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Načrtovanje avtomatiziranih regalnih skladiščnih sistemov z uporabo simulacijskega postopka

The Design of Automated Storage and Retrieval Systems Using a Simulation Modeling Approach

Iztok Potrč - Tone Lerher - Janez Kramberger - Matjaž Šraml

V prispevku je predstavljen simulacijski model avtomatiziranega regalnega skladiščnega sistema z enojno pomično in večpomičnimi mizami. Glavni namen predstavljene raziskave je določitev zmogljivosti sistema z večpomičnimi mizami, glede na sistem z enojno pomično mizo. Slednje pomeni glavni delež in pomoč pri postopku načrtovanja avtomatiziranega regalnega skladiščnega sistema. Povečanje pretočne zmogljivosti transportno-skladiščnih enot je mogoče z uporabo sistema z večpomičnimi mizami, glede na sistem z enojno-pomično mizo. V inženirski praksi se največkrat uporablja sistem z enojno pomično mizo, ki temelji na dvojnem delovnem krogu, medtem ko sistem z večpomičnimi mizami temelji na štirikratnem in šestkratnem delovnem krogu. Problem se pojavi pri uporabi ustrezne upravljalne strategije, za zagotovitev pogoja o najmanjših vožnjah regalnega dvigala. V ta namen smo uporabili posebno domiselno metodo, poimenovano "Strategija x", ki razvršča zaporedje skladiščnih in odpremnih zahtev, z namenom po minimizaciji povprečnega časa vožnje regalnega dvigala. Za ovrednotenje domiselne metode s sistemom večpomičnih miz smo uporabili tehniko diskretnih numeričnih simulacij. Rezultati simulacijske analize so pokazali očitno povečanje pretočnih zmogljivosti sistema z večpomičnimi mizami v primerjavi s sistemom enojne pomične mize.

(Ključne besede: sistemi skladiščni, skladišča avtomatizirana, operacije skladiščne, simulacije diskretne, analiza zmogljivosti)

A simulation model of a single and a multi-shuttle automated storage and retrieval systems is presented in this paper. The main object of the presented research was to determine the efficiency of multi-shuttle systems versus single-shuttle systems, which represents the main share and support in the design process of automated storage and retrieval systems. An improvement of the throughput capacity of the transport unit load is possible with the use of multi- versus single-shuttle systems. Single-shuttle systems are frequently used in engineering practice, and they are based on the dual command cycle, while multi-shuttle systems are based on the quadruple and sextuple command cycles. The main problem is how to incorporate an appropriate control policy so that the condition of minimal empty travel of the storage and retrieval machine will be fulfilled. A special heuristics method, "Strategy x", that sequences storage and retrieval requests in order to minimize the average travel time has been used for this purpose. Discrete event simulations were used to evaluate the heuristics performances within multi-shuttle systems. The results of simulation analyses showed significant improvements in the throughput capacity for multi-shuttle systems in comparison with single-shuttle systems.

(Keywords: storage systems, retrieval systems, storage operations, discrete event simulation, performance analysis)

0 UVOD

Razvojne usmeritve v skladiščenju so spremenile postopke skladiščnega poslovanja. Spremembe se kažejo v kratkih odzivnih časih pri uskladiščenju in odpremi blaga, zmanjševanju zalogovne velikosti skladišča in avtomatizaciji celotnega skladiščnega poslovanja. Številna

0 INTRODUCTION

Technological developments in warehouses have changed the processes of storage operations; this is reflected in the short response times for the storage and retrieval of goods, the reduction of warehouse volume and the automation of the whole of warehouse management. Numerous companies are podjetja zamenjujejo draga in dotrajana običajna skladišča z avtomatiziranimi regalnimi skladiščnimi sistemi (AS/RS). AS/RS lahko razdelimo na AS/RS z enojno pomično (sl. 1) in večpomičnimi mizami (sliki 2 in 3).

