzel osrednji informacijski sistem (OIS) z ustreznimi programskimi orodji, za uporabo katerih morajo biti člani delovne skupine dobro usposobljeni, naloge kadrovskega tima pa bi izvedel vodja projektnega tima.

Za majhno podjetje se načrtuje tudi prehod iz triravninske strukture timov na dvoravninsko strukturo, ki je prikazana na sliki 8.

Jedrni tim, katerega naloga je, da podpira in nadzoruje projekt uvajanja izdelka, naj bi sestavljali:
- vodja jedrnega tima (stalni član),
- vodje strokovnih služb podjetja (stalni člani) in
- vodja projektnega tima (stalni član).

Projektni tim, katerega naloga je izvajanje zastavljenih nalog v terminskem, finančnem in kadrovskem pogledu, naj bi sestavljali:
- vodja projektnega tima (stalni član) in
- strokovnjaki različnih področij dela podjetja ter predstavniki strateških dobaviteljev in kupcev (nestalni člani).

Kot vidimo, naj bi bil projektni tim v majhnem podjetju zasnovan podobno kakor funkcijski tim v velikem podjetju, s to razliko, da je en sam in da skozi stopnje oziroma zanke uvajanja izdelka spreminja svojo sestavo.

V zanki izvedljivosti, v kateri naj bi projektni tim poskrbel za določitev zahtev kupcev, določitev ciljev ter izdelavo različnih variant zamisli izdelka, naj bi projektni tim sestavljali uslužbenci trženja, projektive, konstrukcije ter predstavniki strateških dobaviteljev in kupcev.

V zanki konstruiranja, v kateri naj bi projektni tim poskrbel za idejne rešitve izdelka, projektiranje in konstruiranje izdelka, sklopov in sestavnih delov, razvoj prototipov ter izbira najprimernejših variant z vidika tehnologičnosti, naj bi projektni tim sestavljali uslužbenci projektive, konstrukcije in tehnologije.

V zanki načrtovanja postopkov, v kateri naj bi projektni tim poskrbel za izbiro najprimernejših tehnoloških postopkov izdelave sestavnih delov in montaže sklopov (določitev zaporedja, opravil, izbira strojev in orodij, normirani časi), naj bi projektni tim sestavljali uslužbenci konstrukcije, tehnologije, priprave proizvodnje in predstavniki strateških dobaviteljev.

V zanki priprave proizvodnje, v kateri naj bi projektni tim poskrbel za določitev poteka dela

In a small company a workgroup therefore consists of just two basic teams (Figure 7):
– the logical team, which should ensure that the whole product-development process is divided into logical units and that the interfaces and junctions between process units are defined;
– the technology team, which should be responsible for providing the strategy and concept.

The CIS performs the role of the virtual team with proper software tools (workgroup members should be well trained to use these tools), and the project-team manager carries out the personnel-team tasks.

For a small company, the transition from a three-level to a two-level team structure is planned too, as presented in Figure 8.

The core team, whose task is to support and control the product-development project, should consist of:
- a core-team manager (permanent member),
- department managers (permanent members),
- a project-team manager (permanent member).

The project team, which carries out the tasks given, taking into consideration terms, finance and personnel, should consist of:
- a project-team manager (permanent member),
- experts from various fields in the company and representatives of strategic suppliers and customers (variable members).

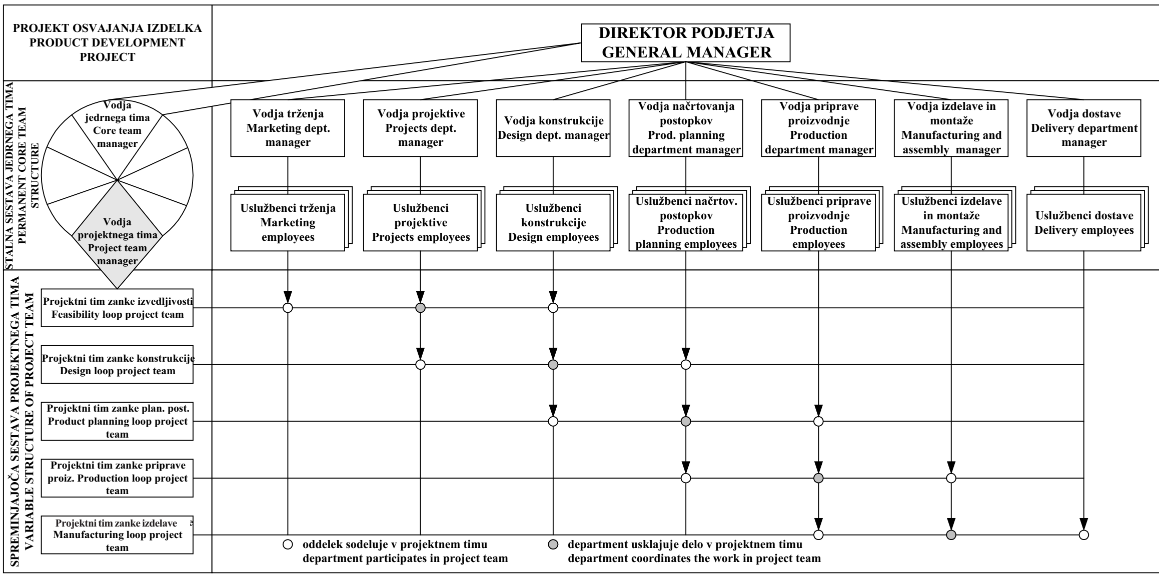
The project team in a small company is therefore designed in a similar way to a functional team in a big company, the difference being that there is just one team and its composition changes in different phases (loops) of the product-development process.

In the feasibility loop, where the project team should define customer requirements and goals, and make several versions of the product design, the project team should consist of employees from the marketing, the product-planning, and the design departments, and the representatives of strategic customers and suppliers.

In the design loop, where the project team should provide general solutions regarding the product, the product planning and the design, its parts and components, the development of prototypes, and the choice of the most suitable versions from the manufacturing point of view, the project team should consist of employees from the product-planning, the design and the production-planning departments.

In the production-planning loop, where the project team should select the best technology operations for the manufacturing of parts and the assembling of components (definition of sequence, operations, selection of machines, tools, and norm times), the project team should consist of employees from the design, the production-planning, and the production departments, and strategic suppliers' representatives.

In the production loop, where the project team should define production type (workshop, cell or



Sl. 9. *Vzorna matrična organiziranost timskega dela v majhnih podjetjih*
Fig. 9. *Ideal matrix organisation in a small company*

(delavniški, celični ali izdelčni potek dela) ter za izbiro najboljše razmestitve delovnih sredstev, naj bi projektni tim sestavljali uslužbenci tehnologije, priprave proizvodnje, izdelave in montaže ter logistike in odpreme.

V zanki proizvodnje, v kateri naj bi projektni tim poskrbel za preizkus prototipov, nabavo potrebne opreme, razmestitev delovnih sredstev, izvedbo in preizkus ničte serije, naj bi projektni tim sestavljali uslužbenci priprave proizvodnje, izdelave in montaže, kakovosti ter uslužbenci skladišč in odpreme.

Naloge stopenjskih timov velikega podjetja naj bi v majhnem podjetju prevzel vodja projektnega tima in ta naj bi poskrbel za uskladitev in uglaševanje ciljev in dejavnosti med projektnim in jedrnim timom ter za zagotavljanje nemotenega prehoda iz ene v drugo zanko uvajanja izdelka.

V velikih podjetjih so običajno člani jedrnega tima, stopenjskih in funkcijskih timov projektno organizirani. Takega načina organizacije timov si majhna podjetja ne morejo privoščiti, in to predvsem zaradi premajhnega števila uslužbencev oddelkov podjetja.

Analiza različnih organizacijskih struktur podjetij oziroma timov ([9] in [10]) je pokazala, da bi bila za majhna podjetja najprimernejša matrična organizacija članov jedrnega in projektnega tima (sl. 9).

Posamezni član jedrnega tima, razen vodje projektnega tima, del delovnega časa opravlja naloge v oddelku, kateremu pripada in bi bil za izvedbo teh nalog odgovoren direktorju podjetja, preostali del delovnega časa pa bi posvetil delu pri projektu uvajanja izdelka, za kar bi bil

product-oriented type of production) and select the optimum layout of production means, the project team should consist of employees from the production-planning department, production, manufacturing and assembly, as well as logistics and delivery.

In the manufacturing loop, where the project team should take care of prototype tests, supply of required equipment, layout of production means, manufacturing and test of the null series, the project team should consist of employees from the production department, manufacturing and assembly, quality assurance, warehouse and delivery departments.

The tasks that are performed by the stage teams in big companies should be done by the project-team manager in a small company, and he/she should coordinate and tune the goals and activities between the project team and the core team, and provide a smooth transition from one phase (loop) of the product-development process to another.

In big companies the members of the core, level and functional teams usually use a project type of organisation. This type of organisation cannot be used in small companies, as they have too few employees.

An analysis of the various organisational structures of companies and teams ([9] and [10]) has shown that in small companies a matrix organisation would be the most suitable for the core- and project-team members (Figure 9).

A member of the core team (with the exception of the project-team manager) would carry out tasks in his/her department for part of his/her working time (for this work he/she would be responsible to the general manager of the company), and the rest of his/her working time he/she would work on the product-development project (for this

Sl. 10. *Mini nakladalnik »VEPER«*
Fig. 10. *The "VEPER" mini-loader*

odgovoren vodji jedrnega tima. Tudi član projektnega tima, razen vodje projektnega tima, bi prav tako del delovnega časa opravljal naloge v oddelku, kateremu pripada in bi bil za izvedbo teh nalog odgovoren vodji oddelka, preostali del delovnega časa pa bi posvetil delu pri projektu uvajanja izdelka, za kar bi bil odgovoren vodji projektnega tima.

Vodja projektnega tima naj bi bil za čas trajanja projekta uvajanja izdelka izločen iz oddelka in naj bi bil polni delovni čas zaposlen samo pri projektu.

3 PRIMER ISTOČASOVNEGA UVAJANJA IZDELKOV V MAJHNEM PODJETJU

Majhno podjetje, ki je izdelovalec strojev za gradbeništvo, se je odločilo za istočasovno osvajanje mini nakladalnika »VEPER« (slika 10).

Podjetje zaposluje 182 delavcev in ima poleg vodstva (direktor, pomočnik direktorja) oblikovanih devet oddelkov, in to:

- komercialni oddelek, ki skrbi za trženje in prodajo, s 7 delavci,
- razvojno-projektivni oddelek, ki skrbi za razvoj in projektiranje izdekov, s 5 delavci,
- konstrukcijski oddelek, ki skrbi za konstruiranje izdelkov, s 6 delavci,
- tehnološki oddelek, ki skrbi za načrtovanje proizvodnje in logistiko, z 12 delavci,
- nabavni oddelek, ki skrbi za nabavo in sodelavo, s 5 delavci,
- proizvodnja, ki skrbi za operativno pripravo

work he/she would be responsible to the core-team manager). A member of the project-team (except the project team manager) would carry out the tasks in his/her department for part of his/her working time (for this work he/she would be responsible to the department manager), and the rest of his/her working time he/she would work on the product-development project (for this work he/she would be responsible to the project-team manager).

The project-team manager would be excluded from his/her department throughout the duration of the product-development project and he/she would work full-time on the project.

3 AN EXAMLE OF THE CONCURRENT DEVELOPMENT OF PRODUCTS IN A SMALL COMPANY

A small company that produces civil engineering equipment decided to concurrently develop a mini-loader called "VEPER" (Figure 10).

There are 182 employees in the company; in addition to the management (the general manager and his assistant) there are nine departments:

- the commercial department is in charge of marketing and sales (7 employees),
- the development and planning department is concerned with development and product planning (5 employees),
- the design department is concerned with product design (6 employees),
- the technology department is concerned with production and logistics (12 employees),
- the supply department is concerned with supply and cooperation (5 employees),
- the production department is concerned with op-

proizvodnje in samo proizvodnjo, s 136 delavci,
- finančni oddelek s 3 delavci,
- oddelek kakovosti s 3 delavci in
- informacijska enota s 3 delavci.

Da bi podjetje lahko prešlo na istočasovno uvajanje mini nakladalnika, se je bilo treba najprej odločiti za sestavo timov istočasovnega uvajanja načrtovanega izdelka.

Vodstvo podjetja se je odločilo za oblikovanje dvoravninske strukture timov, torej za jedrni in projektni tim.

Da bi prišli do najprimernejše sestave jedrnega in projektnega tima, sta bili organizirani dve delavnici ustvarjalnosti [4], v katero so bili povezani direktor in pomočnik direktorja podjetja ter devet vodij oddelkov.

Rezultati izvedbe prve delavnice ustvarjalnosti so pokazali, naj jedrni tim sestavlja enajst delavcev podjetja, in to:
- direktor podjetja, ki bo vodja jedrnega tima,
- devet vodij oddelkov,
- pomočnik direktorja, ki bo vodja projektnega tima.

Vsi člani jedrnega tima bodo stalni člani, torej se sestava jedrnega tima v času uvajanja mini nakladalnika ne bo spreminjala.

Da bi določili stopnje postopka uvajanja mini nakladalnika, stopnjam pripadajoče dejavnosti ter določili odgovornosti oddelkov za izvedbo dejavnosti, je bila izvedena druga delavnica ustvarjalnosti.

Rezultate izvedbe druge delavnice ustvarjalnosti prikazuje preglednica 1.

V preglednici 1 zbrani rezultati določanja stopenj in dejavnosti ter določanja odgovornosti oddelkov za izvedbo dejavnosti in sprejeta odločitev vodstva podjetja o organizaciji 3-T zank postopka uvajanja mini nakladalnika, je predstavljala temelj za oblikovanje sestave projektnega tima v posamezni zanki uvajanja izdelka. Rezultati oblikovanja spreminjajoče sestave projektnega tima v zankah uvajanja mini nakladalnika so vidni v preglednici 2.

Vodja projektnega tima bo stalni član tima, strokovnjaki devetih oddelkov podjetja ter predstavniki oblikovalcev, dobaviteljev in kupcev pa bodo nestalni člani tima.

Iz rezultatov sestave jedrnega in projektnega tima je bilo mogoče načrtati dvoravninsko strukturo timov osvajanja mini nakladalnika (sl. 11).

V podjetju, ki izdeluje mini-nakladalnike, so dosedaj le-te uvajali na zaporedni način. Analiza rezultatov zaporednega uvajanja različnih tipov mini nakladalnikov je pokazala, da je bil povprečni čas uvajanja izdelkov štiri leta.

Današnji trg terja kratke dobavne roke izdelkov oziroma kratke čase uvajanja izdelkov.

Da bi podjetje skrajšalo čas uvajanja mini nakladalnika in s tem postalo bolj konkurenčno na trgu, se je odločilo za istočasovno uvajanje novega tipa mini nakladalnika.

erative production preparation and manufacturing (136 employees),
- the financial department (3 employees),
- the quality assurance department (3 employees),
- the IT department (3 employees).

In order that the company could switch to concurrent development of the mini-loader it was first necessary to decide about the structure and the composition of the concurrent product development teams.

The company management decided to form a two-level team structure (core and project teams).

In order to get the best structure of both teams, two creativity workshops were organised [4], with the general manager, his assistant and nine department managers participating.

The results of the first creativity workshop showed that the core team should consist of eleven company employees:
- the general manager, who would manage the core team,
- the nine department managers,
- the assistant general manager, who would manage the project team.

All core-team members will be permanent members; the core-team composition will therefore not change within the mini-loader development time.

A second creativity workshop was organised in order to define the stages of the mini-loader development process, and their corresponding activities, as well as the responsibilities of the departments to carry out these activities.

The results of the second creativity workshop are presented in Table 1.

The results of the second creativity workshop (presented in table 1) and the selection of the project-team manager, made by the company management, allowed for the definition of the project-team structure in the individual loops of the mini-loader development, as shown in Table 2.

The project-team manager will be a permanent team member, while the experts from the nine departments of the company and the representatives of designers, suppliers and customers will be variable team members.

After the structures of the core team and the project team had been defined, it was possible to design the two-level team structure for the mini-loader development (Figure 11).

Up to now the producer of the mini-loaders has developed the products sequentially. An analysis of the results of the sequential development of various types of mini loaders in the past has shown that the average development time for a particular product was four years.

These days the market demands short delivery terms for products and short development times.

In order to reduce the mini-loader development time (and thus get a competitive advantage) the company decided to concurrently develop a new type of mini-loader.

Preglednica 1. *Stopnje in dejavnosti postopka uvajanja mini nakladalnika*
Table 1. *Stages and activities in the mini-loader development process*

Št. stopnje: / Stage No:	Opis stopnje postopka osvajanja izdelka: / Description of product development stage:	Oddelek: / Department:	Razvoj in projektiva / Develop. and plan. dept.		Konstrukcija / Design dept.	Tehnologija / Technology dept.		Nabava / Supply dept.		Proizvodnja / Production		Komerciala / Marketing and sales dept.		Finance / Financial dept.	Kakovost / Quality dept.	Informacijska enota / Informat. unit	Dostava / Delivery	Oblikovanje / Shaping
		Uslužbenci: / Employees: — Načrtovane dejavnosti stopnje: / Planned activities within the stage:	Razvoj / Development	Projektiranje / Prod. planning	Konstruiranje / Design	Načrtov. proiz. / Prod. proc. plan	Logistika / Logistics	Nabava / Supply	Sodelava / Cooperation	Priprava / Prepare	Izdelava / Manufacturing	Trženje / Marketing	Prodaja / Sales					
1	Definiranje ciljev / Definition of goals	Cilji / Goals	X	X								X						
2	Študija izvedljivosti / Feasibility study	Terminski plan / Term plan	X	X		X		X				X	X			X	X	
		Finančni plan / Financial plan											X	X		X		
		Predkalkulacija / Pre-calculation		X		X		X					X	X		X		
		Cilji trga / Goals of market						X				X	X					
3	Projektiranje / Product planning	Idejni osnutek izdelka / First draft of the product	X	X								X						X
		Idejni osnutki sklopov / First draft of components	X	X	X							X						X
		Projektiranje / Planning of the product	X	X														
4	Konstrukcija / Design	Konstruiranje sklopov / Design of components	X	X	X											X		
		Izdelava delavniških risb / Drawings of parts	X	X	X	X										X		
		Kosovnice / Bills of material		X	X	X	X	X								X		
5	Načrtovanje postopkov / Process planning	Materialne potrebe / Material requirements			X	X	X	X								X		
		Tehnološki postopki / Technology routings				X				X						X		
		Nadzorni postopki / Control procedures				X	X			X					X	X		
		Priprave / Preparations			X	X				X								
		Razpisana dokumentacija / Documentation of orders				X										X		
		Pregled zalog / Overview of stock					X								X	X		
		Oblikovanje naročil / Creation of orders					X	X								X	X	
		Naročanje materiala / Order of material					X	X		X						X	X	
		Prevzem in skladiščenje / Acceptance and storing					X	X							X	X	X	
6	Izdelava in montaža / Manufacturing and assembly	Proženje proizvodnje / Launch of production					X			X	X					X		
		Priprava materiala / Preparation of material					X			X	X					X		
		Izdelava priprav / Manufacturing of appliances				X				X	X					X		
		Izdelava komponent / Manufact. of components				X			X	X	X					X		
		Montaža / Assembly				X				X	X							
		Preizkus / Check				X				X	X							
		Testiranje in nadzor / Test and control								X					X			
7	Trženje in prodaja / Marketing and sales	Ponujanje in sklenitev pogodbe / Offer and contract			X	X				X	X		X	X	X	X		
		Priprava izdelka / Preparation of the product			X	X				X	X							
		Končni nadzor / Final control	X							X	X		X		X			
		Dobava / Supply				X					X		X			X		

Preglednica 2. *Sestava projektnega tima v posamezni zanki uvajanja mini nakladalnika*
Table 2. *Project-team structure in the individual loops of the mini-loader development*

Št. zanke / Loop No.	OPIS ZANKE: DESCRIPTION OF THE LOOP:	V ZANKO VKLJUČENE STOPNJE: STAGES, INCLUDED IN THE LOOP:	ČLANI PROJEKTNEGA TIMA / PROJECT TEAM MEMBERS: VODJA PROJ. TIMA / PROJ.T EAM MANA.	RAZVOJ / DEVELOPMENT	PROJEKTIRANJE / PRODUCT PLAN.	KONSTRUIRANJE / DESIGN	NAČRT. PROIZ. / PROD. PROC. PLAN	LOGISTIKA / LOGISTICS	NABAVA / SUPPLY	SODELAVA / COOPERATION	OPERATIVNA PRIP. / OPERATIVE PREP.	PROIZVODNJA / MANUFACTURING	TRŽENJE / MARKETING	PRODAJA / SALES	FINANCE / FINANCE	KAKOVOST / QUALITY	INFORMAC. ENOTA / INFORMAT. UNIT	DOSTAVA / DELIVERY	OBLIKOVANJE / SHAPING	SKUPNO ŠT. ČLANOV PROJ. TIMA / TOTAL No OF PROJECT TEAM MEM.
1.	ZANKA IZVEDLJIVOSTI FEASIBILITY LOOP	•definiranje ciljev •definition of goals •študija izvedljivosti •feasibility study •projektiranje •planning	X	X	X	X	X		X				X	X	X		X	X	X	12
2.	ZANKA PROJEKTIRANJA PROJECT LOOP	•študija izvedljivosti •feasibility study •projektiranje •planning •konstruiranje •design	X	X	X	X	X	X	X				X	X	X		X		X	12
3.	ZANKA KONSTRUIRA-NJA DESIGN LOOP	•projektiranje •planning •konstruiranje •design •načrtovanje postopkov •process planning	X	X	X	X	X	X	X		X					X	X	X	X	12
4.	ZANKA NAČRTOVANJA POSTOPKOV PROCESS PLANNING LOOP	•konstruiranje •design •načrtovanje postopkov •process planning •izdelava in montaža •manufact. and assembly	X	X	X	X	X	X	X	X	X	X				X	X	X		13
5.	ZANKA IZDELAVE IN MONTAŽE MANUFACTU-RING AND ASSEMBLY LOOP	•načrtovanje postopkov •process planning •izdelava in montaža •manufact. and assembly •trženje in prodaja •marketing and sales	X	X		X	X	X	X	X	X	X		X	X	X	X	X		14

Organizirana je bila delavnica ustvarjalnosti [5], v katero so bili povezani člani jedrnega tima uvajanja mini nakladalnika, in to z nalogo, da ocenijo oziroma določijo:

- čase trajanja posamezne stopnje oziroma dejavnosti postopka istočasovnega uvajanja izdelka,
- možne povezave med stopnjami oziroma dejavnostmi,
- tip in načrtovani čas prekrivanja stopenj oziroma dejavnosti.

Rezultati dela jedrnega tima uvajanja mini nakladalnika so vidni v preglednici 3.