Najosnovnejši elementi AS/RS z enojno pomično mizo (sl. 1) so skladiščni regali (SR), regalno dvigalo (RD), vhodna in izhodna (I/O) lokacija ter zvezni transporterji (sl. 4) [13]. AS/RS so vodeni z računalnikom, ki zbira pomembne informacije in zagotavlja visoko stopnjo organiziranosti skladišča. Te informacije lahko nadalje uporabljamo v proizvodnji, razdelitvi, računovodstvu, prodaji itn. Glavne prednosti pri gradnji AS/RS so učinkovit izkoristek skladiščnega prostora, manjše število poškodb in izgube blaga, povišanje ravni nadzora uskladiščenja in odpreme blaga ter zmanjšanje števila skladiščnih delavcev [2].

Zmogljivost AS/RS je pogosto ovrednotena s številom transportno-skladiščnih enot (TSE) na časovno enoto, ki jih lahko uskladiščimo in odpremimo, kar pomeni pretočno zmogljivost sistema λ. Pri načrtovanju in določitvi AS/RS moramo upoštevati čas vožnje regalnega dvigala pri delovnem krogu, dolgoročne in kratkoročne vzorce toka materiala, podrobno analizo učinka posredovanja (komisioniranja) po nalogu, oceniti povprečni čas med izpadom in popravilom opreme ter sistemske opravilne strategije [12]. Zmogljivost AS/RS je lahko določena tudi s povprečnimi stroški za opravili uskladiščenja in odpreme, oziroma glede na čakalni čas za odpremo.

Zaradi potrebe po večji pretočni zmogljivosti in manjših odzivnih časih pri obdelavi naročil, so bila razvita regalna dvigala, ki lahko sprejmejo več TSE hkrati. Številni proizvajalci skladiščne opreme so začeli ponujati takšne izvedbe regalnih dvigal, ki lahko sprejmejo tudi tri in več TSE hkrati. Tako lahko dosežemo večje pretočne zmogljivosti. Pretočna zmogljivost AS/RS z večpomičnimi mizami se na splošno povečuje s povečevanjem števila pomičnih miz. Zaradi tega se zmanjšujejo nekoristne "prazne" vožnje regalnega dvigala. S povečevanjem števila pomičnih miz se prav tako povečuje vložek kapitala [13].

V prispevku je obravnavan in analiziran AS/RS skladiščenja majhnih delov s sistemom z enojno pomično in večpomičnimi mizami. AS/RS majhnih delov se uporabljajo predvsem na področjih avtomobilske, kemične in farmacevtske industrije, kjer predstavlja TSE geometrijsko majhen zaboj. Regalna dvigala so lažje in kompaktnejše izvedbe od običajnih regalnih dvigal, kjer je osnova za TSE paleta. Pri uporabi AS/RS z večpomičnimi mizami ločimo v splošnem AS/RS z dvema pomičnima (sl. 2) in tremi pomičnimi mizami (sl. 3) ([10], [12] in [13]).

AS/RS so bili v zadnjih desetletjih predmet številnih raziskav. Njihov intenziven razvoj se je začel

replacing costly and outdated traditional warehouses with a system of automated storage and retrieval systems (AS/RSs). AS/RSs can be classified into single (Figure 1) and multi-shuttle (Figures 2 and 3) AS/RSs.

The basic components of the type of single-shuttle AS/RS (Figure 1) are storage racks (SRs), storage and retrieval machine (S/R machine), input and output (I/O) locations and interface conveyors (Figure 4) [13]. The AS/RSs are computer controlled, they collect beneficial information and provide a high degree of inventory visibility, which can be subsequently used for manufacturing, distribution, accounting, sales, etc. The main advantages of building an AS/RS are the efficient utilization of warehouse space, a decrease in the amount of damage and the loose of goods, increased control during the storage and retrieval of goods, and in a reduction in the number of warehouse workers [2]. Therefore, numerous production companies start to replace costly and lasted traditional warehouses with the AS/RS.

The efficiency of an AS/RS is often evaluated by the number of transport unit loads (TULs) per time unit that can be stored and retrieved, e.g., the throughout capacity of the system λ. When designing and evaluating the AS/RS, the designer must consider the S/R machine cycle time, the long-term as well as short-term material flow patterns, a detailed analysis of the order picking activity, an estimated average time between failure and repair for the equipment, systems operating strategies, etc. [12]. The efficiency of the AS/RS can be determined by the average cost per storage-and-retrieval operation or by the waiting time for a retrieval.