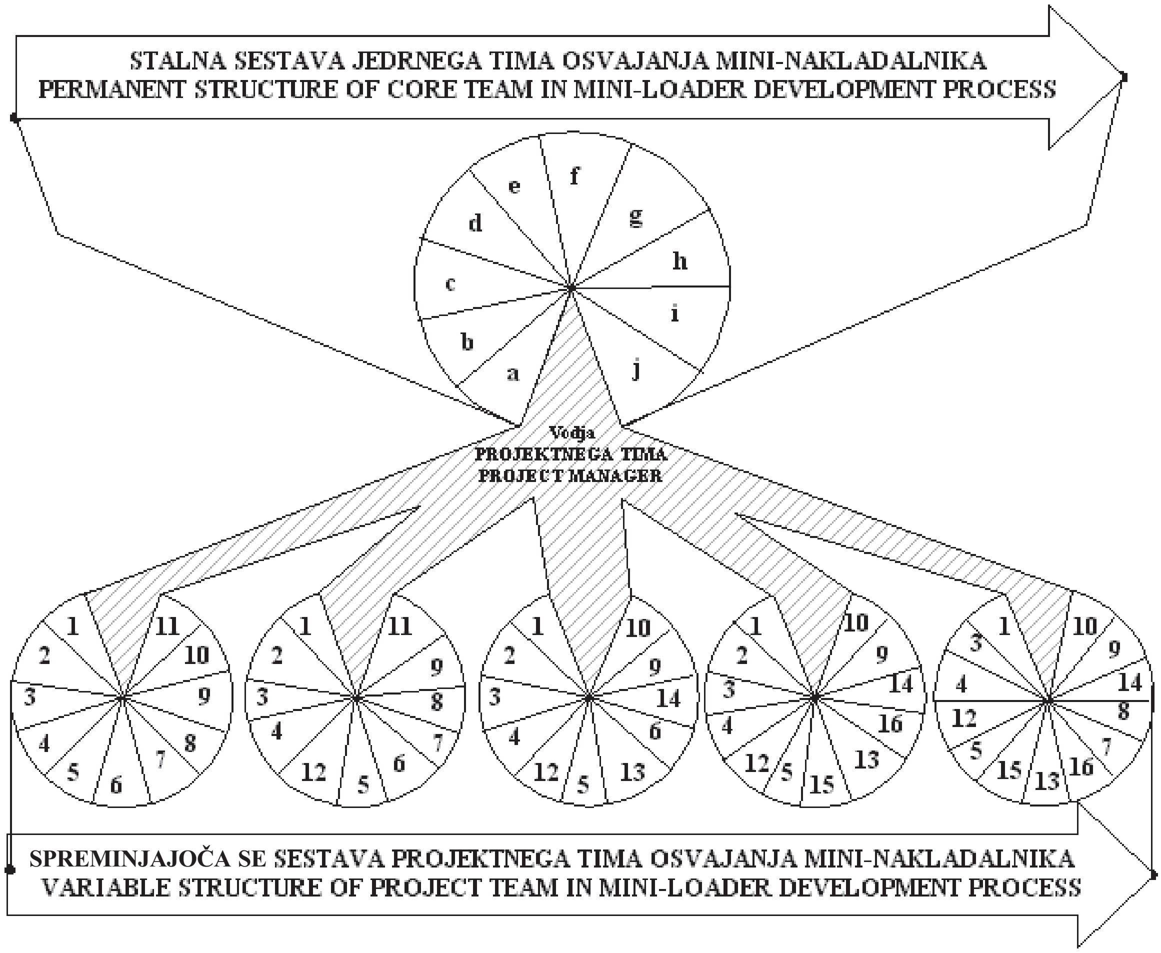
V preglednici 3 zbrani podatki o časih, povezavah in prekrivanjih stopenj oziroma dejavnosti istočasovnega uvajanja mini nakladalnika so predstavljali vhodne podatke za delo s programskim

A creativity workshop was organised [5], with all the members of the core team for the mini-loader development participating. They were asked to estimate or define the following:

- the duration of individual stages (activities) in the concurrent product development process;
- the possible connections between the stages (activities);
- the types and planned times of overlapping stages (activities).

The results of the core-team work during the mini-loader development are presented in table 3.

The data on the times, the connections and the overlapping of levels (activities) in the concurrent mini-loader development (presented in table 3) are the input data for the CA – SPJ software, which



a - Vodja INFORMACIJSKE ENOTE/Manager of IT dept.
b - Vodja KAKOVOSTI/Manager of QUALITY dept.
c - Vodja FINANC/Manager of FINANCIAL dept.
d - Vodja KOMERCIALE/Manager of MARKETING and SALES dept.
e - Vodja PROIZVODNJE/Manager of PRODUCTION dept.
f - Vodja JEDRNEGA TIMA/CORE TEAM manager
g - Vodja RAZVOJA IN PROJEKTIVE/Manager of DEVELOPMENT and PLANNING dept.
h - Vodja KONSTRUKCIJE/Manager of DESIGN dept.
i - Vodja TEHNOLOGIJE/Manager of TECHNOLOGY dept.
j - Vodja NABAVE/Manager of SUPPLY dept.

1 - Razvoj/Development
2 - Projektiva/Product planning
3 - Konstruiranje/Design
4 - Načrtovanje proizv./Prod. proc. plan
5 - Nabava/Supply
6 - Marketing/Marketing
7 - Prodaja/Sales
8 - Finance/Finance
9 - Informacijska enota/ Information unit
10 - Dostava/Delivery
11 - Oblikovanje/Shaping
12 - Logistika/Logistics
13 - Operativna priprava/Operative prepare
14 - Kakovost/Quality
15 - Kooperacija/Cooperation
16 - Izdelava/Manufacturing

Sl. 11. *Dvoravninska sestava timov uvajanja mini nakladalnika*
Fig. 11. *Two-level team structure during the mini-loader development*

paketom CA – SPJ, s katerim je bil narisan gantogram izvedbe postopka istočasnega uvajanja novega tipa mini nakladalnika (sl. 12).

Analiza gantogramov sedanjega zaporednega in načrtovanega istočasovnega uvajanja novega tipa mini nakladalnika je pokazala, da bo podjetje s prehodom iz zaporednega na istočasni inženiring lahko dalo mini nakladalnik na trg, ne v štirih letih, temveč v petindvajsetih mesecih, kar bo bistveno izboljšalo konkurenčno prednost podjetja.

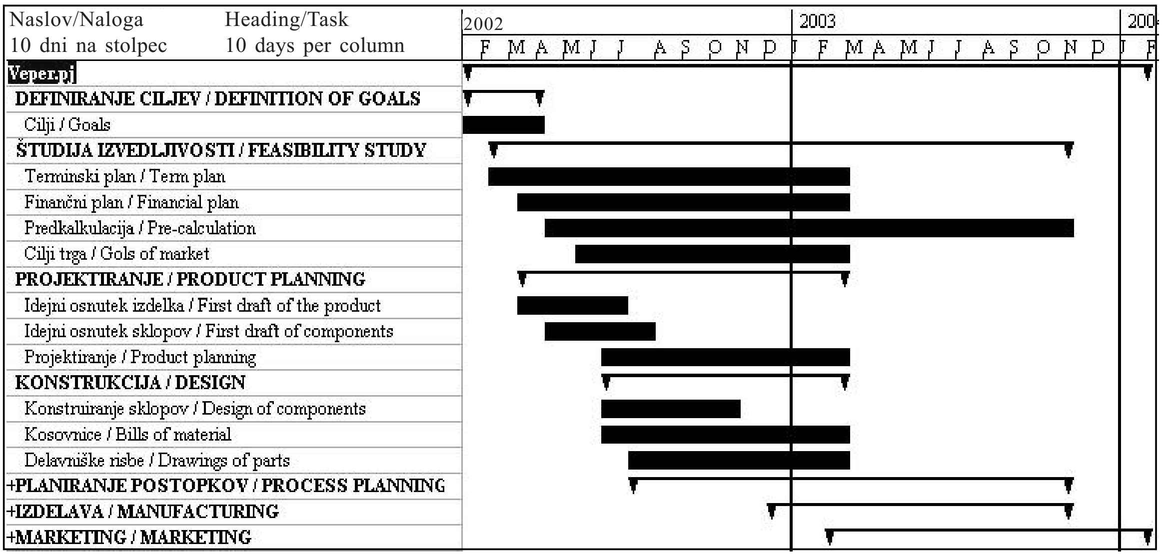
was used to design the Gantt chart of the development process for the new type of mini-loader (Figure 12).

An analysis of the Gantt charts of the existing sequential and the planned concurrent development of the new mini-loader shows that if the company shifts from sequential to concurrent engineering, it will be able to launch a new mini-loader in 25 months instead of 48 month as before – which would considerably improve the competitiveness of the company.

Preglednica 3. *Časi trajanja dejavnosti, tipi in časi prekrivanja dejavnosti istočasovnega uvajanja mini nakladalnika*
Table 3. *Duration of activities, types, and times of overlapping activities the during mini-loader development*

Ident stopje Stage id.	OPIS STOPNJE OSVAJANJA IZDELKA DESCRIPTION OF PRODUCT DEVELOPMENT STAGE	Načrtovane dejavnosti stopnje Planned activities within the stage	Ident dejav. Activity id.	Ocena trajanja dejav. [mes] Activity duration estimation [months]	Ugotav. predhodne dejavnosti Preceding activity iden.	Vrsta prekrivanja Type of overlap			Čas prekrivanja [mes] Time of overlap [months]
						FS	SS	FF	
1	Definiranje ciljev Definition of goals	Cilji Goals	2	3	-				
3	Študija izvedljivosti Feasibility study	Terminski plan Term plan	4	13	2		x		1
		Finančni plan Financial plan	5	12	2		x		2
		Predkalkulacija Pre-calculation	6	19	5		x		1
		Cilji trga Goals of market	7	10	4			x	0
					5			x	0
8	Projektiranje Product planning	Idejni osnutek izdelka First draft of the product	9	4	2		x		2
		Idejni osnutki sklopov First draft of components	10	4	9		x		1
		Projektiranje Planning of the product	11	9	9		x		3
12	Konstrukcija Design	Konstruiranje sklopov Design of components	13	5	9		x		3
					11		x		0
		Izdelava delavniških risb Drawings of parts	14	8	10		x		3
		Kosovnice Bills of material	15	9	9		x		3
16	Načrtovanje postopkov Process planning	Materialne potrebe Material requirements	17	8	9	x			0
					10		x		3
					14		x		0
					15			x	0
		Tehnološki postopki Technology routings	18	11	13		x		3
		Nadzorni postopki Control procedures	19	13	18		x		1
		Priprave Preparations	20	5	19		x		1
		Razpisana dokumentacija Documentation of orders	21	14	18		x		0
		Pregled zalog Overview of stock	22	3	19		x		0
					21		x		1
		Oblikovanje naročil / Creation of orders	23	4	20		x		0
		Naročanje materiala Order of material	24	5	17		x		5
					22		x		2
		Prevzem in skladiščenje Acceptance and storing	25	7	24		x		1
26	Izdelava in montaža Manufacturing and assembly	Proženje proizvodnje Launch of production	27	11	19			x	0
					21			x	0
					24		x		0
		Priprava materiala Preparation of material	28	6	25		x		1
					27		x		2
		Izdelava priprav Manufacturing of appliances	29	8	7	x			0
					14	x			0
					20		x		4
		Izdelava komponent Manufact. of components	30	4	24			x	3
		Montaža / Assembly	31	5	30			x	2
		Preizkus Check	32	4	29			x	0
					31			x	1
		Testiranje in nadzor Test and control	33	4	32			x	0
34	Trženje Marketing	Ponujanje in sklenitev pogodbe Offer and contract	35	11	28		x		0
		Priprava izdelka Preparation of the product	36	4	32		x		0
					33		x		0
		Končni nadzor Final control	37	2	6			x	0
					33			x	0
		Dobava Supply	38	3	35			x	1
					37			x	2

FS: Konec-Začetek/Finish-to-Start
SS: Začetek - Začetek/Start-to-Start
FF: Konec-Konec/Finish-to-Finish



Sl. 12. *Gantogram istočasnega uvajanja novega tipa mini nakladalnika*
Fig. 12. *Gantt chart for the concurrent development of a new type of mini-loader*

Ker je uspešnost realizacije načrtovanega postopka istočasovnega uvajanja mini nakladalnika v veliki meri odvisna od uspešnosti dela spreminjajoče se sestave projektnega tima v zankah uvajanja izdelka, bo nadaljnje delo usmerjeno v podrobno organiziranje in uskladitev članov projektnega tima posamezne zanke uvajanja izdelka.

The success of the concurrent mini-loader development process largely depends on the effectiveness of the work on changing the composition of the project team in the product development loops, and therefore future activities will be directed towards a detailed organisation and coordination of the project-team members during individual loops of the product development.

4 SKLEPI

Svetovni trg zahteva kratke roke za uvajanje izdelkov in to dejstvo sili tudi majhna slovenska podjetja k prehodu od zaporednega na istočasovno uvajanje izdelkov.

Ker je temelj istočasovnega uvajanja izdelkov timsko delo, smo v prispevku posvetili posebno pozornost oblikovanju in sestavi timov v majhnem podjetju. Raziskave so nas pripeljale do sklepa, da naj bo v majhnih podjetjih delovna skupina sestavljena, ne iz štirih, temveč le iz dveh timov (logični in tehnološki podtim), ter da je za majhna podjetja primerna dvoravninska sestava timov (stalni jedrni tim in spreminjajoči se projektni tim).

Predlagano zamisel oblikovanja timov v majhnem podjetju smo preizkusili na primeru določanja sestave timov v podjetju, ki izdeluje mini nakladalnike. Oblikovana je bila tako stalna sestava jedrnega tima kakor tudi spreminjajoča se sestava projektnega tima.

Člani jedrnega tima so določili čase trajanja načrtovanih dejavnosti, možne povezave dejavnosti ter čase prekrivanj dejavnosti. Zbrani podatki o dejavnostih postopka so omogočili delo s programskim

4 CONCLUSIONS

The global market requires short product-development times, and therefore small Slovenian companies are being forced to switch from sequential to concurrent product development.

As the basic element of concurrent product development is team work, this paper pays special attention to the formation and structure of teams in a small company. Research has led us to the conclusion that a workgroup in a small company should consist of just two teams (logical and technology teams) instead of four teams, and that a two-level team structure (a permanent core team and a variable project team) is more suitable for small companies.

The proposed concept of team formation in a small company has been tested in a sample case of team composition in a company producing mini-loaders. First, the permanent core-team structure and then the variable project-team structure have been defined.

The core team members defined the duration of the planned activities, the possible interconnections of activities and the times of overlapping activities. The data obtained on the process activities allowed the use of the CA – SPJ software to make a paketom CA – SPJ, s katerim je bila izvedena časovna analiza dejavnosti in izrisan gantogram istočasnega uvajanja novega tipa mini nakladalnika.

time analysis of the activities and to draw the Gantt chart of concurrent development of a new type of mini-loader.

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Ocenjevanje natančnosti napovedi termohidravličnih programov

The Accuracy Quantification of Thermal-Hydraulic Code Predictions

Andrej Prošek - Borut Mavko

V zadnjem času je velika pozornost namenjena vprašanju natančnosti napovedi termohidravličnih programov pri računanju dinamičnih odzivov sistemov jedrskih reaktorjev. Kljub velikemu napredku je zelo malo zanesljivih in splošnih orodij za ocenjevanje natančnosti računalniških izračunov. Za merljivost natančnosti programa je predlagana nova metoda na temelju naključnostne stopnje aproksimacije (NSA - SARBM). Namen študije je bil tudi raziskati in dokazati primernost predlagane metode.

V postopku kvalifikacije metode NSA z metodo na podlagi hitre Fourierjeve preslikave (HFP - FFTBM) so bili uporabljeni izračuni termohidravličnega računalniškega programa RELAP5/MOD3.2 in eksperimentalni podatki iz naprave BETHSY.

Z grafično primerjavo potekov in primerjavo natančnosti izračunov, dobljenih z metodama NSA in HFP smo pokazali, da metoda NSA dobro napove natančnost izračunanih potekov prehodnih pojavov. Da bi bil izračun natančnosti z metodo NSA podoben postopku z metodo HFP, smo predlagali novo mero za oceno natančnosti, imenovano količnik natančnosti (KN - AF). Dobljeni rezultati za natančnost izbranih BETHSY poskusov kažejo, da je bolje združiti metodi NSA in HFP za oceno natančnosti, kakor pa metodo NSA uporabljati samostojno.

(Ključne besede: natančnost izračunov, programi termohidravlični, NSA - SARBM, BETHSY)

Recently, significant attention has been paid to code accuracy issues in predicting the dynamic responses of nuclear reactor systems. Though significant progress has been made, only a few reliable and general tools to quantify code accuracy are available. A new Stochastic Approximation Ratio Based Method (SARBM) was proposed for accuracy quantification. The objective of this study was to investigate and qualify the proposed method.

The RELAP5/MOD3.2 thermal-hydraulic code calculations and the BETHSY experimental data were used in the process of qualifying the SARBM with a Fast Fourier Transform Based Method (FFTBM).

The obtained results showed that the SARBM was able to satisfactorily predict the accuracy of the calculated transient trends when visually comparing plots and comparing the results with the results obtained by the qualified FFTBM. A new figure of merit for code accuracy, called the accuracy factor (AF), was proposed instead of the stochastic approximation ratio to make the total accuracy calculation with the SARBM more like the FFTBM approach. The accuracy results obtained for the selected BETHSY tests suggest combining the SARBM with the FFTBM for accuracy quantification rather than using it independently.

(Keywords: code accuracy, thermal hydraulic code, SARBM, BETHSY)

0 UVOD

Namen postopka za ocenjevanje velikih termohidravličnih programov z najboljšo oceno (NO - BE) je preveriti njihovo kakovost s primerjanjem računalniških izračunov in izmerjenih podatkov, dobljenih na pomanjšanih eksperimentalnih napravah za jedrske elektrarne. Sistemski termohidravlični programi z najboljšo oceno napovedo prehodne pojave v reaktorjih stvarno, kakor je to najbolj mogoče, tako da fizikalno obnašanje ponazarjajo z določeno natančnostjo. Informacijo o nenatančnosti napovedi dobimo iz postopka ocenjevanja in overitve

0 INTRODUCTION

The assessment process of large thermal-hydraulic best-estimate (BE) computer codes aims principally at verifying their quality by comparing code predictions against experimental data obtained mainly from tests performed on scaled plant experimental facilities. The best-estimate thermal-hydraulic system codes predict reactor transient scenaria as realistically as possible by approximating the physical behaviour with some accuracy. The information on the inaccuracy of the predictions comes from the code assessment and validation process. The first widely računalniškega programa. Prva široko uporabljena metoda za ocenjevanje natančnosti računalniškega programa je bila metoda na podlagi hitre Fourierjeve preslikave (HFP) [1]. To je integralna metoda v frekvenčnem prostoru, ki uporablja hitro Fourierjevo preslikavo (HFP). Uporabljena je bila za številne standardne probleme ([2] do [4]).

Pred kratkim so v Združenih državah Amerike temeljito pregledali tehnike za analizo podatkov, uporabnih za samodejno oceno natančnosti, ter razvili programsko opremo za njihovo uporabo [5]. Za oceno natančnosti časovnih potekov so poleg metode HFP priporočili še nekaj drugih mer natančnosti. Sočasno je Islamov [6] za primerjavo dveh inačic programa RELAP5 v izračunu posamezne spremenljivke predlagal postopek z naključnostno aproksimacijo. V naši študiji je bila vzeta naključnostna aproksimacija in po njej smo razvili metodo NSA za oceno natančnosti programa.

Glavni namen dela je bil metodo NSA kvalificirati z metodo HFP s primerjavo natančnosti izračunov, dobljenih za poskuse na BETHSY (Glej 2.1). V preteklosti smo namreč zelo intenzivno proučevali poskuse z eksperimentalne naprave BETHSY ([7] do [10]), ter jih že tudi ocenili z metodo HFP ([11] do [13]). V nadaljevanju so po kratkem pregledu metod in opisu načina modeliranja predstavljeni glavni rezultati študije.

used methodology suitable to for quantifying the code accuracy was the Fast Fourier Transform Based Method (FFTBM) [1]. This is an integral method in the frequency domain using the Fast Fourier Transform (FFT). It was applied to several standard problems ([2] to [4]).

Recently, a review of data-analysis techniques for applications in automated, quantitative accuracy assessments was done in the United States of America and software was developed to deploy the recommended techniques [5]. For accuracy quantification the FFTBM was adopted and a few other accuracy measures were recommended. At the same time, Islamov [6] proposed a stochastic approximation approach to a comparative analysis of the closeness of two RELAP5 calculation models for single variables. In our study the stochastic approximation was adopted, and based on this approximation the SARBM for code accuracy quantification was developed.

The main purpose of the paper was to qualify the SARBM with the FFTBM by comparing the accuracy obtained for BETHSY (Cfr. 2.1) experiments. In the past the BETHSY experiments were intensively studied ([7] to [10]), and some experiments were also quantitatively assessed with the FFTBM ([11] to [13]). After a brief review of the methods used and the modelling description the main results are discussed.

1 UPORABLJENE METODE

1 THE METHODS USED

1.1 Mera natančnosti na temelju naključnostne aproksimacije

Stopnja naključnostne aproksimacije (SNA - SAR) kot mero negotovosti modela Y, uporabljeno v metodi NSA, je definiral Islamov [6] kot: "Naj so X_1, X_2,…, X_n opazovane naključne spremenljivke in opazovana spremenljivka Z z njimi deterministično povezana tako, da velja $Z(X_1, X_2,\ldots, X_n)$. Pri tem so X_1, X_2,…, X_n vstopne spremenljivke modela Y, odziv modela $Y(X_1, X_2,\ldots, X_n)$ pa naj pomeni pričakovano aproksimacijo spremenljivke Z. Stopnjo naključnostne aproksimacije kot merilo negotovosti modela Y tedaj lahko zapišemo z naslednjo enačbo:

1.1 An accuracy measure based on the stochastic approximation ratio

The Stochastic Approximation Ratio (SAR) measure of the uncertainty of a model Y adopted in the SARBM was defined by Islamov [6] as: "Let X_1, X_2,…, X_n be the observed random parameters, and the observed variable Z is presumed to be somehow deterministically related to the input parameters $Z(X_1, X_2,\ldots, X_n)$. Parameters X_1, X_2,…, X_n are considered as the input data for the model Y, and a model response $Y(X_1, X_2,\ldots, X_n)$ is considered as an anticipated approximation of the variable Z. The Stochastic Approximation Ratio measure of the uncertainty of a model Y can be written as:

$$SAR = \left(1 - \frac{\sqrt{A_{Y-Z}}}{\sqrt{A_Y} + \sqrt{A_Z}}\right)^2 \quad (1),$$

kjer so A_{Y-Z}, A_Y in A_Z drugi momenti – srednje kvadratne vrednosti:

where A_{Y-Z}, A_Y and A_Z are second-order moments:

$$A_{Y-Z} = \int \left[y(x) - z(x)\right]^2 f(x)dx \quad (2)$$

$$A_Y = \int \left[y(x)\right]^2 f(x)dx \quad (3)$$

$$A_Z = \int \left[z(x)\right]^2 f(x)dx \quad (4),$$

kjer $f(x)$ pomeni gostoto verjetnosti." Za nadaljnje podrobnosti in izpeljavo izraza naj si bralec ogleda [6].

and $f(x)$ is density function." For further details and the derivation the reader is referred to [6].

Izvirno predlagan izraz SNA je bil prilagojen za uporabo v istoimenski metodi NSA. V primeru primerjave izračuna s preizkusom je vhodni parameter čas ($x=t$), izračunani signal $y(t)$ in eksperimentalni signal $z(t)$, medtem ko je gostota verjetnosti $f(t)$ v skladu s [6] UNKNOWN, kar pomeni, da je ne upoštevamo. Enačbe od (2) do (4) integriramo v območju [0,T], kjer je zgornja meja integracije T časovni korak, v katerem ocenjujemo natančnost. Ker so eksperimentalni in izračunani podatki diskretni, je v algoritmu SARBM uporabljena diskretna integracijska shema.

Vrednost SNA je v območju [0, 1]. Vrednost $SNA \cong 1$ pomeni, da se eksperimentalni in izračunani signal dobro ujemata. Če je vrednost $SNAR << 1$, pomeni, da se eksperimentalni in izračunani signal razhajata in je nenatančnost velika. Ker pri metodi HFP manjše vrednosti povprečne amplitude pomenijo večjo natančnost, smo definirali novo mero natančnosti, imenovano *količnik natančnosti* (*KN - AF*):

The originally proposed SAR was adopted for use in the SARBM. In the case of a code–experiment comparison the input parameter is time ($x=t$), the calculated signal is $y(t)$, the experimental signal is $z(t)$, while the density function $f(t)$ is, according to [6], UNKNOWN, which means that it is not taken into account. The Eqs. 2 to 4 are integrated over [0, T], where the upper limit T is the time interval for which the accuracy is quantified. Because of the discrete experimental and calculated data a discrete integration scheme is used in the developed SARBM algorithm.

The *SAR* is located in the interval [0, 1]. If $SAR \cong 1$ it means that the experimental and calculated signals are very close. If $SAR << 1$ it means that the experimental and calculated signals are not close and that the inaccuracy is very high. Because in the FFTBM lower values of the average amplitude mean higher accuracy, a new accuracy measure, called the accuracy factor (*AF*), was defined:

$$AF = 1 - SAR \qquad (5).$$

Ta mera natančnosti je bolj praktična za primerjavo rezultatov metode NSA z rezultati metode HFP in za določanje ene same mere za natančnost na podlagi kombinacije več statističnih mer za natančnost.

This accuracy measure is more practical for comparing the results with the FFTBM results and constructing a single measure of the code accuracy from several statistical accuracy measures.

1.2 Mera natančnosti na podlagi povprečne amplitude

Metoda na podlagi hitre Fourierjeve transformacije uporablja za mero natančnosti povprečno amplitudo. Za podrobnosti razvoja in uporabe naj si bralec ogleda ([1] do [4]).

Poglavitna značilnost Fourierjeve transformacije je, da splošno zvezo, veljavno v časovnem prostoru, lahko analiziramo tudi v frekvenčnem prostoru, ne da bi pri tem izgubili informacijo. Ko uporabljamo funkcije, vzorčene v digitalni obliki, lahko uporabimo hitro Fourierjevo preslikavo (HFP), to je algoritem za hitro računanje diskretne Fourierjeve preslikave. Da bi jo lahko uporabili, mora biti število diskretnih vrednosti enako potenci števila 2 in izpolnjen stavek o vzorčenju.

Metoda HFP v frekvenčnem prostoru kaže odstopanje računalniških napovedi od meritev. Za izračun teh odstopanj potrebujemo eksperimentalni signal $F_{exp}(t)$ in razliko signalov $\Delta F(t) = F_{calc}(t) - F_{exp}(t)$ kjer je $F_{calc}(t)$ izračunani signal.

Natančnost programa za posamezno izračunano spremenljivko določimo z uporabo amplitud diskretnega eksperimentalnega signala in signala razlik, dobljenih s HFP pri frekvencah $f_n=n/T_d$, kjer sta ($n=0,1,...,2^m$) in T_d čas trajanja prehodnega pojava vzorčenega signala. Te amplitudne spektre skupaj s frekvencami uporabimo za izračun povprečne amplitude (*PA - AA*), ki označuje natančnost programa pri izračunu posamezne spremenljivke:

1.2 An accuracy measure based on the average amplitude

The FFTBM uses the average amplitude as a measure of the accuracy. For details of its development and use the reader is referred to ([1] to [4]).

A fundamental property of the Fourier transform is that a generic relationship valid in the space identified by its variables can be analysed in a different space identified by different variables without a lack of information. When using functions sampled in digital form, a FFT can be used, i.e. an algorithm that rapidly computes the discrete Fourier transform. To apply it, functions must be identified by a number of values, i.e. a power with a base equal to 2, and the sampling theorem must be fulfilled.

The FFTBM shows the measurement-prediction discrepancies in the frequency domain. To calculate these discrepancies the experimental signal $F_{exp}(t)$ and the error function $\Delta F(t) = F_{calc}(t) - F_{exp}(t)$ are needed, where $F_{calc}(t)$ is the calculated signal.

The code accuracy quantification for an individual, calculated parameter is based on the amplitudes of discrete experimental and error signals obtained with a FFT at frequencies $f_n=n/T_d$, where ($n=0,1,...,2^m$) and T_d is the transient time duration of the sampled signal. These spectra of amplitudes, together with the frequencies, are used for calculating the average amplitude (*AA*) that characterizes the code accuracy in predicting a single variable:

$$AA = \frac{\sum_{n=0}^{2^m} \left| \tilde{\Delta} F(f_n) \right|}{\sum_{n=0}^{2^m} \left| \tilde{F}_{\exp}(f_n) \right|} \quad (6),$$

kjer sta $\tilde{\Delta}F$ amplitudni spekter razlike signalov in $\tilde{F}_{\exp}$ amplitudni spekter eksperimentalnega signala.

1.3 Opis metode NSA

Za skupno natančnost izračuna je bila predlagana nova metoda NSA po vzoru metode HFP [7]. Namesto skupne povprečne amplitude je bil za mero natančnosti predlagan skupni količnik natančnosti:

$$AF_{tot} = \sum_{i=1}^{N_{var}} AF_i \cdot \left(w_f \right)_i \quad \text{z / with} \quad \sum_{i=1}^{N_{var}} \left(w_f \right)_i = 1 \quad (7)$$

kjer je N_{var} število analiziranih spremenljivk, AF_i in $(w_f)_i$ pa sta količnik natančnosti oziroma utežni faktor za i-to analizirano spremenljivko. Običajno za opis prehodnega pojava zadostuje 20 do 25 spremenljivk. Vsak utežni količnik $(w_f)_i$ upošteva natančnost preizkusa, pomembnost spremenljivke za jedrsko varnost in njeno zvezo s primarnim tlakom. Utežni količnik za i-to spremenljivko je definiran kot [2]:

$$(w_f)_i = \frac{\left(w_{\exp} \right)_i \cdot \left(w_{saf} \right)_i \cdot \left(w_{norm} \right)_i}{\sum_{i=1}^{N\ \mathrm{var}} \left(w_{\exp} \right)_i \cdot \left(w_{saf} \right)_i \cdot \left(w_{norm} \right)_i} \quad (8),$$

kjer w_{exp} upošteva natančnost preizkusa, w_{saf} pomembnost spremenljivke za jedrsko varnost in w_{norm} normalizacijo na primarni tlak. Npr.: na natančnost preizkusa vplivajo negotovosti instrumentov, merilnih postopkov in različnih postopkov, uporabljenih za primerjavo meritev in izračunov. Preglednica 1 kaže, da večja ko je negotovost meritve, manjša je utež w_{exp}, s čimer se rezultatu pripiše večjo natančnost. Podobno velja, da bolj ko je parameter pomemben za jedrsko varnost, večja je utež w_{saf}. Uteži se med primerjavami za isto vrsto prehodnega pojava ne smejo spreminjati.

Da bi presodili kakovost izračuna, so bile za KN_{tot} - AF_{tot} na podlagi umetnih podatkov in inženirske presoje določene meje sprejemljivosti [14]. Preglednica 2 kaže meje sprejemljivosti za metodo NSA v primerjavi z mejami za metodo HFP. Za overitev same metode NSA in njenih mej sprejemljivosti so bili uporabljeni preizkusi na BETHSY, opisani v naslednjem poglavju.

Primer, ki kaže razlike v delovanju metode NSA in metoda HFP, je prikazan na sliki 1. Med seboj primerjamo različne stalnice z razmerjem med izračunanim in preizkusnim signalom y(t)/z(t) med 0,5 in 2. Slika kaže različne mere natančnosti spremenljivke v odvisnosti od razmerja y(t)/z(t). Metoda NSA da enak rezultat, če je izračunani signal dvakratnik

where $\tilde{\Delta}F$ and $\tilde{F}_{\exp}$ are the amplitude spectra of the error function and the experimental signal, respectively.

1.3 Overview of SARBM

The SARBM was proposed following the FFTBM approach [2] to get an overall picture of the accuracy for a given code calculation. Instead of the total average amplitude the total accuracy factor was used for the accuracy measure:

where N_{var} is the number of variables analysed, and AF_i and $(w_f)_i$ are the accuracy factor and the weighting factor for i-th analysed variable, respectively. Normally 20 to 25 variables are sufficient to represent the transient. Each $(w_f)_i$ accounts for the experimental accuracy, the safety relevance of particular variables and its relevance with respect to pressure. The weighting factor for the i-th variable is therefore defined as [2]:

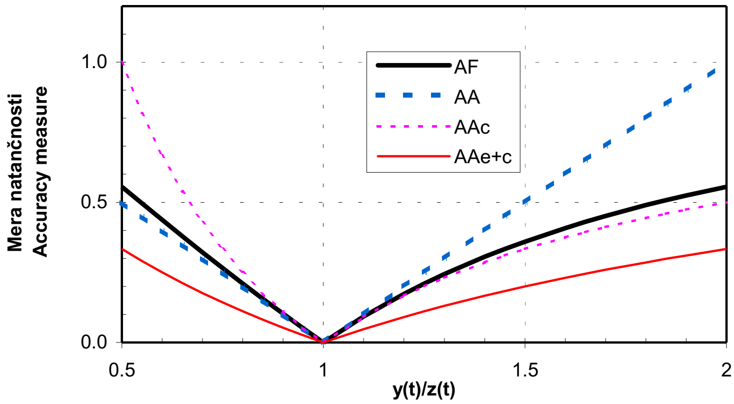
where w_{exp} is the contribution related to the experimental accuracy, w_{saf} is the contribution that expresses the safety relevance, and w_{norm} is the contribution of primary pressure normalization. For example, experimental accuracy is influenced by uncertainty due to the intrinsic characteristics of the instruments, the measurement method and the various evaluation procedures used to compare the experimental measures and the code predictions. Table 1 shows that the more uncertain is the measurement the lower is the weight w_{exp}, resulting in a higher calculation accuracy. Similarly, the more relevant is the parameter to safety the higher is the weight w_{saf}. The weights must remain unchanged during each comparison between code results and experimental data concerning the same class of transient.

To judge the quality of the calculation the acceptability limits for AF_{tot} were defined based on artificial data and engineering judgement [14]. Table 2 shows the acceptability limits for the SARBM compared to the limits for the FFTBM. For a validation of the SARBM and its acceptability limits the BETHSY experiments described in the next section were used.

An example to show the differences in how the SARBM and the FFTBM work is shown in Figure 1. Different constant functions with ratios between the calculated and experimental signal y(t)/z(t) ranging from 0.5 to 2 were compared. In the figure the different single-variable accuracy measures are shown as a function of the ratio y(t)/z(t). The SARBM gives the same

Preglednica 1. *Utežni količniki za analizirane spremenljivke [2]*
Table 1. *Weighting factor components for the analysed variables [2]*

	Wexp	Wsaf	Wnorm
padci tlakov pressure drops	0,7	0,7	0,5
količine mas mass inventories	0,8	0,9	0,9
pretoki flowrates	0,5	0,8	0,5
primarni tlak primary pressure	1,0	1,0	1,0
sekundarni tlak secondary pressure	1,0	0,6	1,1
temperature kapljevine fluid temperatures	0,8	0,8	2,4
temperature srajčk clad temperatures	0,9	1,0	1,2
sesedna raven collapsed levels	0,8	0,9	0,6
moč sredice core power	0,8	0,8	0,5



Sl. 1. *Mere natančnosti primerjave stalnic v odvisnosti od njunega razmerja*
Fig. 1. *Accuracy measures as a function of the ration between constant functions*

eksperimentalnega signala ali nasprotno, KN pa je omejen med 0 in 1, ker je izraz v enačbi (1) normaliziran tako na izračunani kakor na eksperimentalni signal. Pri metodi HFP je AA normaliziran na eksperimentalni signal. Zato smo raziskali primera, ko je PA - AA normaliziran na izračunani signal (primer PA_c - AA_c) in na vsoto izmerjenega in preizkusnega signala (primer PA_{e+c} - AA_{e+c}).

Zanimivo je, da se krivulja KN - AF tesno pokriva z levim delom krivulje PA - AA, ko je izračunani signal manjši od eksperimentalnega, in desnim delom krivulje PA_c - AA_c, ko je izračunani signal večji od eksperimentalnega. Ko pa je PA - AA normalizirana na vsoto obeh signalov, je težnja za PA_{e+c} - AA_{e+c} podobna težnji za KN - AF. To odkritje pojasnjuje nekatere razlike med metodama HFP in NSA pri razlagi rezultatov. Pri majhnih odstopanjih (manj ko 20%) so krivulje za mere natančnosti precej linearne in se ujemajo dobro, saj ima normalizacija manjši vpliv. Pri večjih odstopanjih pa se metodi HFP in NSA zaradi različnega načina

result when the calculated signal is two times the experimental signal or vice versa, and AF is limited between 0 and 1, because the fraction in Eq. 1 is normalized to both the calculated and experimental signals. In the case of the FFTBM the AA is normalized to the experimental signal. Therefore, the average amplitude was investigated for the cases with AA normalised to the calculated signal (case AA_c) and to the sum of the calculated and experimental signals (case AA_{e+c}).

What is interesting is that the AF curve closely matches with the left-hand part of the AA curve when the calculated signal is smaller than the experimental signal and right-hand part of the AA_c curve when the calculated signal is larger than the experimental signal. When the AA is normalized to the sum of both signals the trend for case AA_{e+c} was similar to the AF trend. This finding explains some of differences between the FFTBM and the SARBM when interpreting the accuracy results. At smaller discrepancies (less than 20%) the accuracy-measure curves are rather linear and agree well. At larger discrepancies the FFTBM and normalizacije med seboj dopolnjujeta. Primer takega dopolnjevanja je bil pokazan v študiji [14] za primer padca signala razlike tlakov v tlačniku.

1.4 Postopek za določitev natančnosti izračuna

Ko sta že kvalificirana uporabnik in vhodni model, postopek ocenjevanja izračunov poteka v treh delih. V prvem delu izberemo eksperiment po overitvenih matrikah Komiteja za varnost jedrskih naprav (Committee on the Safety of Nuclear Installations - CSNI) [15] (ali prehodni pojav elektrarne), zatem izračun ocenimo kakovostno in nato še kolikostno.

Kakovostna ocena z vizualno primerjavo izračunanih in eksperimentalnih potekov ter primerjavo posameznih parametrov da prve ocene o izračunu. Kakovostna analiza je potrebni predpogoj kolikostni analizi, ki ji sledi.

Kakovostna analiza temelji na subjektivnih ocenah, te dobimo z ovrednotenjem in razvrstitvijo odstopanj med merjenimi in izračunanimi parametri, ki si jih izberemo za popis pojava. Te ocene so:

- **Odlično**: računalniški program napove parameter v okviru nezanesljivosti eksperimenta.
- **Sprejemljivo**: računalniški program splošno napove vse pojave, časovno obnašanje in usmeritve.
- **Komaj sprejemljivo**: računalniški program ne napove pojava ali parametra, vendar je vzrok znan in ga lahko pojasnimo.
- **Nesprejemljivo**: računalniški program ne napove parametra, in vzrok ni znan.

Kolikostno oceno lahko napravimo z metodama NSA in HFP. Povedati je treba, da metodi NSA in HFP pri kolikostni oceni ne omogočata razpoznave izvora napake (tj. vpliv uporabnika, napačen začetni pogoj, pomanjkljivost vhodnega modela itn.) ali neposredno upoštevata časovni odmik določenih pojavov. Časovni odmik se bolje oceni s kakovostno analizo, ki spremlja kolikostno analizo.

2 OPIS MODELIRANJA

2.1 Opis naprave BETHSY

BETHSY je celostna eksperimentalna naprava, katere namen je bil raziskovati prehodne pojave in nezgode tlačnovodnih lahkovodnih reaktorjev. Naprava je pomanjšava trizančne jedrske elektrarne, proizvajalca Framatome s toplotno močjo 2775 MW. Prostornina je pomanjšana v razmerju blizu 1:100, medtem ko so geodetske višine in tlaki ohranjeni [16]. Moč sredice je omejena na raven zaostale toplote, zato na napravi ni bilo mogoče simulirati prehodnih pojavov, v katerih ne pride do zaustavitve sredice.

the SARBM, due to the different normalization, complement each other. Such an example was shown in [14] for pressurizer differential pressure drop.

1.4 The methodology for quantifying the code accuracy

Given a qualified user and a qualified nodalization scheme, the code assessment process of the calculations involves three steps: the first is the selection of an experiment from the Committee on the Safety of Nuclear Installations (CSNI) validation matrices [15] (or a plant transient), the second is a qualitative assessment, and the last is a quantitative assessment.

The qualitative assessment with visual observation gives the first indications about the calculated predictions. The qualitative assessment phase is a necessary prerequisite for a subsequent quantitative phase.

The qualitative analysis is based on subjective judgement marks obtained by evaluating and ranking the discrepancies between the measured and calculated parameters that describe the phenomena. These marks are:

- **Excellent**: the code predicts the parameter within the experimental uncertainty band;
- **Reasonable**: the code generally predicts the phenomena, the time behaviour and the trends;
- **Minimal**: the code does not predict the parameter or the phenomenon, but the reason for this is understood and predictable;
- **Unqualified**: the code does not predict the parameter, and the reason is not understood.

The subsequent quantitative assessment can be managed by applying the SARBM and the FFTBM. It should be noted that the SARBM and the FFTBM do not allow the identification of the error origin (i.e. the user effect, the wrong initial condition, the nodalization model deficiency, etc.) or to take into account directly the time shift of certain phenomena in the quantitative analysis. The time shift is better characterized through the necessary qualitative assessment that must be associated with the quantitative assessment.

2 A DESCRIPTION OF THE MODELLING

2.1 A description of the BETHSY facility

BETHSY is an integral experimental facility whose purpose was to investigate pressurized-water reactor (PWR) accident transients. The reference plant is a three-loop 2775 MWt Framatome PWR plant. The volume scaling is close to 1:100, while the elevations and pressures are preserved [16]. The core power has been limited to decay heat levels. This obviously implies that accident transients without scram could not be investigated.

2.2 Opis vhodnega modela za RELAP5

Razviti splošni vhodni model BETHSY za RELAP5 je bil optimiran na temelju predhodnih modelov ([7], [9], [17] in [18]). Potem je bil potrjen [20] v skladu z mednarodnimi priporočili (geometrijska oblika, ustaljeno stanje, itn.). Vsako od treh zank smo modelirali posebej ne da bi upoštevali majhno asimetrijo, ki vlada med zankami. Modelirali smo vse pomembne dele reaktorskega hladilnega sistema: cevovode reaktorskega hladilnega sistema, črpalko reaktorskega hladiva, sredico, povratni kanal v reaktorski posodi in uparjalnike. Sekundarna stran sestoji iz uparjalnikov in cevovodov. Vhodni model BETHSY za RELAP5 vsebuje 398 vozlišč, 408 spojev in 402 toplotni telesi s 1573 mrežnimi točkami.

2.3 Izbrani poskusi BETHSY

Za kvalifikacijo metode NSA z metodo HFP so bili izbrani poskusi, izvedeni na poskusni napravi BETHSY (Boucle d'Études Thermohydrauliques de Systemes)*. Prvi izbrani poskus je bil BETHSY 6.2 TC, to je 15,24 cm (6-palčni) zlom v hladni veji brez visokotlačnega in nizkotlačnega varnostnega vbrizgavanja (dvojnik poskusov, izvedenih na Veliki poskusni napravi (Large Scale Test Facility - LSTF), na Zanki za preučevanje neobičajnega obnašanja (Loop for Off-normal Behaviour Investigation (LOBI) in Simulatorju za varnostne preskuse (Simulatore per esperienze di sicurezza - SPES)).

Drugi izbrani poskus je bil BETHSY 9.1b, 5,08 cm (2-palčni) zlom v hladni veji z zamujenim končnim posegom, znan tudi kot mednarodni standardni problem št. 27.

Tretji izbrani poskus je bil BETHSY 4.1a TC, kjer so simulirali naravno pretakanje (dvojnik s poskusom na LSTF).

Eksperimentalne podatke smo dobili skupaj s pripadajočimi nezanesljivostmi. Npr.: negotovosti za tlak in temperaturo poskusa BETHSY 9.1b, ki ju prikazuje slika 2, sta 0,18 MPa oz. 4 K [19].

3 REZULTATI

Uporabljen je bil postopek za določitev natančnosti izračuna, opisan v 1. poglavju. V kakovostni fazi ocene z vizualnim opazovanjem grafično prikazanih rezultatov smo prehodne pojave najprej razdelili v časovna okna. Potem smo vizualno opazovali rezultate in jih kakovostno ocenili. Da bi dobili vtis o poteku prehodnih pojavov, slika 2 kaže primarni tlak in temperaturo grelne palice v vrhnjem delu sredice za izmerjene eksperimentalne podatke in rezultate, izračunane z RELAP5/MOD3.2 za izbrane poskuse na BETHSY. Primer subjektivne ocene kot del kakovostne analize je prikazan v preglednici 3. Zaradi kratkosti so grafi za druge spremenljivke in

* Zanka za toplotnohidravlično preučevanje sistemov

2.2 A description of the RELAP5 input model

The developed universal RELAP5 input model for BETHSY was optimised based on previous models ([7], [9], [17] and [18]). Then it was qualified [20] according to the international guidelines (geometry, steady-state etc.). Each of the three loops was represented explicitly without taking into account the small asymmetry between the loops. All major reactor coolant system components were modelled: reactor coolant system piping, reactor coolant pumps, core section, reactor vessel downcomer and steam generators. The secondary side consists of steam generators and steamlines. The RELAP5 input model of the BETHSY facility contains 398 volumes, 408 junctions and 402 heat structures with 1573 mesh points.

2.3 Selected BETHSY experiments

For qualification of the SARBM with the FFTBM three experiments performed on the Boucle d'Etudes Thermohydrauliques de Systemes (BETHSY) were selected. The first selected experiment was BETHSY 6.2 TC, a 15.24-cm (6-inch) cold leg break without a high- and low-pressure safety-injection system (counter-part test with Large Scale Test Facility (LSTF), Loop for Off-normal Behaviour Investigation (LOBI) and Simulatore per esperienze di sicurezza (SPES)).