Due to increased requests for higher throughput capacities and shorter response times during the handling of orders, special designs of S/R machines that can carry several TULs simultaneously, have been constructed. Warehouse-equipment producers have begun to offer S/R machines that can receive up to the three TULs simultaneously and, as a result, higher throughput capacities can be achieved. The throughput capacity of a multi-shuttle AS/RS, tends to increase as the number of shuttles increases and, correspondingly, the amount of empty travel of the S/R machine decreases. The capital investment of the system also increases as the number of the shuttles increases [13].

Mini-load single- and multi-shuttle AS/RSs are discussed and evaluated in the presented study. The mini-load AS/RSs are most frequently used in the automotive, chemical and pharmaceutical industries, where the TUL represents a container. S/R machines are lighter and more compact than conventional S/R machines, where the TUL represents a palette. In the material-handling industry, generally, the dual-shuttle (Figure 2) and the triple-shuttle (Figure 3) AS/RSs can be used ([10], [12] and [13]).

AS/RSs have been the subject of much research over the past few years. Their intensive z razvojem informatike in računalništva, ki predstavljata pomemben element skladiščne organizacije. Prav tako ne smemo pozabiti na organizacijsko raven sistema, ki s svojimi domiselnimi strategijami vodi in ureja njihovo delovanje.

Hausman in sodelavci [8] so analizirali enojni delovni krog (EK) samo za skladišča, ki so kvadratna po času (SIT)[1]. Primerjali so učinkovitost treh različnih skladiščnih odločitvenih pravil, kot so: strategija naključnega skladiščenja, strategija namenskega skladiščenja, strategija skladiščenja na podlagi določitve skladiščne cone. Graves in sodelavci [5] so razširili modele [8] na bolj zmogljiv dvojni delovni krog (DK) z različnimi skladiščnimi odločitvenimi pravili za skladišča SIT. Analitične modele za določitev statističnega povprečja EK in DK, za skladišča splošnih oblik (skladišča, ki niso SIT) sta razvila Bozer in White [2]. Njuni analitični modeli temeljijo na strategiji naključnega skladiščenje z različno vhodno in izhodno razporeditvijo vhodnega zalogovnika. Pogosta praksa pri določitvi zaporedja zahtev za uskladiščenje in odpremo je, da sta obe zahtevi izpolnjeni na podlagi pravila "prvi pride prvi obdela" (PPPP - FCFS)[2]. Omenjeno pravilo je bila predpostavka tudi v modelih, ki sta jih predstavila Bozer in White [2]. Predpostavka PPPP je smiselna za uskladiščenje v AS/RS, saj večina teh sistemov uporablja za vhodno in izhodno lokacijo zvezni transporter. V tem primeru bi bilo težko spremeniti zaporedje TSE, določenih za uskladiščenje. Kakorkoli že, predpostavka PPPP je manj primerna za odpremo, ki pomenijo le elektronska sporočila in so lahko na lahek način urejena v zaporedje [9]. Zaradi tega so Han in sodelavci [7] pokazali, da lahko povečamo pretočno zmogljivost, če nadomestimo zaporedje FCFS odpreme z novo, "najbližji sosed" (NS)[3] domiselno metodo. Po njihovi navedbi prispeva 50% zmanjšanja prazne vožnje regalnega dvigala pri DK k povečanju pretočne zmogljivosti za 10 do 15 %. Takšno povečanje pretočne zmogljivosti lahko pomaga pri premagovanju v konicah povpraševanja v fazi proizvodnje ali celo zmanjšanje skladiščnega hodnika, kar vodi k pomembnim prihrankom ([7] in [10]).

Po pregledu pregleda literature in dosedanjega dela na obravnavanem področju ugotavljamo, da je večina avtorjev analizirala AS/RS z enojno pomično mizo. Ti sistemi delujejo na temelju EK in DK, kjer lahko hkrati uskladiščimo in odpremimo samo eno TSE. Pretočna zmogljivost AS/RS z enojno pomično mizo je tako omejena z največjo zmogljivostjo regalnega dvigala in optimalnim tlorisom skladiščnega regala. Če želimo povečati pretočno zmogljivost,

[1] SIT – velja za AS/RS, pri katerih je razmerje med obliko SR in zmogljivostjo regalnega dvigala enaka izrazu ($L/v_x = H/v_y$).

[2] PPPP - FCFS – pravilo, pri katerem so TSE razporejene v smislu zaporedja prihoda.

[3] NS - NN – pravilo, ki rangira vse odpremne zahteve v skladiščnem regalu v smislu njihovih razdalj od trenutne skladiščne lokacije.

development began with the development of informational and computer science, which represents an important part of warehouse operations. However, the organizational level of the system, which leads and manages the warehouse activities using different heuristics strategies, must also be taken into account.

Hausman et al. [8] analysed Single command Cycle (SC) only for Square-In-Time (SIT)[1] racks. They compared the performances of three storage-assignment policies, e.g., random, full-turnover-based and class-based turnover assignment. Graves et al. [5] extended models [8] to the more efficient Dual command Cycle (DC), with different assignment policies for SIT racks. Analytical models for expected SC and DC for storage racks of general shapes (non-SIT rack) have been developed by Bozer and White [2]. Their analytical models are based on randomized storage with different input and output configurations of the input queue. A common practice in sequencing storage and retrieval requests is that both requests are processed with a "first-come-first-served" (FCFS)[2] policy, which was also the assumption in theanalytical models of Bozer and White [2]. The FCFS assumption is reasonable for storages, since most of the AS/RSs are interfaced with a conveyor for input and output location. In this case it is difficult to change the sequence of TULs presented for storage operation. However, the FCFS assumption is less suitable for retrievals, which are just electronic messages and can be easily sequenced [9]. Therefore, Han at al. [7] showed that the throughput capacity can be increased by replacing the FCFS retrieval sequencing with a new "nearest neighbor" (NN)[3] heuristics policy. According to their statement, a 50 % or even more decrease in the interleave time for a dual command cycle leads to an increase in throughput of 10 to 15 %. Such an increase in throughput capacity could help to handle peak demand in the operation phase or even to eliminate an aisle, which leads to considerable savings ([7] and [10]).

From the literature survey and present work on this field, the majority of researchers analysed the single-shuttle AS/RS. These systems work on the basis of SC and DC, where only one storage and retrieval could be achieved simultaneously. The throughput capacity of the single-shuttle AS/RS is therefore limited by the maximum efficiency of the S/R machine and the optimal layout of the SR. Therefore, multi-shuttle AS/RSs have to be used in order to

[1] SIT – deals for storage racks where the relationship between the layout of the SR and the efficiency of the S/R machine is equal ($L/v_x = H/v_y$).

[2] FCFS – a policy that TULs are sequenced in order of arrival.

[3] NN – a policy that ranks all the retrieval requests in the SR in terms of their distance from the present storage location.

moramo uporabiti AS/RS z večpomičnimi mizami. Pri AS/RS z dvema pomičnima mizama lahko regalno dvigalo opravi dvojno uskladiščenje in dvojno odpremo v delovnem krogu, kar imenujemo štirikratni delovni krog (ŠK). Nadalje, pri AS/RS s tremi pomičnimi mizami lahko regalno dvigalo opravi trojno uskladiščenje in trojno odpremo v delovnem krogu, kar imenujemo šestkratni delovni krog (ŠEK) [13]. Problem pri AS/RS z večpomičnimi mizami nastane pri izbiri ustrezne domiselne metode, ki poskrbi za pogoj o najmanjših praznih vožnjah regalnega dvigala.