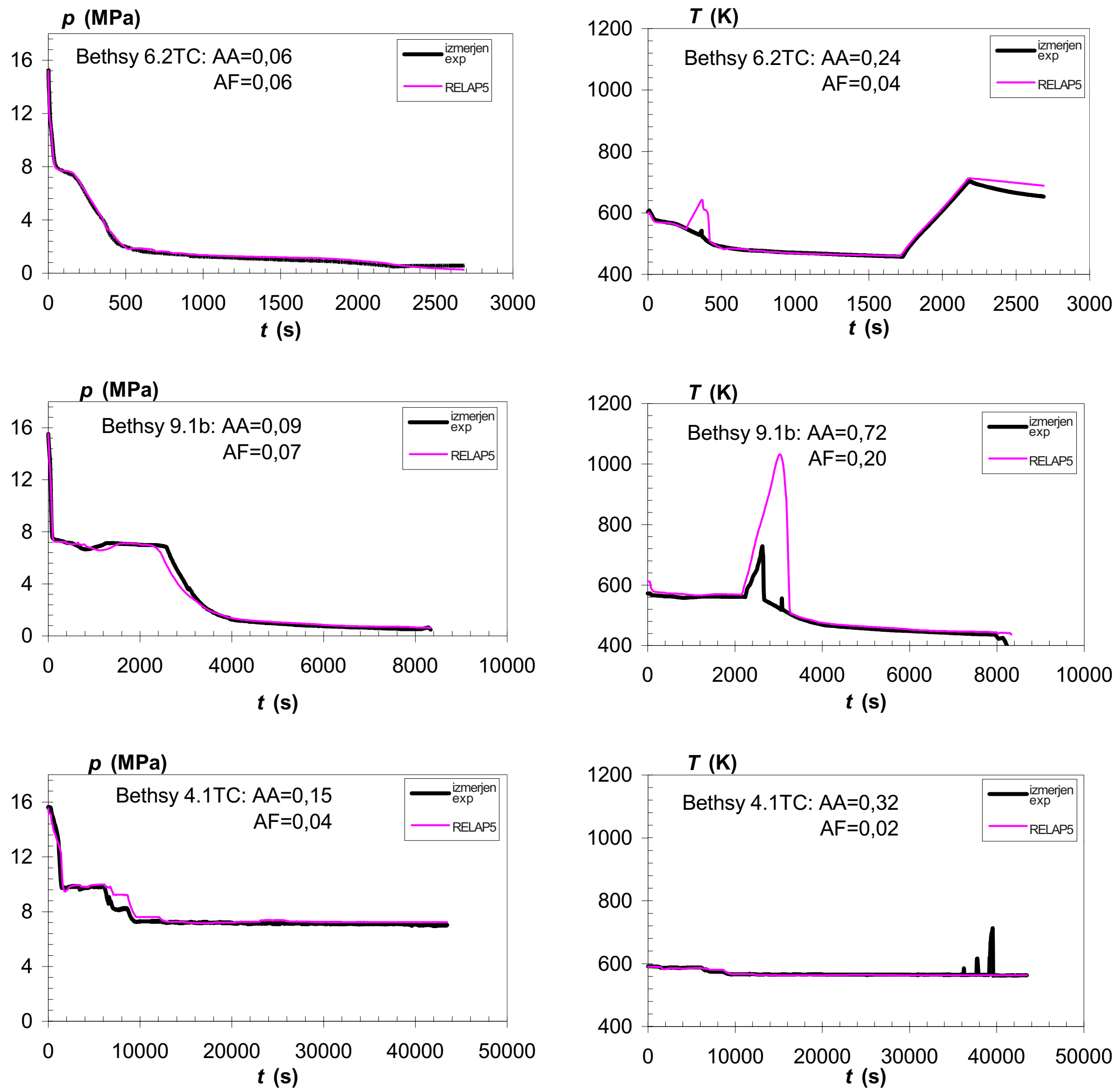
The second selected experiment was BETHSY 9.1b, 5.08-cm (2-inch) cold leg break without a high-pressure injection system and with a delayed ultimate procedure, also known as the international standard problem ISP-27.

The third experiment selected was the BETHSY 4.1a TC natural circulation test (counter-part test with LSTF).

The experimental data were obtained with associated measurement uncertainties. For example, the uncertainty of the pressure and the temperature for BETHSY 9.1b, shown in Figure 2, are 0.18 MPa and 4 K, respectively [19].

3 RESULTS

The methodology for quantifying the code accuracy described in Section 1 was used. In the qualitative assessment phase, including a visual observation of the plotted results, the transients were first subdivided into time windows. Then a visual observation with a qualitative assessment was performed. To give a picture of the transient progression, Fig. 2 shows the primary pressure and the heater-rod temperature at the top of the core for experimental and RELAP5/MOD3.2 calculated results for the selected BETHSY transients. An example of subjective judgement as part of the qualitative analysis is shown in Table 3. For brevity, the other plots and all



Sl. 2. *Primarni tlak in temperatura srajčke za poskuse BETHSY*
Fig. 2. *Primary pressure and cladding temperature for BETHSY experiments*

vse podrobnosti kakovostnih analiz na tem mestu izpuščeni – bralec naj se obrne na [20].

Za kakovostno analizo so bila uporabljena časovna območja, določena na temelju časovnih oken. Za poskus na BETHSY 6.2 TC so bila za analizo natančnosti uporabljena štiri časovna območja: od odprtja zloma do časa izpraznjenja sifona (0 do 140 s), do časa vklopa akumulatorjev (0 do 350 s), do konca vbrizgavanja akumulatorjev (0 do 980 s), in do konca prehodnega pojava (0 do 2687 s). Za poskus BETHSY 9.1b so bila za analizo izbrana tri časovna območja: od trenutka zloma do časa vklopa akumulatorjev (0 do 2962 s), do časa vklopa nizkotlačnega varnostnega vbrizgavanja (0 do 5177 s) in do konca prehodnega pojava (0 do 8330 s). Za poskus BETHSY 4.1a TC so bila za analizo natančnosti ponovno uporabljena tri časovna območja: od začetka prehodnega pojava do konca pojava enofazne naravne cirkulacije (0 do 4380 s), do konca pojava dvofazne naravne cirkulacije (0

the details of the qualitative assessment are not provided in this paper – the reader is referred to [20].

For the quantitative analysis, time intervals were determined based on the time windows. For BETHSY 6.2 TC four time intervals were chosen for the accuracy analysis: from the time of the opening of the break to the time of loop-seal clearance (0 to 140 s), to the time of accumulators start (0 to 350 s), to the end of accumulator injection phase (0 to 980 s), and to the transient end (0 to 2687 s). For BETHSY 9.1b accuracy analysis, three time intervals were selected: from the break occurrence to the time of accumulator injection start (0 to 2962 s), to the time of the low-pressure injection system start (0 to 5177 s), and to the transient end (0 to 8330 s). For the BETHSY 4.1a TC accuracy analysis also three time intervals were selected: from the beginning to the end of the single-phase natural circulation (0 to 4380 s), to the end of the two-phase natural circulation phase (0 to

Preglednica 2. *Meje sprejemljivosti za natančnost izračuna [2]*
Table 2. *Acceptability limits for calculation accuracy [2]*

NSA - SARBM	Mera Measure	HFP - FFTBM
$AF_{tot} \leq 0,1$	zelo dobro very good	$AA_{tot} \leq 0,3$
$0,1 < AF_{tot} \leq 0,25$	dobro good	$0,3 < AA_{tot} \leq 0,5$
$0,25 < AF_{tot} \leq 0,45$	slabo poor	$0,5 < AA_{tot} \leq 0,7$
$AF_{tot} > 0,45$	zelo slabo very poor	$AA_{tot} > 0,7$

Preglednica 3. *Subjektivna ocena izračuna za eksperiment na BETHSY 9.1b [20]*
Table 3. *Subjective judgement of code calculation of BETHSY 9.1b experiment [20]*

Pojav Phenomenon	Parameter, ki opisuje pojav Parameter describing phenomenon	preskus exp.	R5	Ocena Judgement
1. okno: 0 do 2962 s 1st window: 0 to 2962 s				
praznjenje tlačnika pressurizer emptying	tlačnik izpraznjen (s) pressurizer empty (s)	116	125	E
obnašanje primarnega tlaka primary pressure behaviour	primarni tlak (PT) v 2900. s (MPa) primary pressure (PP) at 2900. s (MPa)	4,5	3,66	R
obnašanje sekundarnega tlaka secondary pressure behaviour	sekundarni tlak (ST) v 2900. s (MPa) secondary pressure (SP) at 2900. s (MPa)	4,4	3,52	R
iztok hladiva skozi zlom break flow	povprečen iztok hladiva skozi zlom (kg/s) average break flow (kg/s)	0,53	0,51	E
2. okno: 2962 s do 5177 s 2nd window: 2962 s to 5177 s				
obnašanje akumulatorjev accumulators behaviour	čas vklopa akumulatorjev (s) accumulator injection start (s)	2966	2800	R
	čas izklopa akumulatorjev (s) accumulator injection stop (s)	3856	3900	R
iztok hladiva skozi zlom break flow	čas, ko se PT izenači s ST (s) the time PP equals SP (s)	2366	2275	E
	povprečen iztok hladiva skozi zlom (kg/s) average break flow (kg/s)	0,097	0,112	R
praznjenje sifonov loop seal clearing	čas izpraznitve sifona (s) time of loop seal clearing (s)	-	1975	M
izsušitev sredice core dryout	čas izsušitve sredice (s) time of core dryout (s)	3036	2800	R
	najvišja temperatura srajčke (K) peak cladding temperature (K)	734	1103	M
3. okno: 5177 s do 8330 s 3rd window: 5177 s to 8330 s				
delovanje nizkotlačnega varnostnega vbrizgavanja (LPIS) low pressure injection system (LPIS) intervention	čas vklopa LPIS (s) LPIS start (s)	5184	5775	R
	količina dovedenega hladiva z LPIS (kg) total mass delivered by LPIS (kg)	3077	2049	M

E – odlično, R – sprejemljivo, M – komaj sprejemljivo, R5 – RELAP5
E - excellent, R - reasonable, M – minimal, R5 – RELAP5

do 29375 s) in do konca pojava povratne kondenzacije (0 do 43461 s).

Za analizo natančnosti so bile uporabljene iste spremenljivke, skupno 23 (21 v primeru poskusa 9.1b). Preglednica 4 kaže rezultate kolikostne analize za poskus BETHSY 9.1b za izbrana časovna območja. Izbrane spremenljivke so bile: primarni tlak (PP), sekundarni tlak (P47), tlak v akumulatorju (PSM2), vstopna temperatura v sredico (TF012A), izstopna temperatura iz sredice (TF0304), temperatura hladiva

29375 s), and to the end of reflux condensation mode (0 to 43461 s).

The same set of 23 variables (21 in the case of the 9.1b test) was selected for calculating the code accuracy. Table 4 shows the results of the quantitative analysis for the BETHSY 9.1b test in the three selected time intervals. The selected variables were: pressurizer pressure (PP), secondary pressure (P47), accumulator pressure (PSM2), core inlet temperature (TF012A), core outlet temperature (TF0304), upper-v glavi reaktorske posode (TF042), integrirani pretok skozi zlom (INTQMB), temperatura v povratnem kanalu uparjalnika (SG) št. 1 (TF454C), masni iztok hladiva (QMB), integrirani pretok sistema za zasilno hlajenje sredice (INTQMS), temperatura srajčke (sredina sredice) (TS0215), temperatura srajčke (vrh sredice) (TS0228), sesedna raven hladiva v sredici (ZT0200), tlačna razlika v ceveh U uparjalnika št. 1 (tok navzgor) (DP426), tlačna razlika v uparjalniku št. 1 (DP4), moč sredice (W02), tlačna razlika v sifonu št. 1 (tok navzdol) (DP12VG), tlačna razlika v sifonu št. 1 (tok navzgor) (DP12VP), tlačna razlika v tlačniku (DPP1), tlačna razlika na vstopu v uparjalnik št. 1 (DP41) in tlačna razlika v glavi reaktorske posode (DP050). Za primarni tlak se pri metodi HFP zahteva večja natančnost (PA - AA=0,1) kakor za druge spremenljivke, saj tlak narekuje potek prehodnega pojava. Razen za poskus BETHSY 4.1a TC je bil kriterij za tlak izpolnjen, kar se vidi na sliki 2. Kljub temu lahko vidimo, da je za poskus BETHSY 4.1a TC količnik natančnosti boljši kakor v preostalih dveh primerih. Do razlike pride zaradi različnih značilnosti metod NSA in HFP. Ko si vizualno pogledamo poteke tlakov na sliki 2, lahko sklenemo, da je ujemanje za primarni tlak zelo dobro.

Preglednica 5 kaže skupno natančnost za izbrane prehodne pojave v različnih časovnih območjih. Ko med seboj primerjamo metodi (na podlagi mej sprejemljivosti za skupno natančnost), se rezultati ujemajo zelo dobro. Edina izjema je BETHSY 6.2 TC, kjer je metoda HFP dala oceno zelo dobro (rahlo pod mejo za zelo dobro) in NSA oceno dobro (rahlo nad mejo za zelo dobro) v prvem in četrtem časovnem območju. Izračun BETHSY 9.1b je bil z obema metodama ocenjen kot dobro v vseh časovnih območjih, medtem ko je bil izračun poskusa BETHSY 4.1a TC ocenjen kot zelo dobro v vseh časovnih območjih. S tem smo pokazali, da NSA daje primerljive rezultate kot preverjena metoda HFP. Ko metodi dasta različne rezultate, je potrebna podrobna analiza z vizualnim opazovanjem, da presodimo pomembnost razlike.

4 SKLEPI

V študiji je bila predstavljena nova razvita metoda NSA za oceno natančnosti. Za njeno preveritev smo uporabili tri različne poskuse, izvedene na eksperimentalni napravi BETHSY. Dobljene ocene smo primerjali z rezultati ocenjevanja z metodo HFP.

Prvi pomemben rezultat raziskave je bila ugotovitev, da je natančnost, izračunana z metodo NSA, v časovnem prostoru primerljiva z izračuni natančnosti z metodo HFP v frekvenčnem prostoru. Izračuni z računalniškim programom RELAP5/MOD3.2 za različne poskuse so bili ocenjeni kot zelo dobri ali dobri. Rezultati kažejo, da je bolje združiti metodi NSA in HFP za oceno natančnosti kakor pa metodo NSA

head top temperature (TF042), integrated break mass flow (INTQMB), steam generator (SG) no. 1, downcomer bottom temperature (TF454C), break flow (QMB), integrated emergency core cooling system mass flow (INTQMS), cladding temperature (middle) (TS0215), cladding temperature (top) (TS0228), core collapsed level (ZT0200), SG no. 1 U-tube upflow differential pressure (DP426), SG no. 1 U-tube inlet to outlet differential pressure (DP4), core power (W02), loop seal 1 downflow differential pressure (DP12VG), loop seal 1 upflow differential pressure (DP12VP), pressurizer differential pressure (DPP1), SG no. 1 inlet plenum differential pressure (DP41) and downcomer to upper head differential pressure (DP050). For primary pressure the FFTBM method requires higher accuracy (AA=0.1) than for other variables as the pressure determines the sequence of events for a transient. Except for BETHSY 4.1a TC this criterion was achieved, which can be seen in Figure 2. However, when looking at the accuracy factor, the highest accuracy was obtained for the BETHSY 4.1a TC test. This is because of the different characteristics of the methods. When visually observing the pressure trends in Figure 2 it can be concluded that the agreement for the primary pressure is very good.

Table 5 shows the total accuracy obtained for the selected transients for different time intervals. When comparing the methods (based on the acceptability limits for total accuracy) the results agree very well. The only exception was BETHSY 6.2 TC, where the FFTBM gave very good (slightly below the limit for very good) and the SARBM gave good (slightly above the limit for very good) in the first and fourth time intervals. The BETHSY 9.1b calculation was quantified with both methods as good for all the time intervals, while the BETHSY 4.1a TC calculation was quantified as very good for all time intervals. With this it was shown that the SARBM gives results comparable to the qualified FFTBM. When the methods give different results, a detailed analysis with visual observation is needed to judge the importance of the difference.

4 CONCLUSIONS

In this study the developed SARBM for accuracy quantification was presented. For its validation three different tests performed on the BETHSY facility were used. The obtained accuracy was compared against the results of accuracy quantification by the FFTBM.

The first key result of the investigation was that the calculation accuracy obtained with the SARBM in the time domain is comparable to the calculation accuracy obtained with the FFTBM in the frequency domain. The RELAP5/MOD3.2 calculations of various experiments were quantified as very good or good. The results suggest combining the SARBM with the FFTBM for accuracy quantifica-

Preglednica 4. *Rezultati kolikostne analize za poskus BETHSY 9.1b*
Table 4. *Results of quantitative analysis of BETHSY 9.1b experiment*

Št. No.	Parameter Parameter	Časovno območje - Time interval					
		0 do/to 2962 s		0 do/to 5177 s		0 do/to 8330 s	
		AA	*AF*	*AA*	*AF*	*AA*	*AF*
1	PP	0,13	0,07	0,08	0,07	0,09	0,07
2	P47	0,20	0,07	0,10	0,07	0,10	0,07
3	PSM2	0,36	0,03	0,11	0,05	0,12	0,06
4	TF012A	0,05	0,01	0,03	0,01	0,09	0,02
5	TF0304	0,34	0,05	0,37	0,05	0,36	0,04
6	TF042	0,30	0,04	0,25	0,06	0,22	0,05
7	INTQMB	0,05	0,07	0,05	0,04	0,20	0,16
8	TF454C	0,10	0,03	0,07	0,03	0,08	0,02
9	QMB	0,69	0,32	0,69	0,34	0,85	0,45
10	INTQMS	0,00	0,00	1,00	1,00	0,35	0,44
11	TS0215	1,10	0,20	0,69	0,19	0,58	0,16
12	TS0228	1,37	0,20	0,79	0,23	0,72	0,20
13	ZT0200	0,23	0,12	0,32	0,11	0,39	0,12
14	DP426	0,63	0,31	0,63	0,31	1,41	0,31
15	DP4	0,56	0,65	0,55	0,65	0,58	0,64
16	W02	0,09	0,06	0,09	0,05	0,12	0,05
17	DP12VG	1,33	0,46	0,99	0,47	0,67	0,34
18	DP12VP	0,87	0,18	0,88	0,21	1,08	0,20
19	DPP1	0,13	0,14	0,12	0,14	0,14	0,16
20	DP41	1,16	0,68	1,16	0,68	1,30	0,79
21	DP050	0,83	0,94	0,83	0,94	0,88	0,95
	skupaj total	**0,41**	**0,20**	**0,35**	**0,16**	**0,34**	**0,14**

Preglednica 5. *Ocena skupne natančnosti izračunov s HFP in NSA*
Table 5. *Total accuracy obtained by FFTBM and SARBM*

Časovno območje time interval	BETHSY 6.2 TC		BETHSY 9.1b		BETHSY 4.1a TC	
	AA_{tot}	AF_{tot}	AA_{tot}	AF_{tot}	AA_{tot}	AF_{tot}
1.	0,08	0,13	0,41	0,20	0,09	0,04
2.	0,20	0,09	0,35	0,16	0,13	0,05
3.	0,16	0,08	0,34	0,14	0,17	0,06
4.	0,27	0,11	-	-	-	-

uporabljati samostojno, ker se njuni oceni dopolnjujeta in združeni povečujeta zaupanje v rezultate.

tion rather then using it independently. Namely, the results complement each other and when combined they increase confidence in the results.

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Hitri algoritem za rekonstrukcijo in odvoj digitaliziranih ploskev

A Fast Algorithm for Reconstructing and Flattening Digitised Surfaces

Simon Kolmanič - Nikola Guid

Odvoj ploskev je bistvenega pomena za načrtovanje ravninskih vzorcev, potrebnih za izdelavo npr.: letalskih kril, ladijskih trupov, delov avtomobilske pločevine, zgornjih delov čevljev in oblačil. Čeprav lahko za gradnjo sodobnih ladijskih trupov uporabljamo tudi kompozitne materiale, pa ostaja jeklo v ladjedelništvu še vedno najpogosteje uporabljan material. Zaradi tega ima postopek načrtovanja ravninskih vzorcev še vedno pomembno vlogo pri konstrukciji ladij. Odvoj večjega dela ladijskega trupa je dokaj preprost, izjema sta le premec in krma, ki ju odlikuje zahtevna oblika, zaradi česar potrebujemo učinkovit algoritem za odvoj ploskev. V tem prispevku je predstavljen novi hitri algoritem za rekonstrukcijo in odvoj ploskev, ki temelji na strategiji "deli in vladaj". Za rekonstrukcijo ploskve se uporabljajo odvojni trakovi. Na ta način se lahko ploskev odvije v ravnino brez deformacij.

(Ključne besede: ploskve odvite, ploskve premonosne, vzorci ravninsi, ploskve digitalizirane)

The problem of surface flattening is an important one in pattern engineering. Surface flattening is needed for the design of thin-walled objects, such as airplanes' wings, outer ship hulls, parts of car bodies, shoe uppers, and textile products. Although composite materials can be used for building modern ships' hulls, steel is still the most commonly used material for the ship-building industry. Therefore, the pattern engineering process still has an important role in ship designing. For most of the ship's hull the flattening is quite simple; the problem is the flattening of the stem and the stern, because the surfaces of these parts of the ship are very complex, and therefore an efficient surface-flattening algorithm is needed. In this article a new fast algorithm for surface reconstruction and surface flattening, based on a divide-and-conquer strategy, is presented. Developable stripes are used to approximate the surface, and in this way the surface can be flattened quickly and without any distortion.

(Keywords: surface flattening, developable surfaces, ruled surfaces, flat pattern, digital surfaces)

0 UVOD

Odvoj ploskev je že dolgo znan in zelo razširjen problem. Najdemo ga tako v kartografiji kakor tudi v različnih vejah industrije. Odvoj ploskev je preslikava 3D ploskve v ravnino, pri čemer moramo ohranjati razdalje med točkami ploskve. Kot rezultat te preslikave dobimo ravninski vzorec. Na žalost pa lahko brez napak, ki se kažejo kot prekrivki in vrzeli v nastalem ravninskem vzorcu, odvijemo le določene tipe ploskev. Te ploskve imenujemo odvojne ploskve in v splošnem velja, da poljubne ploskve ne moremo odviti v ravnino brez deformacij [1]. Jasno je, da želi načrtovalec ravninskih vzorcev deformacije zmanjšati na najnižjo mogočo raven. To je težko avtomatizirati, čeprav obstajajo metode, ki

0 INTRODUCTION

The problem of surface flattening is an old one, and is common in cartography and in various branches of industry. Surface flattening is the mapping of a 3D surface onto a 2D plane, where the distances between surface points have to be preserved. As a result of this operation a flat pattern is generated. Unfortunately, only special types of surfaces can be unrolled onto a plane without errors that result in tearing and overlapping in the generated, flat pattern. These surfaces are known as developable surfaces [1]. It is clear that pattern designers would like to reduce distortions to a minimum. This is very hard to do automatically, although some methods of significantly reducing the distortions do already exte deformacije občutno zmanjšajo ([2] in [3]). Posebno težak problem pri načrtovanju vzorcev so prekrivki v končnem ravninskem vzorcu [4]. Prekrivki v ravninskem vzorcu namreč pomenijo vrzel na 3D ploskvi, ki jo iz takega vzorca dobimo. V kartografiji je ta problem rešen z uporabo raznih projekcij, toda odvoj industrijskih predmetov je veliko zahtevnejši, ker so ti pogosto dvojno ukrivljeni. V tem primeru je namreč prekrivke še posebej težko odstraniti [4]. Problem odvoja ploskev je znan tudi v ladjedelništvu, saj je ladijski trup sestavljen iz ravninskih materialov. Na tem mestu je treba omeniti, da se je v zadnjih dveh desetletjih pri izdelavi ladijskih trupov močno povečala uporaba kompozitnih materialov, na primer steklena vlakna, saj jih odlikuje izjemno razmerje med trdnostjo in težo. So tudi zelo upogljivi in zato nadvse primerni za oblikovanje zahtevnih ploskev. Odvoj ploskev, ki jih želimo izdelati s kompozitnimi materiali, je poseben problem, ki ga ne moremo primerjati z odvojem ploskev, izdelanih iz jekla in podobnih materialov. Ta problem je podrobneje obdelan v [5] in ne bo predmet obravnave v tem prispevku. Kljub vsem prednostim kompozitnih materialov pa ostaja jeklo v ladjedelništvu še vedno najpogosteje uporabljan material. Odvoj takih ploskev je v bistvu običajen primer odvoja ploskev, znan tudi v čevljarski in podobnih vejah industrije.