Keserla in Peters [10] sta predstavila analizo AS/RS z dvema pomičnima mizama. Predstavila sta domiselno metodo za minimizacijo prazne vožnje regalnega dvigala pri dvojnem delovnem krogu. Pokazala sta, da je pretočna zmogljivost pri uporabi ŠK večja v primerjavi z DK, in sicer med 40 in 45 odstotki. Analitične modele AS/RS z večpomičnimi mizami sta predstavila tudi Meller in Mungwatana [13]. Pri skladiščnih opravilih ŠK in ŠEK sta predstavila spremenjeno ŠK in ŠEK pri NS in "nasprotni najbližji sosed" (NNS - RNN) domiselni metodi. Njuni analitični modeli temeljijo na predpostavki, da regalno dvigalo potuje ves čas z ustaljeno hitrostjo (osnovo njunega dela predstavljajo analitični modeli, ki sta jih prva predstavila Bozer in White [2]), kar pa se ne ujema z dejanskim stanjem. Njihovo delo se razlikuje v strategiji uskladiščenja in v pravilu izbrane odločitve in zato ni neposredno uporabno za našo analizo, ki temelji na domiselni metodi "strategiji x".

Medtem ko je v dosedanjih analitičnih modelih za AS/RS z večpomičnimi mizami upoštevana le ustaljena hitrost, smo v predstavljenem delu uporabili za ovrednotenje učinkovitosti in zmogljivosti AS/RS diskretne simulacije. V nadaljevanju smo upoštevali dejavnike, ki imajo pomemben vpliv na povprečni čas vožnje regalnega dvigala pri delovnem krogu, to so:

- tloris skladiščnega regala,
- zmogljivost regalnega dvigala in
- upravljalno pravilo.

1 TEORETIČNE OSNOVE

V predstavljenem delu smo uporabili naslednje predpostavke in omejitve ([2], [10] in [13]):

- AS/RS z enojno pomično in večpomičnimi mizami je predpostavljen kot AS/RS z enojnim regalnim hodnikom.
- Skladiščni regal je predpostavljen z zvezno pravokotno obliko, pri je V/I lokacija postavljena v spodnjem levem robu skladiščnega regala.
- Znani sta dolžina (*L*) in višina (*H*) skladiščnega regala, prav tako sta znani tudi hitrosti regalnega dvigala v vodoravni smeri x in navpični smeri y.
- Regalno dvigalo lahko potuje hkrati v vodoravni in navpični smeri.
- Pri izračunu povprečnega časa vožnje regalnega

increase the throughput capacity of the system. The multi-shuttle AS/RSs are, in general, divided into the dual-shuttle and the triple-shuttle AS/RSs. In the dual-shuttle AS/RSs, the S/R machine can perform up to two storages and two retrievals in a cycle, e.g.m Quadruple command Cycle (QC). Furthermore, in the triple-shuttle AS/RSs, the S/R machine can perform up to the three storages and three retrievals in a cycle, e.g., Sextuple command Cycle (STC) [13]. The main problem within the multi-shuttle AS/RSs is to find the appropriate heuristics that provide the condition of minimum empty travel of the S/R machine.

Keserla and Peters [10] presented an analysis of dual-shuttle AS/RSs. The heuristics for minimizing the interleave time for DC is presented and the throughput-capacity improvement using QC in comparison with DC is in the range 40–45 %. Analytical models under multi-shuttle AS/RS were also presented by Meller and Mungwatana [13]. Within the storage operation of QC and STC, they presented a modified QC and STC with NN and a "reverse nearest neighbour" (RNN) request selection rule. Their analytical models are based on the assumption that the S/R machine travels all the time with uniform velocity (the basis of their work is the analytical models of Bozer and White [2]), which does not fit with the actual situation. However, they used a different approach to storage-location assignment policy and request selection rule. Therefore, their model is not directly applicable to our analysis, which is based on "Strategy x" heuristics.

Whereas in the existing analytical models for multi-shuttle AS/RS only uniform velocity is considered, the discrete event simulation for evaluating the performance and the efficiency of the AS/RS was used [11]. Several aspects, which have significant influences on the average cycle time, were considered, as follows:

- the layout of the SR,
- the efficiency of the S/R machine,
- the control policies.