Ker je izdelava ravninskih vzorcev iz 3D ploskev že dolgo znan problem, obstaja mnogo metod, ki ga skušajo rešiti. Te metode smo razdelili v dve skupini: metode, ki skušajo odviti ploskev v enem kosu, in metode za odvoj ploskev po delih [6]. Metode iz prve skupine niso najbolj primerne za odvoj poljubnih ploskev, saj prekrivke v dobljenem ravninskem vzorcu odpravijo le, če je ploskev odvojna. Metode iz druge skupine ploskev razdelijo v manjše krpe, ki jih lažje odvijejo v ravnino in ob tem prihaja do manj deformacij.

Delitev ploskve na manjše krpe je odvisna od samo enega numeričnega parametra in ne zahteva dodatnega uporabnikovega posredovanja. Metoda, predstavljena v tem prispevku, temelji na podobni zamisli. V sistemih računalniško podprtega načrtovanja (RPN - CAD) so ploskve večinoma predstavljene z množico točk in trikotnikov, ki jih povezujejo. Včasih pa se zgodi, da je ploskev predstavljena samo z oblakom točk v 3D prostoru. V tem primeru je treba ploskev poprej rekonstruirati. Za to nalogo smo uporabili odvojne trakove. Po končani rekonstrukciji je odvoj ploskve preprost, saj moramo v ravnino odviti le odvojne trakove. Zamisel odvoja ploskev po delih ni nova, predhodno jo je uporabljal že Elber [7], nato pa še Hoschek za odvoj vrteninskih ploskev [8]. Le-to smo priredili in jo prilagodili delu z digitaliziranimi ploskvami. Postopek približkov krmili samo en numerični parameter in je zaradi tega preprost za uporabo.

ist ([2] and [3]). The biggest problem in pattern generation is overlaps in the generated pattern [4]. These overlaps in the flat pattern represent gaps in the 3D surface obtained by such a pattern. In cartography this problem is already solved by various projections, but the flattening of industrial objects is far more complicated because they are often double curved. In this case the overlaps are especially difficult to eliminate [4]. The problem of surface flattening is also present in the ship-building industry because ships' hulls are assembled from flat material. We should mention here that in the last two decades the use of advanced composite materials, such as fibreglass, for the manufacture of ships' hulls has increased because of their remarkable strength-to-weight ratio and high pliability when deformed into complex, curved shapes. The problem of the flattening of surfaces to be made of a composite material is very specific and cannot be compared with the flattening of surfaces to be made from steel or similar materials. This problem is further discussed in [5], and it will not be covered in this paper. In spite of the advantages of composite materials steel remains the most used material when building ships' hull. The flattening of such a surface is a classical flattening problem that is also encountered in the shoe and similar industries.

Since deriving patterns from 3D surfaces is an old problem, many methods already exist. We have divided them into two groups: methods for flattening the surfaces in one piece and methods for flattening the surfaces using more than one piece [6]. The methods of the first group are not suitable for the automatic flattening of arbitrary surfaces, since the overlaps are eliminated from the generated pattern only if the surface is developable. The methods of the second group divide the surface into smaller patches, which can be flattened more easily and therefore with fewer distortions.

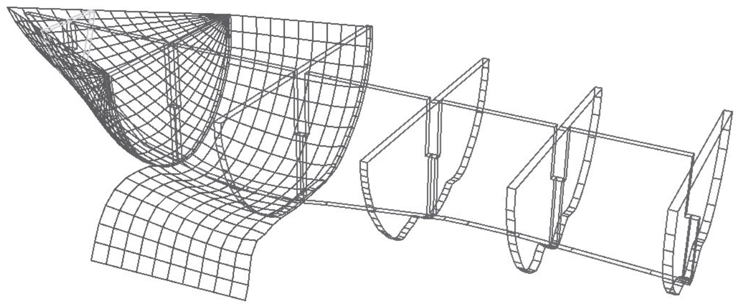
A division of the surface into smaller patches is controlled by simple numerical parameters and does not require any additional interference by the user. The method presented in this paper is based on a similar idea. In computer aided design (CAD) systems the surfaces are usually represented by a set of points and the triangles that connect them. But sometimes the surface is represented only by a cloud of 3D points. In this case the surface has to be reconstructed first. We have used developable stripes to do this. After the surface reconstruction is completed, the flattening is easy, since we only have to unroll the developable stripes onto the plane. The idea of multi-parts surface flattening is not new. Originally it was used by Elber [7] and by Hoschek to flatten surfaces of revolution [8]. We have adopted the Hoschek idea to work with surfaces obtained by digitisation. The approximation process is controlled by only one numerical parameter, and therefore it is very simple to use.

1 PROBLEM ODVOJA PLOSKEV V LADJEDELNIŠTVU

Ladjedelništvo ima že dolgo zgodovino. Stoletja so gradili ladje, podobne telesom vretenčarjev. Ladijska rebra so prekrili z lupino iz usnja, lubja, desk ali jeklenih plošč. Medtem ko ladijska rebra popolnoma določajo obliko ladijskega trupa in mu dajejo trdnost, omogoča lupina ladijskemu trupu vodotesnost in plovnost. Lupina poleg tega daje ladijskemu trupu potrebno trdnost, da vzdrži kombinacijo sil: navzgor usmerjeno silo vzgona, navzdol usmerjeno silo teže in močno silo morskih valov.

1 THE PROBLEM OF SURFACE FLATTENING IN THE SHIP-BUILDING INDUSTRY

The ship-building industry has a long history. For hundreds of years ships have been built like the bodies of vertebrate animals: the ships' ribs have been covered with hide, bark, planks or metal plates. The form of the ship's ribs completely defines the form of the ship, while the skin makes the ship watertight and buoyant. The skin also provides the ship's hull with the necessary strength to withstand a combination of forces: the upward force of buoyancy, the downward force of gravity, and the force of sea waves.



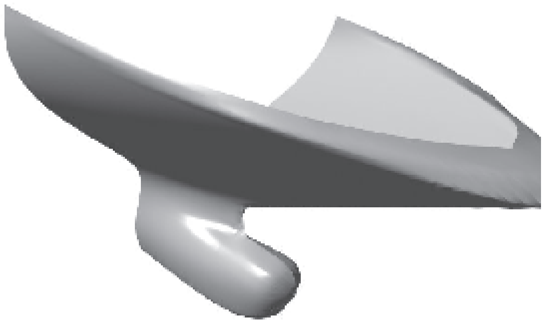
Sl. 1. *Izdelava lupine ladijskega trupa z uporabo ravninskega materiala*
Fig. 1. *Generation of a ship's outer hull using a plane material*

Glede na to, da je lupina izdelana iz ravninskega materiala, moramo pred izdelavo ladje rešiti problem odvoja ploskve. Če je oblika ladijskega trupa nezahtevna, je to dokaj preprosto (sl. 1). Toda če želimo, da je ladja hitra, je oblika ladijskega trupa veliko zahtevnejša. Da zmanjšamo zaviranje valov in trenja, uporabimo premec z zaobljenim profilom, na krmi pa dodamo koleno ([9] in [10]). Premec z zaobljenim profilom in koleno sta zahtevni 3D ploskvi (sl. 2), kar močno otežuje postopek odvoja celotnega ladijskega trupa. Nove oblike ladijskih trupov se dandanes načrtujejo v posebnih sistemih RPN/RPI (računalniško podprte izdelave) z vgrajenimi metodami računalniške dinamike tekočin (RDT - CFD), ki jih uporabljamo za optimizacijo ploskve. Dodatno lahko ploskev optimiziramo tudi v testnih bazenih, kjer lahko merimo zaviranje zaradi trenja. Pred začetkom uporabe sistemov RPN/RPI in metod RDT so bili testni bazeni glavni pripomoček pri načrtovanju novih tipov ladijskih trupov. Ladijski modeli so bili tako najprej izboljšani in nato razžagani v prereze. Vsak prerez je natančno izmerjen, na podlagi meritev pa je nato izdelan načrt prereza. Načrte nato ustrezno povečajo, da ustrezajo dejanski velikosti ladje. Iz teh načrtov nato izdelajo posamezne dele, ki jih sestavijo v ladijski trup naravne velikosti.

Geometrijsko obliko modela ladijske lupine lahko dobimo tudi z njeno digitalizacijo, ki jo izvedemo na vzporednih ravninah v prostoru. Enako ustvarjeno množico točk lahko približamo s 3D ploskvijo ([11] do [15]). Da lahko dobimo načrt za ravninski material lupine, je treba tako dobljeno ploskev odviti. Večina

Since the skin is made of a flat material, it is clear that the surface flattening problem has to be solved before the ship can be built. If the form of the ship's hull is simple, this is quite easy (see Figure 1). However, if the ship is to be fast, the hull shape will need to be more complex: to reduce friction and wave drag, a bulb is added to the bow of the ship and at the stern skegs can be added ([9] and [10]). The shapes of the bulb and the skegs are complex 3D surfaces (see Figure 2), which makes the flattening process of the ship's hull difficult. Today, new hull forms are designed in special CAD/CAM (Computer Aided Manufacturing) systems with integrated computational fluid dynamics (CFD) methods, which are used for surface optimisation. In addition the surface can be optimised in testing pools, where the drag on the ship's model can be measured. The designing of new ships' hulls using testing pools was the main design method before CAD/CAM systems and CFD methods were used. After the models were approved, they were sawed into cross sections; blueprint measurements were made from each cross section; these were then mathematically enlarged so that the ship could be built to full scale. From the full-scale measurements, parts were constructed and assembled to build the full-sized hull.

The geometry of the ship's hull model can also be obtained by surface digitising, made on parallel planes in 3D space. The set of points generated in this way can be approximated by a 3D surface ([11] to [15]). To get the blueprint for the plane material of the skin, the obtained surface has to



Sl. 2. *Ploskev testnega premca z zaobljenim profilom za zmanjšanje trenja*
Fig. 2. *The bow surface of the test hull with the bulb for friction-drag minimisation*

metod, uporabljenih v današnjih tržnih paketih RPN, ki temeljijo na geometrijskem načinu odvoja, je približnih. Izvirno 3D ploskev približajo s trikotniki, ki sestavljajo 3D mrežo. Pri odvoju nato izberemo začetni trak ter smer odvoja, nakar odvijemo prvi trak v ravnino. Preostali del ploskve nato odvijemo na podoben način ([2] in [16]). Glavna pomanjkljivost teh metod so prekrivki in razpoke med trakovi v nastalem ravninskem vzorcu. Do omenjenih nepravilnosti prihaja zaradi kotne okvare, ki jo najdemo v definiciji Gaussove ukrivljenosti v posamezni točki triangulacijske ploskve [16]:

be flattened. Most of flattening methods used in commercial CAD systems that are based on a geometrical approach are approximate. The original 3D surface is approximated by triangles forming a 3D grid. Then the starting strip and the direction are chosen, along which these triangles are unfolded into the plane. The rest of the surface is unfolded in similar fashion ([2] and [16]). The main disadvantage of these methods is the presence of gaps and overlaps between the stripes in the generated, flat pattern. These anomalies arise from the angular defect, which can be found in the definition of the Gaussian curvature at a given point on the triangulated surfaces [16]:

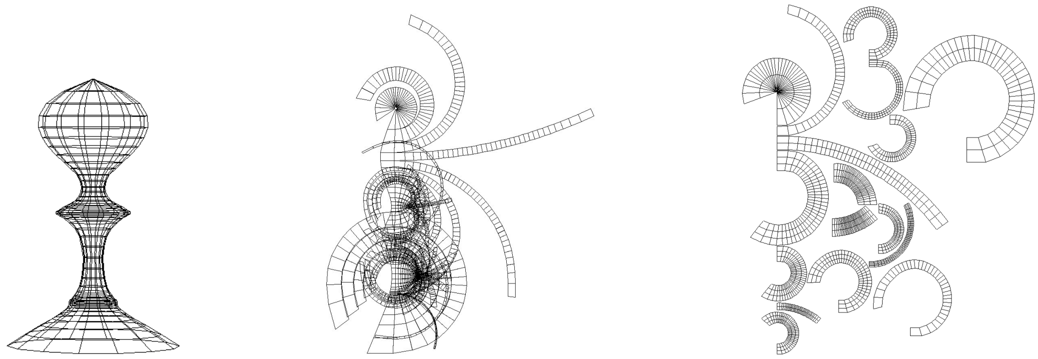
$$K = \frac{\delta}{S} \qquad (1),$$

kjer je δ kotna okvara, ki je enaka kotu 2π, zmanjšanem za vsoto notranjih kotov trikotnikov pri dani točki, S pa je enak 1/3 ploščine teh trikotnikov. Iz enačbe (1) je razvidno, da je kotna okvara odvisna od vrednosti Gaussove ukrivljenosti v dani točki in od dane triangulacije, saj z manjšimi trikotniki zmanjšamo tudi kotno okvaro in s tem napako v ravninskem vzorcu. Ker pa je v našem primeru triangulacija odvisna od algoritma za rekonstrukcijo predmeta, to ne pomaga veliko. Na število napak v ravninskem vzorcu pomembno vpliva tudi izbira začetnega traku in smeri odvoja, kar pa je prav tako zahteven problem.

Da v celoti odpravimo prekrivke v ravninskem vzorcu, obenem pa se izognemo težavam pri izbiri začetnega traku in smeri odvoja, smo uporabili zamisel odvoja ploskev po delih [6]. Tudi v tem primeru gre za približni postopek, vendar je kakovost ravninskega vzorca boljša. Razliko lahko prikažemo že na preprosti vrteninski ploskvi, prikazani na sliki 3a. Metoda, temelječa na Gaussovi ukrivljenosti [16], vrne ravninski vzorec, prikazan na sliki 3b, ki je zaradi številnih prekrivkov neuporaben. Ravninski vzorec na sliki 3c je dobljen z metodo, temelječo na strategiji "deli in vladaj" [6], ki ploskev razdeli na posamezne, med seboj neodvisne trakove. To metodo smo tudi izbrali za izhodišče pri razvoju metode za rekonstrukcijo in odvoj digitaliziranih ploskev.

where δ is the angular defect equal to 2π less the sum of the interior angles meeting at the given point, and S is equal to 1/3 of the areas of those triangles. In equation 1 it can be seen that the angular defect depends on the value of the Gaussian curvature at the given point and for a given triangulation, since the angular defect, and with it also the error in the flat pattern, can be decreased by the use of smaller triangles. Because in our case the triangulation depends on the object-reconstruction algorithm, this is not helpful. The number of errors in the flat pattern is related to the choice of the starting strip and the unfolding direction, which is also a complex problem.

To eliminate completely the overlaps in the flat pattern and, at the same time, to avoid the difficulties associated with the choice of starting strip and unfolding direction, we use the approach of per partes surface flattening [6]. This is also an approximate approach, but the quality of the pattern is better. The difference can be shown on simple surfaces of revolution, shown in Figure 3a. The method, based on Gaussian curvature [16], generates the pattern shown in Figure 3b, which is unusable because of the numerous overlaps in it. The pattern shown in Figure 3c is generated by a method based on a divide-and-conquer strategy [6], which divides the surface into a set of independent stripes. We have chosen this method as the origin for developing a method for the reconstructing and flattening of digitized surfaces.



a) b) c)

Sl. 3. *a) Preprosta vrteninska ploskev*
b) Ravninski vzorec, dobljen z metodo, temelječo na [16], ob slabo izbranem začetnem traku.
c) Ravninski vzorec, dobljen z metodo, temelječo na strategiji "deli in vladaj" [6]
Fig. 3 *a) Simple surface of revolution*
b) Flat pattern generated by the method based on [16] with a badly chosen starting strip
c) Flat pattern generated by the method based on a divide-and-conquer strategy [6]

Množico 3D točk približamo z množico odvojnih trakov. Metoda za rekonstrukcijo ploskev, temelječa na uporabi odvojnih trakov, je predstavljena bolj podrobno v naslednjem razdelku.

2 REKONSTRUKCIJA PLOSKEV Z UPORABO ODVOJNIH TRAKOV

Digitalizacijo izvedemo tako, da točke ležijo v vzporednih ravninah. Zaradi splošnosti je v ravninah dovoljeno različno število točk. Če v vsaki ravnini med seboj povežemo točke v vrstnem redu, določenem z digitalizacijo, dobimo krivulje prečnih prerezov, ki jih bomo označevali s $\mathbf{c}^i$, $i = 1, 2, \ldots, N$. V [6], [17] lahko vidimo, da je med dvema krivuljama prečnih prerezov mogoče skonstruirati odvojni trak. Tem krivuljam pravimo tudi vodila. Odvojni trak je posebna premonosna ploskev [1]. Daljico, ki povezuje dve točki na vodilih, imenujemo generator [17]. Rekonstrukcijo ploskve začnemo z izvedbo odvojnega traku med prečnima prerezoma $\mathbf{c}^1$ in $\mathbf{c}^N$. To dosežemo s klicem postopka `divide(1, N)`, ki uporablja strategijo "deli in vladaj" (izpis 1). Nato je treba izračunati presečišča med odvojnim trakom in ravninami, v katerih ležijo vmesni prečni prerezi. Če je razlika med izračunanimi presečišči in danimi prečnimi prerezi prevelika, odvojni trak z uporabo strategije "deli in vladaj" zožimo. Postopek večkrat ponavljamo, dokler ne dosežemo želene natančnosti. Če zapišemo problem bolj splošno, velja, da odvojni trak, $\mathbf{s}(\mathbf{c}^b, \mathbf{c}^f)$, napet med krivuljama $\mathbf{c}^b$ in $\mathbf{c}^f$ ($1 \le b < f \le N$), seka ravnine prečnih prerezov $\mathbf{c}^k$, $b < k < f$ (sl. 4).

Presečišče $\mathbf{s}_j^k = \left(s_{xj}^k,\ \ s_{yj}^k,\ \ s_{zj}^k\right)$ med j-tim generatorjem odvojne ploskve, to je daljico, ki povezuje j-to točko na b-ti prečni krivulji, tj. $\mathbf{c}_j^b = \left(c_{xj}^b,\ \ c_{yj}^b,\ \ c_{zj}^b\right)$, in j-to točko na f-ti prečni

The set of 3D points is approximated by the set of developable stripes. In the next section the method of surface reconstruction using the approximation with developable stripes is explained in more detail.

2 SURFACE RECONSTRUCTION USING DEVELOPABLE STRIPES

The surface digitisation is performed in such a way that all the points lie in parallel planes. Generally, there are a different number of points in the planes. If line segments connect the points in each plane in the order given by the digitising process, cross-section curves are generated that will be denoted by $\mathbf{c}^i$, $i = 1, 2, \ldots, N$. As shown in [6] and [17], a developable surface can be constructed between two cross-section curves. These kinds of curves are also known as directrix curves. The developable stripe is a special case of a ruled surface [1]. A line segment connecting two points on directrices is called a linear generator [17]. The surface reconstruction is started by the generation of a developable stripe between the cross-section curves $\mathbf{c}^1$ and $\mathbf{c}^N$. This can be done with the call of the procedure `divide(1, N)`, based on the divide-and-conquer strategy (see listing 1). Then the intersecting points between the generated developable stripe and the cross-section planes lying in between have to be calculated. As long as the difference between the calculated intersection and cross-section points is not small enough, the developable stripe is narrowed with the help of the divide-and-conquer strategy. The procedure is recursively repeated until the desired precision is achieved. If we state this problem more generally, it is necessary that the developable stripe $\mathbf{s}(\mathbf{c}^b, \mathbf{c}^f)$ between the cross-section curves $\mathbf{c}^b$ and $\mathbf{c}^f$ ($1 \le b < f \le N$) intersects the planes of the cross-section curves $\mathbf{c}^k$, $b < k < f$ (see Fig. 4).

The intersection point $\mathbf{s}_j^k = \left(s_{xj}^k,\ \ s_{yj}^k,\ \ s_{zj}^k\right)$ between the j-th surface generator, this is the line segment connecting the j-th point of the b-th cross-section curve, $\mathbf{c}_j^b = \left(c_{xj}^b,\ \ c_{yj}^b,\ \ c_{zj}^b\right)$, and the j-th point

Izpis 1. *Algoritem za rekonstrukcijo ploskev, temelječ na strategiji "deli in vladaj"*
Listing 1. *Algorithm for surface reconstruction based on the divide-and-conquer strategy*

```
procedure divide(b, f)
 Vhod/Input:   indeksa vodilj/indexes of directrix curves
 Izhod/Output:  množica odvojnih trakov/set of developable stripes

begin
  Generiraj odvojni trak med prečnima prerezoma z indeksoma b in f./
  Generate a developable stripe between cross sections b and f.

  if curveDifference(b, f) > e then
   begin
    if f-b = 1 then /* končni pogoj rekurzije/ end condition of recursion
*/
      Shrani odvojni trak v množico odvojnih trakov./
      Save the developable stripe in a set of developable stripes.
    else
     begin          /* w določa enačba 6/ w is defined by Eq. 6*/
      divide(b, w); /* rešitev levega podproblema/ solution of the left
subproblem */
        divide(w, f); /* rešitev desnega podproblema/ solution of the
right subproblem */
     end
   end
  else
   Shrani odvojni trak v množico odvojnih trakov./
   Save the developable stripe into a set of developable stripes.
end
```

krivulji, tj. $\mathbf{c}_j^f = \left(c_{xj}^f,\ c_{yj}^f,\ c_{zj}^f\right)$, ter k-to ravnino prečnega prereza izračunamo z naslednjimi enačbami:

of the f-th cross-section curve, $\mathbf{c}_j^f = \left(c_{xj}^f,\ c_{yj}^f,\ c_{zj}^f\right)$, and the k-th cross section plane is calculated using the following equations:

$$s_{xj}^k = -\frac{Ba + Cb + D}{A + Bl + Ch}$$
$$s_{yj}^k = l s_{xj}^k + a \qquad (2),$$
$$s_{zj}^k = h s_{xj}^k + b$$

kjer so A, B, C, in D parametri k-te ravnine prečnega prereza ($Ax + By + Cz + D = 0$), ki jih določimo iz naslednjih enačb:

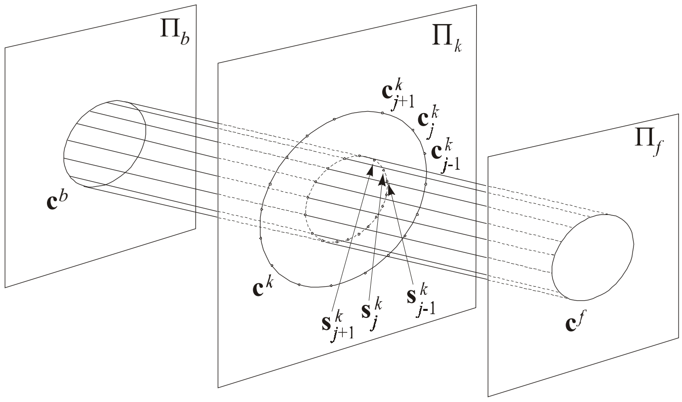
where A, B, C, and D are parameters of the k-th cross-section plane ($Ax + By + Cz + D = 0$), determined by the following equations:

$$A = c_{yu}^k(c_{zv}^k - c_{zt}^k) + c_{yv}^k(c_{zt}^k - c_{zu}^k) + c_{yt}^k(c_{zu}^k - c_{zv}^k)$$
$$B = c_{xu}^k(c_{zt}^k - c_{zv}^k) + c_{xv}^k(c_{zu}^k - c_{zt}^k) + c_{xt}^k(c_{zv}^k - c_{zu}^k)$$
$$C = c_{yu}^k(c_{xt}^k - c_{xv}^k) + c_{yv}^k(c_{xu}^k - c_{xt}^k) + c_{yt}^k(c_{xv}^k - c_{xu}^k) \qquad (3).$$
$$D = c_{xu}^k(c_{yt}^k c_{zv}^k - c_{yv}^k c_{zt}^k) + c_{xv}^k(c_{yu}^k c_{zt}^k - c_{yt}^k c_{zu}^k) + c_{xt}^k(c_{yv}^k c_{zu}^k - c_{yu}^k c_{zv}^k)$$

Točke $\mathbf{c}_u^k = \left(c_{xu}^k,\ c_{yu}^k,\ c_{zu}^k\right)$, $\mathbf{c}_v^k = \left(c_{xv}^k,\ c_{yv}^k,\ c_{zv}^k\right)$ in $\mathbf{c}_t^k = \left(c_{xt}^k,\ c_{yt}^k,\ c_{zt}^k\right)$ so točke k-te krivulje prečnega prereza, ki so med seboj najbolj oddaljene. Vrednosti l, h, a in b v enačbi 2 so parametri j-tega linearnega generatorja, ki ga izračunamo z enačbami:

The points $\mathbf{c}_u^k = \left(c_{xu}^k,\ c_{yu}^k,\ c_{zu}^k\right)$, $\mathbf{c}_v^k = \left(c_{xv}^k,\ c_{yv}^k,\ c_{zv}^k\right)$ and $\mathbf{c}_t^k = \left(c_{xt}^k,\ c_{yt}^k,\ c_{zt}^k\right)$ are the three most distant points of the k-th cross-section curve. The values l, h, a, and b in Equation 2 are the parameters of the j-th linear generator, which can be calculated with the following equations:

$$l = \frac{c_{yj}^f - c_{yj}^b}{c_{xj}^f - c_{xj}^b},\quad h = \frac{c_{zj}^f - c_{zj}^b}{c_{xj}^f - c_{xj}^b},\quad a = c_{yj}^b - k c_{xj}^b \text{ in/and } b = c_{zj}^b - h c_{xj}^b \qquad (4).$$



Sl. 4. *Rekonstrukcija ploskve z uporabo odvojnih trakov*
Fig. 4. *Reconstruction of a surface with developable stripes*

Ustrezno presečišče je treba določiti za vsak linearni generator posebej.

Vektor napake $\mathbf{e}=\left(e_x, \quad e_y, \quad e_z\right)$, ki določa razliko med prečnim prerezom in izračunanimi presečišči, izračunamo z obrazci:

The intersection point has to be calculated for all linear generators.

The blunder vector $\mathbf{e}=\left(e_x, \quad e_y, \quad e_z\right)$, representing the difference between the cross-section curve and the intersection points, is calculated using the formulae:

$$e_x=\frac{1}{n}\sum_{j=1}^{n}\left|s_{xj}^k-c_{xj}^k\right|, \quad e_y=\frac{1}{n}\sum_{j=1}^{n}\left|s_{yj}^k-c_{yj}^k\right|, \quad e_z=\frac{1}{n}\sum_{j=1}^{n}\left|s_{zj}^k-c_{zj}^k\right| \qquad (5),$$

kjer je n število točk prečnega prereza. Dane enačbe so preproste in hitre. Odvojni trak je treba zožiti, kakor je prikazano v izpisu 1, če je izpolnjen pogoj 6:

where n is the number of points on the cross-section curve. The formulae are simple and fast. The developable stripe has to be narrowed, as shown in listing 1, if the condition 6 is true:

$$e=\frac{e_x+e_y+e_z}{3}>\varepsilon \qquad (6),$$

kjer je ε tolerančni prag, ki pomeni vrednost v milimetrih, saj so predmeti izraženi v tej merski enoti. Enačbi (5) in (6) sta v izpisu 1 zajeti v klicu funkcije `curveDifference(e, f)`, kjer najprej določimo enačbo sredinske ravnine prečnega prereza med krivuljama $\mathbf{c}^b$ in $\mathbf{c}^f$. Nato izračunamo presečišča med to ravnino in odvojnim trakom (2). Če je razlika znotraj tolerance, izračunamo še presečišča s preostalimi ravninami. Izračun ustavimo takoj, ko je pogoj 6 izpolnjen. Ko moramo odvojni trak zožiti, je treba poiskati novo krivuljo prečnega prereza $\mathbf{c}^w$. Njen indeks w je celo število, ki ga dobimo z izločitvijo decimalnega dela aritmetičnega povprečja indeksov b in f:

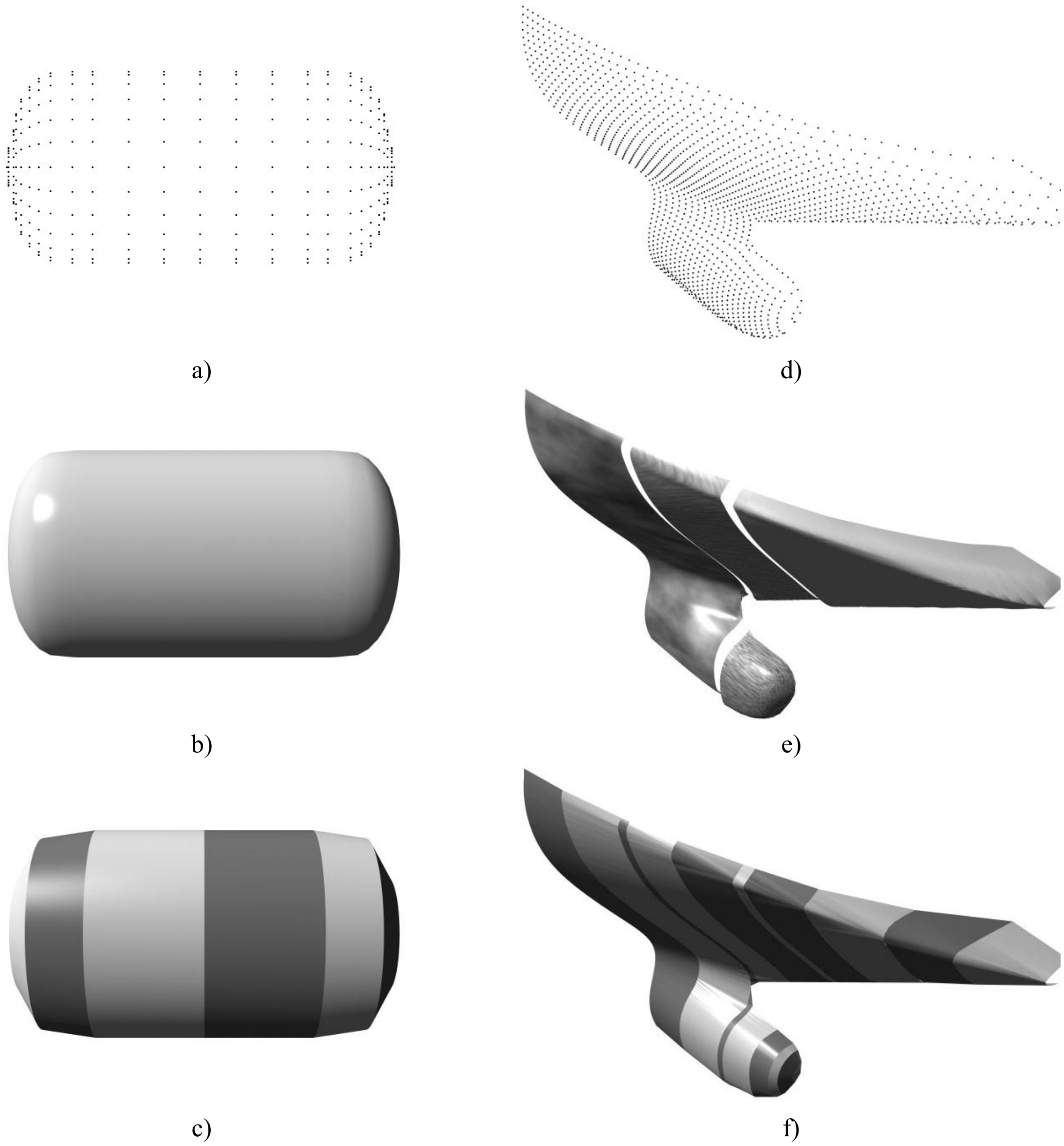
Kot rezultat dobimo dva trakova $\mathbf{s}(\mathbf{c}^b, \mathbf{c}^w)$ in $\mathbf{s}(\mathbf{c}^w, \mathbf{c}^f)$, ki ju ponovno zožimo, če nista znotraj tolerančnega praga. Kakovost približka je odvisna tudi od natančnosti digitalizacije. Če je bila pri digitalizaciji izpuščena kakšna podrobnost, tega ne moremo popraviti.

Rezultate rekonstrukcije ploskve, ki temelji na strategiji "deli in vladaj" ob uporabi odvojnih trakov, lahko vidimo na sliki 5, kjer sta predstavljeni rekonstrukciji hrama za gorivo in polovice ladijskega premca, katerega podatke smo dobili v ladjedelnici Fincantieri v Trstu. Medtem ko je bila rekonstrukcija hrama goriva preprosta, smo morali premec poprej

where ε is a tolerance limit, which is a numerical value measured in millimetres (because our objects are measured in this unit). Equations 5 and 6 are included in the call of a function `curveDifference(e, f)` (see listing 1), where the equation of the middle cross-section plane between the cross sections $\mathbf{c}^b$ and $\mathbf{c}^f$ is determined first. Then the intersection points between that plane and developable stripe are calculated (Eq. 2). If the difference is within the tolerance, the intersection points with the other planes are calculated too. The calculation is stopped when the condition 5 is true. If the developable stripe needs to be narrowed, the new cross-section curve $\mathbf{c}^w$ has to be found. The index w is an integer value, determined by the extraction of the decimal part of the mean value of the indexes b and f:

As a result, two stripes, $\mathbf{s}(\mathbf{c}^b, \mathbf{c}^w)$ and $\mathbf{s}(\mathbf{c}^w, \mathbf{c}^f)$, are generated, which are recursively narrowed if they are not within the tolerance limit. The approximation quality also depends on the digitisation precession. If some details have been missed in the digitisation process, they cannot be corrected here.

The results of the surface reconstruction, based on the divide-and-conquer strategy and the use of the developable stripes, can be seen in Figure 5, where the reconstruction of a fuel tank and a half of a ship's bow, obtained in the shipyard Fincantieri in Trieste, is presented. While the reconstruction of the fuel tank was easy, the reconstruction of the ship's bow was more



Sl. 5. *a) Množica 3D točk, ki določa ploskev hrama za gorivo.*
b) Pričakovana ploskev hrama.
c) Rekonstrukcija ploskve hrama za gorivo (z dolžino 3,6 m), pri tolerančnem pragu ε = 1,50 mm.
d) Množica 3D točk, ki določa obliko polovice ladijskega premca z zaobljenim profilom.
e) Delitev premca, potrebna za odstranitev nezveznosti v prečnih prerezih zaobljenega profila.
f) Rekonstrukcija premca, pri tolerančnem pragu ε = 0,50 mm.
Fig. 5. *a) Set of 3D points defining the surface of the fuel tank*
b) Expected surface of the fuel tank
c) Reconstructed surface of the fuel tank (its length is 3.6m) with the tolerance limit ε = 1.50 mm
d) Set of 3D points defining the shape of the half of the bow
e) The division of the bow necessary to eliminate the discontinuity in the cross-sections of the bulb
f) Reconstruction of the bow with the tolerance limit ε = 0.50 mm

razdeliti na štiri dele (sl. 5e), da smo odstranili nezveznost v prečnih prerezih zaobljenega profila. Vse štiri dele smo ločeno rekonstruirali in potem združili v sliki 5f. Trakove, uporabljene v rekonstrukciji predmeta, je treba še odviti v ravnino. Opis tega postopka lahko najdemo v naslednjem razdelku.

complicated. First, the ship's bow had to be divided into four parts (see Figure 5e) in order to remove the discontinuation of the cross-section curves of the bulb. All four parts were reconstructed separately, and then joined in Figure 5f. After the surface reconstruction the stripes had to be flattened. The description of that process can be found in the next section.

3 ODVOJ PLOSKVE V RAVNINO

Odvojni trak sestavljajo 3D štirikotniki, ki povezujejo po dve ustrezni točki med sosednjimi vodili (na primer $\mathbf{p}_1^*$ s $\mathbf{p}_4^*$ in $\mathbf{p}_2^*$ s $\mathbf{p}_3^*$, sl. 6). Njegov odvoj v ravnino je v bistvu preslikava 3D štirikotnikov v ravnino, pri čemer je treba ohraniti dolžine robov. Ta preslikava mora biti pri tem natančna in hitra. Zaradi tega ustrezen štirikotnik raje skonstruiramo v ravnini, kakor da bi izvirni 3D štirikotnik postavili v ravnino s pomočjo zasukov. Naj bodo dana oglišča 3D štirikotnika $\mathbf{p}_1^*$, $\mathbf{p}_2^*$, $\mathbf{p}_3^*$ in $\mathbf{p}_4^*$, ki je v splošnem neravninski. Iz razdalj med oglišči določimo dolžine njegovih stranic: d_1, d_2, d_3 in d_4. Neravninski štirikotnik moramo skonstruirati v ravnini z uporabo dveh trikotnikov, ki ju dobimo z eno od diagonal štirikotnika. Pri tem ni pomembno, katero od diagonal izberemo. Naj prvi trikotnik določajo točke $\mathbf{p}_1^*$, $\mathbf{p}_2^*$ in $\mathbf{p}_4^*$, drugi trikotnik pa točke $\mathbf{p}_2^*$, $\mathbf{p}_3^*$ in $\mathbf{p}_4^*$. Če želimo drugi trikotnik postaviti v ravnino prvega, moramo izračunati dolžino skupne stranice, ki jo označimo z d_5 (ta pomeni razdaljo med točkama $\mathbf{p}_2^*$ in $\mathbf{p}_4^*$). Točke, ki določajo ravninski štirikotnik, označimo s $\mathbf{p}_1$, $\mathbf{p}_2$, $\mathbf{p}_3$ in $\mathbf{p}_4$.

Najprej izračunamo vrednosti notranjih kotov ravninskega štirikotnika α, β in γ z naslednjimi enačbami (sl. 6a):

3 UNROLLING THE SURFACE ONTO THE PLANE

The developable stripe is composed of 3D quadrangles, which connect at two points of neighbouring directrices (for example $\mathbf{p}_1^*$ with $\mathbf{p}_4^*$ and $\mathbf{p}_2^*$ with $\mathbf{p}_3^*$, see Figure 6). The unrolling of the developable surface is, in fact, a mapping of the 3D quadrangles onto the plane, where the edge distances are preserved. The mapping process must be fast and accurate. Therefore, we construct the quadrangles in the plane instead of rotating the original 3D quadrangles onto the plane. Let $\mathbf{p}_1^*$, $\mathbf{p}_2^*$, $\mathbf{p}_3^*$ and $\mathbf{p}_4^*$ be vertices of a general nonplanar 3D quadrangle. The lengths of the edges (d_1, d_2, d_3, and d_4) are determined by the distances between the vertices. The nonplanar quadrangle has to be constructed in the plane with the help of two triangles that we get with the help of one of its diagonals. It is not important which diagonal is chosen. Let us take the first triangle be determined by the points $\mathbf{p}_1^*$, $\mathbf{p}_2^*$ and $\mathbf{p}_4^*$, and the second one by the points $\mathbf{p}_2^*$, $\mathbf{p}_3^*$ and $\mathbf{p}_4^*$. If we want to set the second triangle in the plane of the first one, we have to calculate the distance of their common edge, denoted by d_5 (which is the distance between the points $\mathbf{p}_2^*$ and $\mathbf{p}_4^*$). The points, determined on the planar quadrangle, are denoted by $\mathbf{p}_1$, $\mathbf{p}_2$, $\mathbf{p}_3$, and $\mathbf{p}_4$.

First we calculate the values of the inner angles α, β, and γ of a planar triangle using the following equations (see Figure 6a):

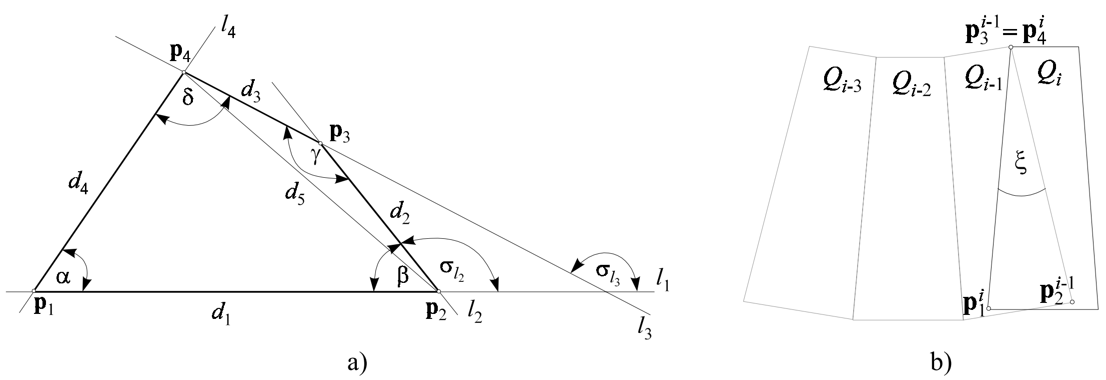
$$\alpha = 2\arctan\left(\frac{r_1}{s_1 - d_5}\right),\ \beta = 2\left(\arctan\left(\frac{r_1}{s_1 - d_4}\right) + \arctan\left(\frac{r_2}{s_2 - d_3}\right)\right),\ \gamma = 2\arctan\left(\frac{r_2}{s_2 - d_5}\right) \quad (7),$$

kjer so / where

$$s_1 = \frac{d_4 + d_1 + d_5}{2},\ r_1 = \sqrt{\frac{(s_1 - d_4)(s_1 - d_1)(s_1 - d_5)}{s_1}},\ s_2 = \frac{d_5 + d_2 + d_3}{2} \text{ in / and } r_2 = \sqrt{\frac{(s_2 - d_5)(s_2 - d_2)(s_2 - d_3)}{s_2}} \quad (8).$$

Brez izgube splošnosti lahko skonstruiramo ravninski štirikotnik $\mathbf{p}_1\mathbf{p}_2\mathbf{p}_3\mathbf{p}_4$ v ravnini xy. Njegovo konstrukcijo začnemo z določitvijo lege enega od njegovih oglišč, na primer oglišča $\mathbf{p}_1$. Nato izberemo eno izmed dveh stranic, s katerima je povezano

Without any loss of generality we can construct the quadrangle $\mathbf{p}_1\mathbf{p}_2\mathbf{p}_3\mathbf{p}_4$ in the xy plane. We start its construction by defining the position for one of the vertices, for example, the vertex $\mathbf{p}_1$. Then we select one of two edges that are connected to the



Sl. 6. *a) Konstrukcija splošnega ravninskega štirikotnika*
b) Ohranjanje odvisnosti sosednosti pri preslikavi štirikotnikov
Fig. 6. *a) Construction of an arbitrary planar quadrangle*
b) Preserving the neighbouring relation by quadrangle mapping

izbrano oglišče $\mathbf{p}_1$. Naj bo to stranica $\mathbf{p}_1\mathbf{p}_2$, ki leži na premici l_1. Zaradi enostavnosti računanja postavimo, da je premica l_1 vodoravna. Lego oglišča $\mathbf{p}_2$ tako izračunamo kot (x_1+d_1, y_1). Izračun lege oglišča $\mathbf{p}_3$ je nekoliko zahtevnejši, saj je treba ohraniti vrednost notranjega kota β. Na sliki 5a lahko vidimo, da ležita oglišči $\mathbf{p}_2$ in $\mathbf{p}_3$ na skupni premici l_2. Premica l_2 je določena z lego oglišča $\mathbf{p}_2$ in vrednostjo kota σ_{l_2}, ki je zunanji kot h kotu $\beta(\sigma_{l_2} = \pi - \beta)$. Lego oglišča $\mathbf{p}_3$, ki je od oglišča $\mathbf{p}_2$ oddaljena za razdaljo d_2, lahko izračunamo z naslednjima enačbama:

vertex $\mathbf{p}_1$. Let it be the edge $\mathbf{p}_1\mathbf{p}_2$ that lies on the line l_1. To reduce the computational complexity, we define that the line l_1 is horizontal. The position of the vertex $\mathbf{p}_2$ is (x_1+d_1, y_1). The calculation of the position of the vertex $\mathbf{p}_3$ is not so easy, since the angle β has to be preserved. In Figure 5a it can be seen that the vertices $\mathbf{p}_2$ and $\mathbf{p}_3$ lie on the same line l_2. The line l_2 is determined by the position of the vertex $\mathbf{p}_2$ and the angle σ_{l_2}, which is the supplementary angle to the angle $\beta(\sigma_{l_2} = \pi - \beta)$. The position of the vertex $\mathbf{p}_3$, whose distance to vertex $\mathbf{p}_2$ is d_2, can be calculated using the following equations:

$$x_3 = \frac{-(2kN - 2x_2 - 2ky_2) \pm \sqrt{(2kN - 2x_2 - 2ky_2)^2 - 4(1+k^2)(x_2^2 + y_2^2 - d_2^2 + N^2 - 2Ny_2)}}{2+2k^2} \qquad (9),$$

$$y_3 = kx_3 + N$$

kjer sta $k = \tan(\sigma_{l_2})$ in $N = y_2 - kx_2$. Enačbi (9) določata dve možni rešitvi. Prava je tista, ki določa pozitivno usmeritev štirikotnika.