1 THEORETICAL BACKGROUNDS

The main assumptions and notations of the present work are ([2], [10] and [13]):

- A single- and multi-shuttle AS/RS is considered to be a single picking aisle AS/RS.
- The SR is considered to be a continuous rectangular pick face, where the I/O location is located at the lower left-hand corner of the SR.
- The length (*L*) and the height (*H*) of the SR, as well as the S/R machine velocities in the horizontal x and vertical y directions, are known.
- The S/R machine travels simultaneously in the horizontal and vertical directions.
- In calculating the average travel time, non-constant

dvigala upoštevamo, da hitrosti regalnega dvigala v vodoravni in navpični smeri nista stalni.
- Časi za nalaganje in odlaganje TSE so nespremenljivi in se lahko preprosto dodajo v izraze za izračun povprečnega časa delovnega kroga.
- Regalno dvigalo deluje na podlagi EK, DK, ŠK in ŠEK.
- Za izvedbo domiselne metode "strategije x" obstaja množica *n* zasedenih lokacij za izvedbo zaporedja odpreme. Prav tako obstaja tudi množica *m* možnih lokacij za izvedbo zaporedja uskladiščenja v skladiščnem regalu.

Sistem simbolov:
- v_x hitrost regalnega dvigala v vodoravni smeri,
- v_y hitrost regalnega dvigala v navpični smeri,
- a_x pospeševanje/pojemanje regalnega dvigala v vodoravni smeri,
- a_y pospeševanje/pojemanje regalnega dvigala v navpični smeri,
- H višina skladiščnega regala,
- L dolžina skladiščnega regala,
- E(T(SA)) statistično povprečje časa vožnje regalnega dvigala za eno smer v skladiščnem regalu,
- E(T(SC)) statistično povprečje časa vožnje regalnega dvigala pri enojnem delovnem krogu,
- E(T(DC)) statistično povprečje časa vožnje regalnega dvigala pri dvojnem delovnem krogu,
- E(T(QC)) statistično povprečje časa vožnje regalnega dvigala pri štirikratnem delovnem krogu,
- E(T(STC)) statistično povprečje časa vožnje regalnega dvigala pri šestkratnem delovnem krogu.

1.1 AS/RS z enojno pomično mizo

Značilen AS/RS z enojno-pomično mizo ima regalno dvigalo, ki prenaša TSE k določenim skladiščnim položajem ali od njih na obeh straneh regalnega hodnika. Velike dvižne razdalje, velike hitrosti v vodoravni in navpični smeri, natančno rokovanje in nadzorovano premikanje so pomembni značilnosti regalnega dvigala. Regalno dvigalo se sestoji iz pomičnega okvirja, ki vodi in podpira dvižno mizo, na kateri so položene TSE. Pomična miza ali teleskopska naprava na dvižni mizi vodi TSE v položaj v skladiščnem regalu in iz njega. AS/RS z enojno pomično mizo se nanašajo na EK ali DK.

EK se sestoji iz skladiščnega ali odpremnega opravila. Pri uskladiščenju je EK sestavljen iz časa za nalaganje TSE na V/I položaju, vožnje do skladiščnega položaja, odlaganje TSE na omenjenem položaju ter vrnitve na V/I položaj. EK za odpremo je izveden podobno [10].

DK obsega hkrati uskladiščenje in odpremo. DK obsega čas za nalaganje TSE na V/I lokaciji, vožnjo do skladiščne lokacije, odlaganje TSE v skladiščni regal, prazno vožnjo do odpremnega položaja,

velocities are used for the horizontal and vertical travel.
- The pickup and deposit times associated with the TUL's handling are assumed to be constant and, therefore, these could easily be added to the cycle time expressions.
- The S/R machine operates either on the SC, DC, QC or STC.
- For the "Strategy x" heuristics, a block of *n* occupied locations is available for retrievals sequencing and there are a block of *m* initial open locations for storage sequencing in the SR.