Nazadnje je treba določiti še lego oglišča $\mathbf{p}_4$. Ker leži oglišče $\mathbf{p}_4$ na premici l_3, moramo poprej določiti vrednost kota σ_{l_3}. To vrednost lahko izračunamo z enačbo:

where $k = \tan(\sigma_{l_2})$ and $N = y_2 - kx_2$. Equations 9 define two possible solutions. We take the vertex that defines the positive orientation of the quadrangle.

Finally, the position of the vertex $\mathbf{p}_4$ has to be calculated. Since the vertex $\mathbf{p}_4$ lies on the line l_3, we have to determine the angle value σ_{l_3} first. This can be calculated using the following equation:

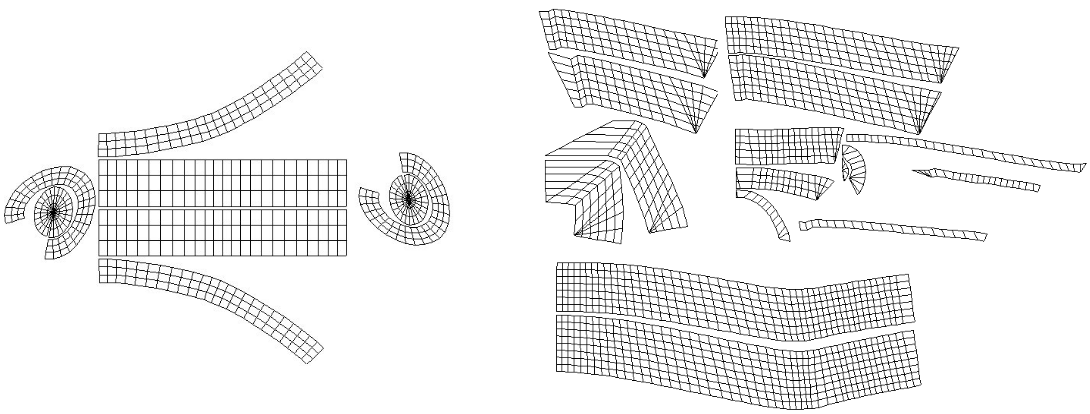
$$\sigma_{l_3} = 2\pi - \beta - \gamma \qquad (10).$$

Lego oglišča $\mathbf{p}_4$ lahko določimo z enačbo (9), kjer sta $k = \tan(\sigma_{l_3})$ in $N = y_3 - kx_3$, namesto x_2 in y_2 pa vzamemo koordinati x_3 in y_3 oglišča $\mathbf{p}_3$, namesto d_2 pa d_3.

Odvoj štirikotnika je končan, ko vzpostavimo odvisnost sosednosti do predhodno odvitih štirikotnikov. Označimo oglišča tekočega štirikotnika Q_i s $\mathbf{p}^i_j$ (j = 1, 2, 3, 4). Štirikotnik Q_i ima stranico $\mathbf{p}^i_1\mathbf{p}^i_4$ enako stranici $\mathbf{p}^{i-1}_2\mathbf{p}^{i-1}_3$ sosednjega štirikotnika Q_{i-1}. Zato moramo najprej premakniti skonstruiran štirikotnik Q_i v takšno lego, da se točki $\mathbf{p}^{i-1}_3$ in $\mathbf{p}^i_4$ ujemata. Nato ga

The position of the vertex $\mathbf{p}_4$ can be determined by Eq. 9, where $k = \tan(\sigma_{l_3})$, $N = y_3 - kx_3$, and instead of the parameters x_2 and y_2 the coordinate values x_3 in y_3 of the vertex $\mathbf{p}_3$ are used. Instead of d_2 the distance d_3 is used.

The flattening of a quadrangle is finished after the neighbouring relation to a previously flattened quadrangle is established. Let us denote the vertices of the running quadrangle Q_i by $\mathbf{p}^i_j$ (j = 1, 2, 3, 4). The edge $\mathbf{p}^i_1\mathbf{p}^i_4$ of the quadrangle Q_i and $\mathbf{p}^{i-1}_2\mathbf{p}^{i-1}_3$ of its neighbour Q_{i-1} are the same. Therefore, we have to translate the quadrangle Q_i into the position where the vertices $\mathbf{p}^{i-1}_3$ and $\mathbf{p}^i_4$ coincide. Second, the generated quadrangle Q_i has to be rotated, by



a) b)

Sl. 7. *a) Rezultat odvoja hrama za gorivo*
b) Rezultat odvoja polovice ladijskega premca
Fig. 7. *a) Result of flattening the fuel tank*
b) Result of flattening one half of the ship's bow

zavrtimo za kot ξ v lego, da se zgoraj omenjeni stranici ujemata (sl. 6b). Vrednost kota ξ računamo podobno kot vrednost kota α (7). Rezultata odvoja ploskev pri uporabi opisanega algoritma sta prikazana na sliki 7.

Testni ploskvi smo rekonstruirali z različnima vrednostima tolerančnih pragov. Pri rekonstrukciji hrama je bila vrednost tolerančnega praga enaka ε = 1,50 mm, pri rekonstrukciji ladijskega premca je bila ta vrednost enaka ε = 0,50 mm. Prvo ploskev smo približali z osmimi odvojnimi trakovi, drugo pa s šestnajstimi. Hram goriva sestavlja 577 točk in polovico ladijskega premca 2550 točk. Za rekonstrukcijo in odvoj hrama z gorivom smo potrebovali 0,120s, za rekonstrukcijo in odvoj polovice ladijskega premca pa 0,260s. Čeprav so druge metode za odvoj ploskev po delih opisanemu algoritmu idejno blizu, jih neposredno z našim algoritmom ne moremo primerjati, saj so vezane na točno določene tipe predstavitve ploskev. Algoritem smo testirali na osebnem računalniku Athlon 900 MHz.

the angle with value ξ, into the position where the above-mentioned edges coincide (Figure 6b). The angle value ξ is calculated in the same way as the angle value α (Eq. 7). The results of surface flattening, using the described algorithm, can be seen in Figure 7.

The test surfaces were reconstructed with a different value of the tolerance limit, which was ε = 1.50 mm for the fuel tank and ε = 0.50 mm for the ship's bow. The first surface was approximated with 8 developable stripes and the surface of the ship's bow was approximated with 16 stripes. The fuel tank consists of 577 points and one half of the ship's bow consists of 2550 points. We needed 0.120s for the reconstruction and the flattening of the fuel tank and 0.260s for the reconstruction and the flattening of one half of the ship's bow. Although there are other methods for per partes surface flattening based on the same idea, we cannot compare them with our algorithm directly, since they are bound to particular surface representation types. The algorithm was tested on an Athlon 900 MHz personal computer.

4 SKLEP

V prispevku smo predstavili novo metodo za rekonstrukcijo in odvoj digitaliziranih krivulj, ki temelji na strategiji "deli in vladaj" ob uporabi odvojnih trakov za približek ploskve. Metoda je hitra, ni pa primerna za rekonstrukcijo predmetov z odprtinami. Metodo smo testirali na dejanskih podatkih ladje, pri kateri smo nezveznost v delu prečnih prerezov premca odpravili tako, da smo le-tega razdelili na štiri dele, ki smo jih nato ločeno rekonstruirali in nato odvili. Za uporabo te metode v ladjedelništvu bi morali še dodatno razviti metodo za določanje oblike jeklenih plošč glede na odvoj in obliko lupine. S tem bi lahko v veliki meri avtomatizirali postopek konstrukcije ladijskih trupov, s čimer bi lahko prihranili precej časa. Metodo bi bilo treba še dodatno prilagoditi za odvoj lupin, izdelanih iz kompozitnih materialov. Čeprav je ostalo še veliko dela, pomeni opisana metoda dober temelj za prihodnje delo.

4 CONCLUSION

In this paper we have presented a new method for reconstructing and flattening digitised surfaces that is based on the divide-and-conquer strategy using the approximation of the surface with developable stripes. The method is fast, but it cannot be used for the reconstruction of objects with holes. We have tested the method on the real data of a ship, where the discontinuation of part of the cross-section curves was eliminated by dividing the bow into four parts that were reconstructed and then flattened separately. To use this method in the ship-building industry, a method for a determining the shape of steel plates, according to the skin flattening and the hull form, has to be developed. This could automate a large part the hull-construction process, which could save a lot of time. Additionally, the method could be adopted to flatten the hulls of ships made of composite materials. Although there is much work to be done, the described method represents a good basis for future work.

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Uporaba trdih prevlek PVD v strojništvu – možnosti in omejitve

Hard PVD Coatings in Mechanical Engineering – Perspectives and Limitations

Bojan Podgornik - Jože Vižintin

Zadnjih 20 do 30 let je bilo razvitih veliko novih trdih prevlek, kakor tudi tehnik za njihovo nanašanje. Tako smo soočeni s plazemsko podprtimi postopki nanašanja ter diamantnimi in diamantu podobnimi prevlekami, ki jih je mogoče nanašati že pri temperaturah, nižjih od 200 °C, in dajejo izjemne tribološke lastnosti. Kljub temu, da je ob odlični obrabni odpornosti mogoče doseči tudi razmeroma nizek koeficient trenja, pa je uporaba trdih zaščitnih prevlek v strojništvu še vedno bolj izjema kakor pravilo. Glavni problem pomenijo razmeroma visoki stični tlaki ter zelo zahtevno napetostno-deformacijsko polje, ki so mu strojni elementi izpostavljeni med delovanjem. Mnoge numerične in analitične raziskave so pokazale, da se pri oplaščenih sistemih plastična deformacija prične v podlagi in da je zmožnost prevleke prenašati obremenitev v največji meri odvisna prav od podlage. To pomeni, da ob trdi, obrabno odporni površini, potrebujemo tudi primerno pripravljeno podlago, ki bo zmožna dajati oporo trdi in s tem krhki prevleki.

Čeprav imamo neomejeno število mogočih kombinacij priprave podlage in nanosa trde zaščitne prevleke, pa moramo biti pri tem zelo pazljivi. Neprimerna kombinacija lahko, namesto želenega izboljšanja, privede do nepričakovanega poslabšanja lastnosti elementa ali naprave. Prav to je razlog, da se je v praksi uspešno uveljavilo le nekaj postopkov, izmed katerih kombinacija nitriranja v plazmi ter fizikalnega nanašanja iz faze pare kaže največji potencial za uporabo trdih prevlek v strojništvu.

(Ključne besede: prevleke trde, trenje, obraba, nitriranje plazemsko)

A lot of new technologies, and thin films with very good tribological properties, like diamond and diamond-like carbon coatings, were introduced in the past 2 to 3 decades. However, the use of hard, thin films in the field of machine elements is the exception rather than the rule. The main problem lies in the relatively high contact pressure and the very complex loading of the machine components, which demand a hard resistant surface and a tough core. It was found during many numerical and experimental analyses that in the case of hard, thin films the plastic deformation of the composite starts in the substrate. Therefore, the ability of the film to sustain the loading depends principally on the load-carrying capacity of the substrate.

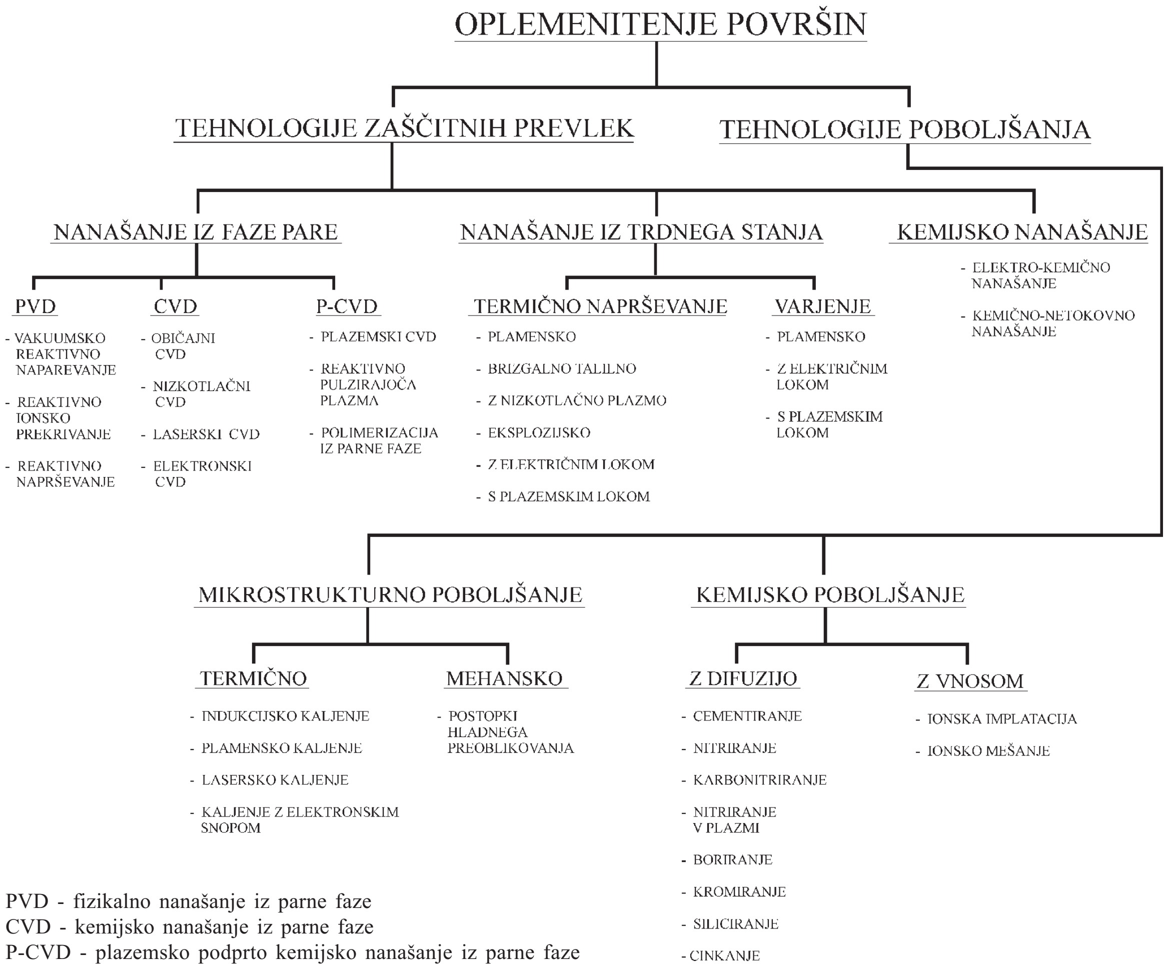
Although there are an almost unlimited number of possibilities, we have to be very careful when combining different surface treatments and thin-film deposition techniques. It should be pointed out that the wrong combination can very easily lead to an undesirable deterioration of the properties, either of the film or the substrate, instead of an improvement. This is why only a few combinations can be successfully used in practice. One of the most promising ones, already proven in the case of high-speed steel, is the combination of plasma nitriding of a steel substrate followed by PVD (physical vapour deposition) thin-film deposition.

(Keywords: hard coatings, friction, wear, plasma nitriding)

0 UVOD

Za spremembo ali oplemenitenje stičnih površin in izboljšanje njihovih triboloških lastnosti imamo na razpolago najrazličnejše postopke poboljšanja ter postopke nanosa trde zaščitne prevleke. V primeru, da je na površino nanesena plast novega materiala, govorimo o postopkih nanašanja, če pa pride do spremembe mikrostrukture obstoječe površine, pa o postopkih poboljšanja (slika 1). Lastnosti površine, kakor so zmožnost nošenja obremenitve, obrabna odpornost ter ustrezen koeficient trenja, so seveda odvisne od uporabljenega postopka oplemenitenja površine ([1] do [10]).

Izbira najprimernejšega postopka oplemenitenja površine je odvisna od mnogih dejavnikov, pri čemer so najpomembnejši delovne zahteve, izbrani osnovni material, parametri oplemenitenja površine ter zahtevane



Sl. 1. *Tehnologije oplemenitenja površin*

lastnosti površine ([5], [7], [11] in [12]). V prvi vrsti morajo biti postopki oplemenitenja ali spremembe površine združljivi z izbranim osnovnim materialom elementa. To pomeni, da sta poleg trdote površine najpomembnejša parametra za izbiro postopka oplemenitenja površine temperatura oplemenitenja ter debelina modificirane oziroma nanesene plasti. Trdota oplemenitenih površin se giblje od 250 do 350 HV za toplotno napršene prevleke, do 1000 HV za nitrirana in cementirana jekla, vse do 3500 HV pri trdih keramičnih prevlekah, nanesenih iz faze pare (CVD in PVD), medtem ko diamantne in diamantu podobne prevleke dosegajo celo trdoto naravnega diamanta. Debeline plasti so v območju od nanometra do milimetra, temperature oplemenitenja pa med 20 °C in 1000 °C ([6] in [10]).

Za doseganje želenih triboloških lastnosti morajo oplemenitene površine združevati ustrezno kombinacijo lastnosti; primerno trdoto, žilavost, toplotno razteznost, adhezijo, koeficient trenja itn. Kljub velikemu razponu razpoložljivih materialov in tehnik oplemenitenja se je izkazalo, da preprosto in z uporabo posameznih postopkov oplemenitenja vseh teh lastnosti ni mogoče doseči hkrati. To spoznanje in vse večje zahteve industrije po uporabi lahkih in cenenih osnovnih materialov je vodilo do razvoja novih zamisli oplemenitenja površine (večkomponentne in večplastne prevleke ter kombinacija kemotoplotne priprave podlage in nanosa trdih prevlek, znana tudi kot tehnologija “duplex”) ([7] do [9], [13] do [15]). Poglavitna zamisel vseh zasnutkov oplemenitenja površine je povečanje odpornosti in optimizacija mikrostrukture kompozita, s čimer je mogoče doseči ustrezne lastnosti tako na površini kakor tudi v podlagi.

Izbira ustreznega postopka oplemenitenja površine je že sama po sebi zelo zahtevna naloga. Z združevanjem različnih tehnik oplemenitenja površine se zahtevnost izbire še precej poveča. Tako izbira ustrezne priprave podlage in nanosa trde zaščitne prevleke terja celovito poznavanje prednosti in pomanjkljivosti posameznih tehnologij oplemenitenja ter možnosti njihove kombinacije. Na drugi strani je končna odločitev o načinu oplemenitenja površine vedno kompromis med tehnološkimi in gospodarskimi zahtevami.

1 Tribološki stik

O tribološkem stiku govorimo, kadar imamo v stiku dve površini, ki se medsebojno relativno gibljeta. S časom pride znotraj tribološkega stika do spremembe geometrijske oblike in materialnih lastnosti stičnih površin, kar se kaže v energijsko povezanih izhodnih veličinah; trenje, obraba, povišana temperatura, nihanja itn. [15]. Kot tak je tribološki stik zelo zahteven, še posebej ker hkrati vključuje spremembe, tako na makro kakor tudi na mikro nivoju, tribokemijske spremembe in prenos materiala.

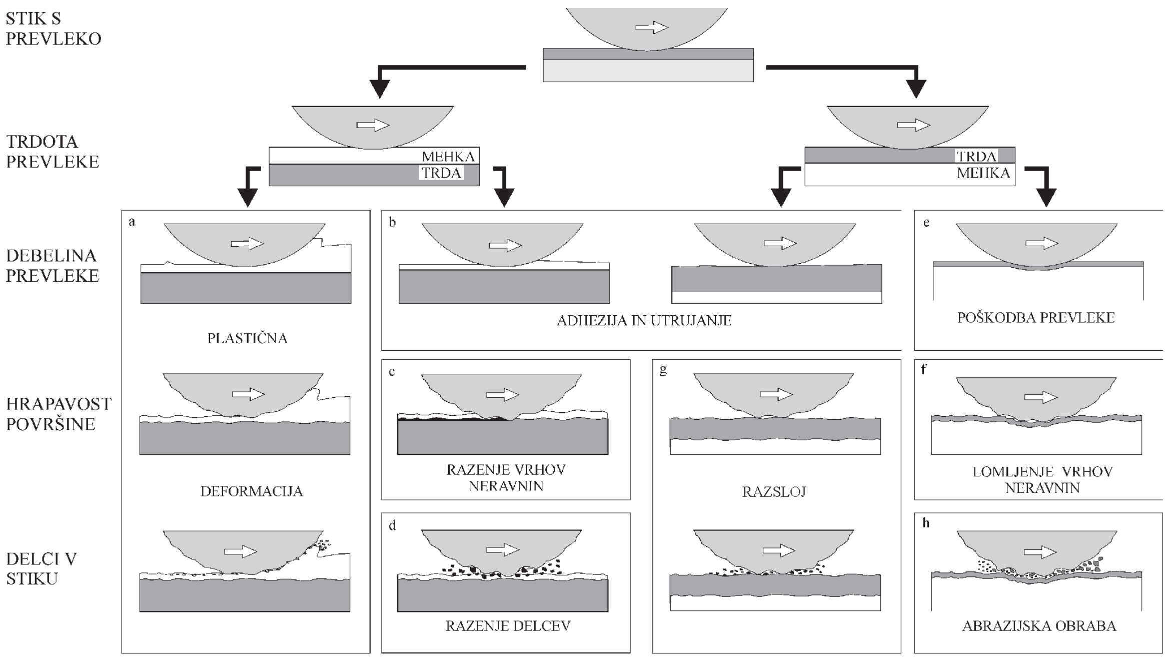
V primeru površin prekritih s trdimi prevlekami, je njihovo tribološko obnašanje odvisno od štirih parametrov, to so:
- trdota prevleke
- debelina prevleke
- hrapavost površine
- velikost in trdota delcev v stiku

Glede na kombinacijo teh štirih parametrov se lahko srečamo z najrazličnejšimi stičnimi situacijami, ki jih okarakterizirajo specifični obrabni mehanizmi ([10], [16] in [17]), kar prikazuje slika 2.

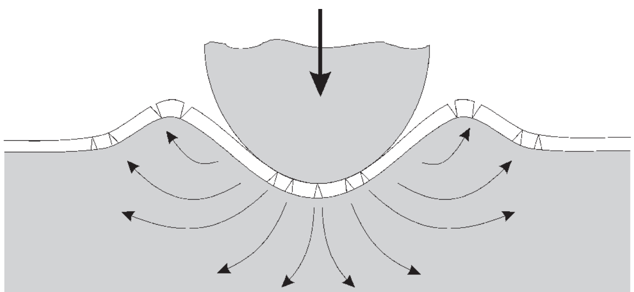
1.1 Trdota prevleke

Eden najpomembnejših parametrov, ki vplivajo na tribološko obnašanje oplaščenih površin, je trdota prevleke oziroma razmerje med trdoto prevleke in trdoto podlage. Prednost uporabe mehkih prevlek je v znižanju koeficienta trenja [18], prav tako pa znižajo tudi natezne napetosti v stiku, ki zelo negativno vplivajo na širjenje razpok in s tem na obrabno odpornost elementa. Po drugi strani mehke prevleke niso zmožne prenašati obremenitve.

Trda prevleka nanesena na "mehko" podlago preprečuje razenje površine ter s tem zmanjša njeno obrabo [17]. Imajo pa trde keramične prevleke pomanjkljivost, da povečajo trenje v tribološkem stiku, zaradi česar so uporabne predvsem v abrazijskih okoljih. S tvorjenjem mikrofilma z nizko strižno odpornostjo na površini prevleke je možno tudi v primeru trdih prevlek doseči nizek koeficient trenja in majhno stopnjo obrabe [19]. V tem primeru se striženje



Sl. 2. *Obrabni mehanizmi pri prekritih površinah [17]*



Sl. 3. *Poškodba trdega površinskega sloja na "mehki" podlagi [10]*

(drsenje) pojavi znotraj mikroplasti, medtem ko sama trda prevleka nosi obremenitev. Nadaljnje zniževanje trenja in obrabe je mogoče doseči s povečanjem trdote podlage, s čimer preprečimo deformacijo površine in vpliv razenja ([16], [19] in [20]).

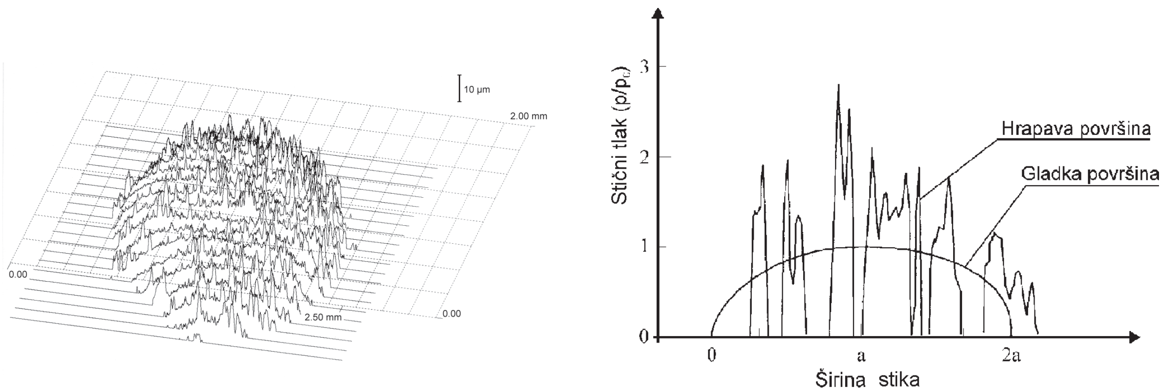
1.2. Debelina prevleke

Naloga prevleke je ločevati stični površini ter z utrditvijo površine zmanjšati njuno obrabo. Če pri tem podlaga ni dovolj toga, da bi nosila obremenitev in dajala zadostno podporo trdi prevleki, lahko le-ta izgubi svojo vlogo. Pod vplivom obremenitve se bo prevleka deformirala v skladu z deformacijo podlage, pri čemer lahko upogibne napetosti v prevleki ter napetosti na meji med prevleko in podlago presežejo kritične vrednosti. To vodi do nastanka in širjenja razpok ter v končni fazi do odpovedi prevleke, kakor je prikazano na sliki 3 [21]. Poškodbo prevleke, zaradi prekomerne deformacije podlage, je mogoče rešiti s povečanjem debeline prevleke, ki nato sama lahko nosi obremenitev. S tribološkega vidika je uporaba tankih trdih prevlek primernejša, in to iz več vzrokov. Nanos debelih prevlek, še posebej v primeru fizikalnega nanašanja iz faze pare, je povezan z nastankom visokih tlačnih napetosti v prevleki, ki v najslabšem primeru lahko privedejo do luščenja prevleke [22]. Po drugi strani je, ob enakem upogibu, debela prevleka izpostavljena večjim upogibnim napetostim kakor tanka prevleka in nastale razpoke hitreje presežejo kritične vrednosti za porušitev ([23] in [24]).

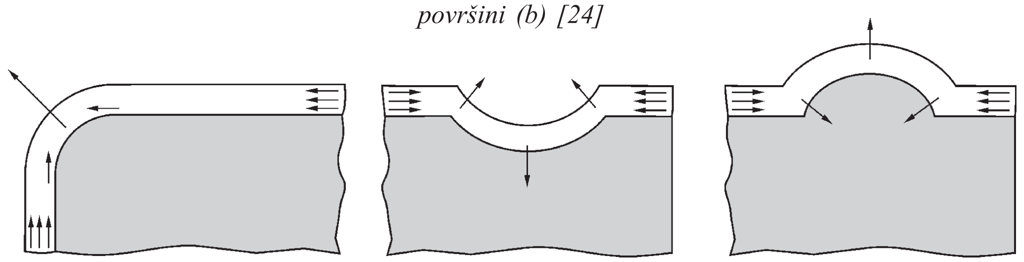
1.3. Hrapavost površine

V strojništvu se z idealno gladkimi površinami zelo redko srečujemo. To pomeni, da je treba hrapavost površine upoštevati pri analizi tribološkega stika. Enako velja tudi v primeru oplemenitenih stikih površin. V odvisnosti od metode oplemenitenja lahko ostane hrapavost površine več ali manj nespremenjena, lahko pa pride tudi do njenega povečanja. Pri drsenju dveh hrapavih površin razijo vršički neravnin trde oplemenitene površine po nasprotni površini, kar vpliva na povečanje trenja in obrabe, še posebej v začetni fazi drsenja ([24] in [25]). Hrapavost površine pa vpliva tudi na zmanjšanje realne stične površine in s tem na povečanje stičnega tlaka. Kakor je prikazano na sliki 4, ima hrapavost površine precejšen vpliv na porazdelitev stičnega tlaka p. Le-ta postane nepovezana in lahko mestoma tudi do trikrat preseže nominalne vrednosti Hertz-ovega stičnega tlaka p_0 [24]. Visoki stični tlaki ter krhkost prevleke pa zahtevajo dovolj togo podlago, ki je zmožna nositi obremenitev in dajati zadostno podporo prevleki.

Zaradi same narave procesa nanašanja trdih zaščitnih prevlek te vsebujejo visoke zaostale napetosti. Tlačne zaostale napetosti na splošno izboljšajo obrabno odpornost trdih prevlek, kar pa velja le v primeru idealno gladkih in ravnih površin. Pri strojnih elementih imamo vedno opazno hrapavost površine ter robove, prehode ipd. Na teh geometrijskih nepravilnostih zaostale napetosti inducirajo natezne in strižne sile, ki pospešujejo



Sl. 4. *Topografija dejanske hrapave površine (a) in porazdelitev stičnega tlaka pri gladki in hrapavi površini (b) [24]*



Sl. 5. *Natezne in strižne napetosti na meji med prevleko in podlago, nastale na: robu (a), vboklini (b) in izboklini (c) [22]*

medploskovno širjenje razpok, kakor prikazuje slika 5. Elementi so med obratovanjem izpostavljeni tudi zunanjim obremenitvam, ki se dodajo na zaostale napetosti. Vsota stičnih in zaostalih napetosti pa lahko na mestu geometrijskih nepravilnosti preseže oprijemljivost prevleke na podlago in s tem privede do luščenja prevleke [22]. Za preprečitev luščenja prevlek je tako treba hrapavost površine prilagoditi debelini in tipu prevleke ter stopnji obremenitve.

2 PLASTIČNA DEFORMACIJA

Pri večini oplemenitenih površin je običajna obraba le redko razlog za odpoved sistema. Odpoved oplaščene površine se pojavi zaradi luščenja prevleke (adhezijska poškodba), pokanja prevleke (kohezijska poškodba) ali zaradi poškodbe podlage ([7], [9] in [27]). V vseh primerih je poškodba sistema posledica nastanka in širjenja razpok v prevleki ali v njeni neposredni bližini ([27] in [28]). Za napoved obnašanja oplemenitenih površin in določitev območja delovanja je tako nujna določitev porazdelitve napetosti ter začetka in širjenja cone plastične deformacije ([29] in [30]).

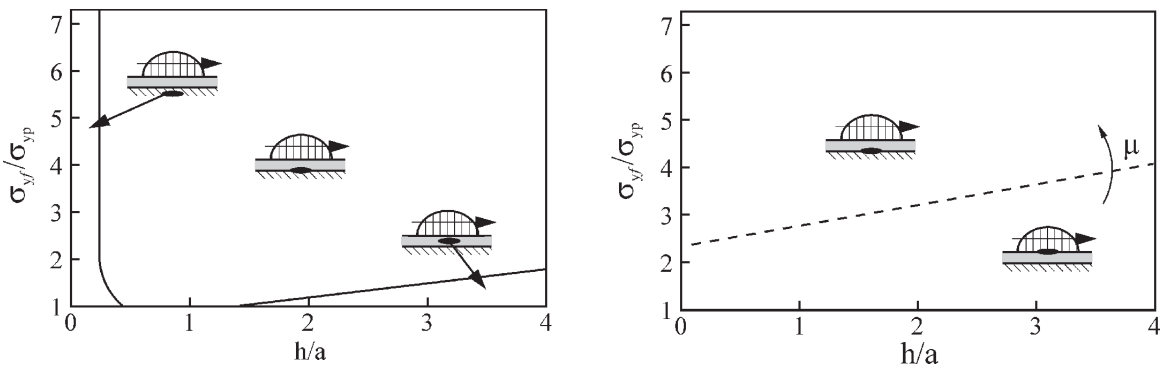
V primeru trdih prevlek je lega največjih strižnih napetosti odvisna od koeficienta trenja, debeline prevleke in togosti podlage [29] in [30] (sl. 6). V primeru nizkega koeficienta trenja (< 0,3) se le pri zelo tankih prevlekah plastična deformacija prične v podlagi, in to neodvisno od razmerja meje plastičnosti prevleke in podlage (σ_{yf}/σ_{yp}). S povečevanjem debeline prevleke se točka začetnega tečenja pomika na mejo med prevleko in podlago, v primeru razmeroma debelih prevlek nanesenih na togo podlago pa v samo prevleko, kakor prikazuje slika 6a. V primeru visokega koeficienta trenja (> 0,3) verjetnost nastanka plastične deformacije v podlagi ali v prevleki izgine in ostaneta le še dve možni legi, površina in vmesna plast med prevleko in podlago [30], (sl. 6b).

V večini dejanskih primerov, pri katerih imamo tanko obrabno odporno prevleko naneseno na razmeroma mehko podlago iz konstrukcijskega jekla, se plastična deformacija prične na meji med prevleko in podlago in le redko znotraj same prevleke ([29] in [30]). S povečanjem koeficienta trenja in debeline prevleke pa se točka krajevnega tečenja pomakne na samo površino. Iz tega je razvidno, da napake materiala, kakor so mikro razpoke, vključki in hrapavost površine prevleke in podlage pomenijo vir zgostitve napetosti in začetka odpovedi oplaščenega sistema.

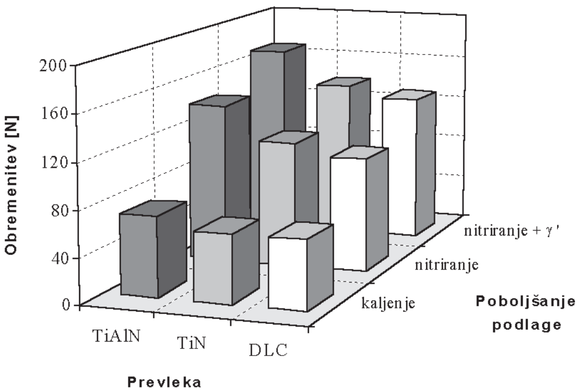
3 KOMBINACIJA KEMOTOPLOTNE PRIPRAVE PODLAGE IN NANOSA TRDE ZAŠČITNE PREVLEKE ALI PREVLEKE »DUPLEX«

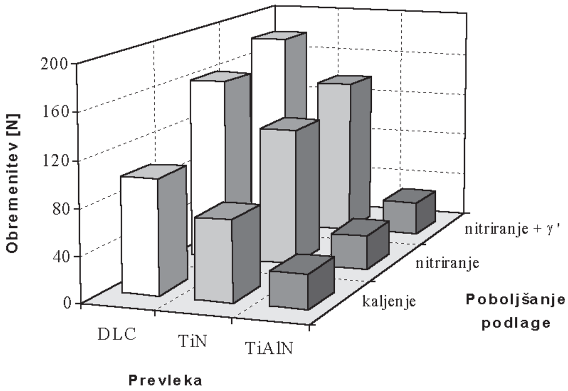
Odpornost materiala proti obrabi, utrujanju ter koroziji je moč doseči z uporabo različnih postopkov poboljšanja ter postopki nanosa trdih zaščitnih prevlek. S povečevanjem zahtev po vse večjem izkoristku, daljši dobi trajanja in večji zanesljivosti elementov mehanskih sistemov, izpostavljenih zahtevnim obremenitvam, pa posamezni postopki poboljšanja ne dajejo več želenih rezultatov. Postopki nitrocementacije in nitriranja, ki so zagotavljali boljšo obrabno odpornost ter odpornost proti utrujanju pri "običajnih" konstrukcijah, ne zmorejo več zagotavljati zapletenih zahtev po odpornosti proti utrujanju, obrabni odpornosti pri povišanih temperaturah, nizkemu trenju ter zmožnosti nošenja obremenitve. Kljub temu, da smo s prihodom tehnik nanašanja trdih prevlek dobili dodatne možnosti za oplemenitenje površine, pa so trde zaščitne prevleke običajno krhke in razmeroma tanke. V primeru nanosa prevleke na poboljšana konstrukcijska jekla z nizko trdoto površine bo prišlo pod vplivom obremenitve do elastične ali celo plastične deformacije podlage in s tem posledično do pokanja ter odpovedi prevleke ([17] in [31]). V nasprotju z žilavimi konstrukcijskimi jekli, ki so zmožna prenesti precejšnje elastične ali celo plastične deformacije brez poškodbe, pa lahko trde in krhke prevleke odpovedo že pri majhnih deformacijah podlage.

Rešitev opisanega problema je ponudila nova tehnika oplemenitenja površine, imenovana poboljšanje "duplex" ali prevleka "duplex". "Duplex" poboljšanje vključuje uporabo dveh različnih tehnik



Sl. 6. *Pričetek plastične deformacije pri oplaščeni površini (h – debelina prevleke in 2a – širina stika); μ = 0,25 (a), μ ≥ 0,5 (b) [30]*





Sl. 7. *Kritična obremenitev poškodbe nizkolegiranega jekla, prekritega s trdo prevleko pri drsenju (a) in kotaljenju (b)*

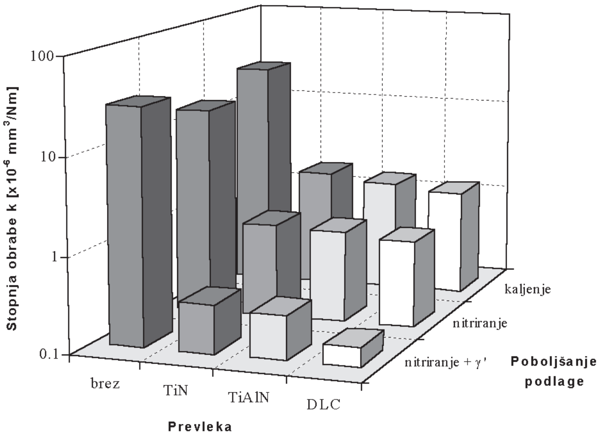
oplemenitenja površine in zagotavlja mehanske, metalurške, kemijske in tribološke lastnosti, ki z uporabo posameznega postopka oplemenitenja niso dosegljive ([9] in [14]). Osnovno načelo oplemenitenja "duplex" je združitev kemotoplotne priprave podlage in nanosa trde zaščitne prevleke, in sicer tako, da se njune prednosti združijo in pomanjkljivosti po možnosti izničijo [32]. Kompozit tako sestoji iz tanke zaščitne prevleke, ki zagotavlja želeno trdoto in tribološke lastnosti površine, plasti utrjenega materiala podlage, odgovornega za nošenje obremenitve ter žilavega jedra.

Izmed vseh možnih kombinacij se je kombinacija nitriranja v plazmi in fizikalnega nanosa trde prevleke iz faze pare izkazala kot najprimernejša za izboljšanje odpornosti ter triboloških lastnosti strojnih elementov ([14] in [33]). Nitriranje v plazmi poveča trdoto podlage ter vodi do nastanka visokih tlačnih napetosti v materialu podlage. Večja trdota podlage zmanjša njeno deformacijo in daje boljšo podporo prevleki (sl. 7). Po drugi strani imamo manjši gradient trdote in napetosti na meji med prevleko in podlago in s tem bolj enakomerno polje deformacij in napetosti. Eksperimentalni rezultati so pokazali, da nitriranje v plazmi izboljša tudi oprijemljivost prevleke na podlago ([15] in [34]).

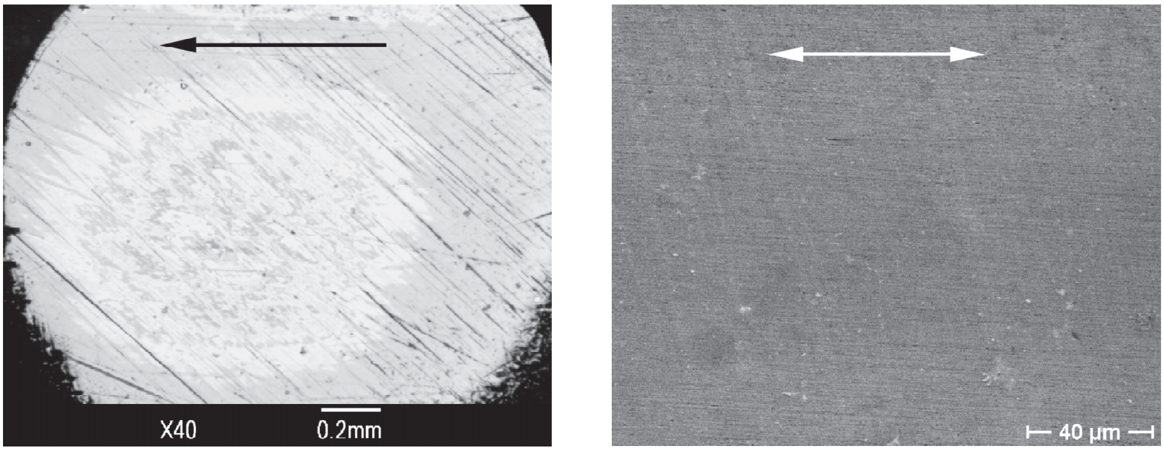
Analiza triboloških preizkusov je pokazala, da kombinacija nitriranja v plazmi ter nanosa trde zaščitne prevleke TiN, TiAlN ali diamantu podobne prevleke (DPP - DLC) daje površini boljšo zmožnost prenašati obremenitev ter tribološke lastnosti nizkolegiranih jekel, ki jih drugače ni moč doseči ([15], [19], [33] do [35]). Kakor prikazuje slika 8, je mogoče s pravilno izbiro kemotoplotnega oplemenitenja podlage ter nanosa trde zaščitne prevleke doseči izredno majhno stopnjo obrabe površine. Največje izboljšanje obrabne odpornosti je mogoče zaslediti v primerih, ko je diamantu podobna prevleka (DPP) nanesena na nitrirano podlago s tanko spojinsko plastjo λ', in to tako v primeru drsenja kakor tudi kotaljenja (sl. 8 in 9) ([34] in [35]). Na sliki 10 je prikazanih nekaj praktičnih primerov uporabe prevlek DPP na strojnih elementih.

4 SKLEPI

- Tribološko obnašanje površin, oplemenitenih s trdimi prevlekami, je odvisno od velikega števila parametrov, od katerih so najpomembnejši razmerje trdote prevleke in podlage, debelina prevleke, hrapavost površine in zmožnost prevleke delati mikroplast z nizko strižno odpornostjo.



Sl. 8. *Stopnja obrabe oplemenitenega nizkolegiranega jekla pri drsenju*



Sl. 9. *Površina nizkolegiranega jekla, prekrita s prevleko DPP, po preizkusu; (a) drsenje (v_d = 1 m/s, F_N = 60 N, s = 1000 m), in (b) kotaljenje (n = 150 min^{-1}, F_N = 50 N, 10^6 ponovitev)*

Sl. 10. *Primeri uporabe prevlek DPP na strojnih elementih: (a) zobniki, (b) elementi motorja in (c) hidravlični elementi [36]*

- Glavna zahteva za uspešno delovanje oplaščenih sestavnih delov sta zadostna oprijemljivost prevleke na podlago ter zmožnost podlage dati zadostno oporo prevleki. Priprava podlage ima tako ključen vpliv na tribološko obnašanje trdih prevlek, namenjenih strojnim delom. Pri tem je treba poudariti, da še tako trda in obrabno odporna prevleka odpove, če podlaga ne zagotavlja zadostne podpore, in/ali če je oprijemljivost prevleke na podlago neprimerna.
- Med sedanjimi postopki kemotoplotnega poboljšanja se je nitriranje v plazmi izkazalo kot najprimernejši postopek predpriprave površine strojnih delov za nanos trde zaščitne prevleke. S povečanjem nosilne zmožnosti jeklene podlage in izboljšanjem oprijemljivosti prevleke na podlago nitriranje v plazmi zagotavlja želene lastnosti strojnih delov, prekritih s trdo zaščitno prevleko.
- Zaradi krhkosti trdih prevlek in pomanjkanja znanja o vplivu maziva je uporaba trdih prevlek v strojništvu še vedno več ali manj omejena na preproste primere drsnega stika.

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Osebne vesti
Personal Events

Doktorati, magisteriji, diplome

DOKTORATI

Na Fakulteti za strojništvo Univerze v Ljubljani so z uspehom zagovarjali svoje doktorske disertacije, in sicer:

dne 8. aprila 2003: **mag. Petar Orbanić**, z naslovom: "Napovedovanje zdržljivosti izdelkov v razvoju";

dne 15. aprila 2003: **mag. Miha Nastran**, z naslovom: "Prispevek k stabilizaciji procesa hladnega preoblikovanja žice", in

dne 16. aprila 2003: **mag. Andrej Kitanovski**, z naslovom: "Dvofazni trdno-kapljevinski tok vode in ledu za transport hladilne energije".

S tem so navedeni kandidati dosegli akademsko stopnjo doktorja tehničnih znanosti.

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Ljubljani je z uspehom zagovarjal svoje magistrsko delo, in sicer:

dne 23. aprila 2003: **Viktor Zaletelj**, z naslovom: "Metoda za modeliranje računalniško integriranih proizvodnih sistemov".

Na Fakulteti za strojništvo Univerze v Mariboru so z uspehom zagovarjali svoja magistrska dela, in sicer:

dne 17. aprila 2003: **Tone Lerher**, z naslovom: "Simulacijski model visokoregalnega skladiščnega sistema";

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dne 25. aprila 2003: **Janez Vidovič**, z naslovom: "Analiza mehanskih izgub v majhnem štiritaktnem motorju z notranjim zgorevanjem".

S tem so navedeni kandidati dosegli akademsko stopnjo magistra tehničnih znanosti.

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- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 tipkanih strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

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Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in Italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

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