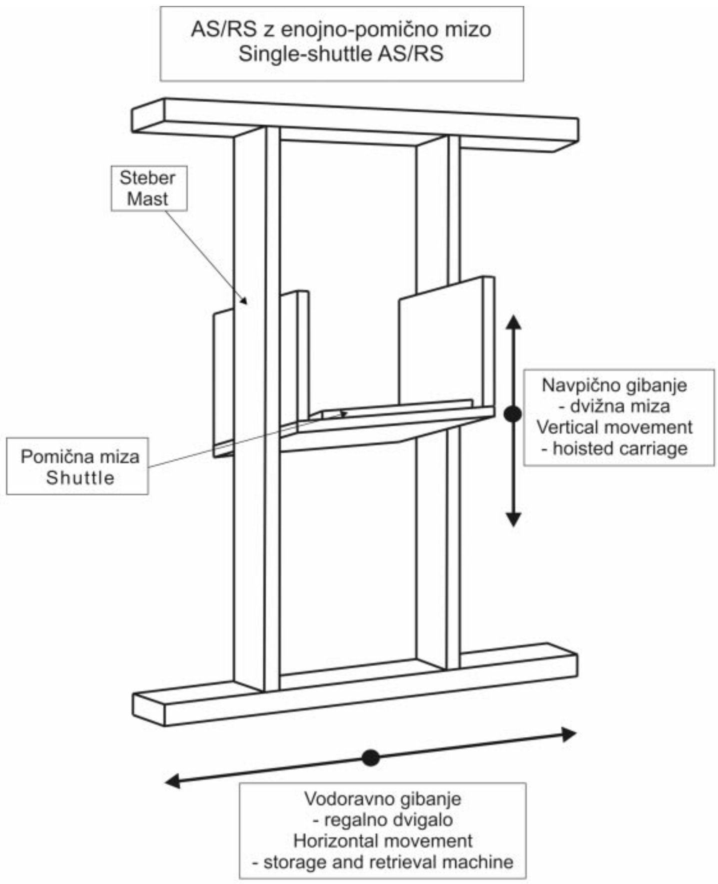
Notations:
- v_x velocity of the S/R machine in the horizontal direction,
- v_y velocity of the S/R machine in the vertical direction,
- a_x acceleration/deceleration of the S/R machine in the horizontal direction,
- a_y acceleration/deceleration of the S/R machine in the vertical direction,
- H height of the SR,
- L length of the SR,
- E(T(SA)) the expected one-way travel time,
- E(T(SC)) the expected single command travel time,
- E(T(DC)) the expected dual command travel time,
- E(T(QC)) the expected quadruple command travel time,
- E(T(STC)) the expected sextuple command travel time.

1.1 Single-shuttle AS/RS

A typical single-shuttle AS/RS has an S/R machine that moves TULs to or from specific storage locations on either side of the picking aisle. High lifting distances, high velocity in horizontal and vertical directions, precise handling and controlled movement are important features of the S/R machine. The S/R machine consist of a travelling structural frame, which guides and supports a hoisted carriage on which the TUL is placed [12]. The shuttle or extraction device on the hoisted carriage manipulates TULs into and out of the SR position. The single-shuttle AS/RS corresponds to SC or to DC.

The SC consists of either the storage or retrieval operation. For storage, the SC consists of the time to pickup the TUL at the I/O location, travel to the storage location, depositing the TUL at that location and the return to the I/O location. The SC for a retrieval operation is developed similarly [10].

The DC involves both storage and retrieval operations simultaneously. The DC involves the time to pickup the TUL at the I/O location, travel to the storage location, placing the TUL in the SR, traveling empty to the retrieval location, retrieving the TUL,



Sl. 1. *Regalno dvigalo za AS/RS z enojno pomično mizo*
Fig. 1. *The S/R machine for single-shuttle AS/RS*

odpremo TSE ter vrnitev in odlaganje TSE na V/I položaja [10].

V literaturi poznamo mnogo matematičnih izrazov za določitev delovnega kroga AS/RS. V nadaljevanju bodo predstavljeni modeli, ki so jih predlagali Bozer in White [2] ter Gudehus [6].

Bozer in White [2] sta razširila analitične izraze predhodno predstavljene pri Hausmanu in sodelavcih [8] ter Gravesu in sodelavcih [5]. Izpeljala sta analitične modele za določitev statističnega povprečja EK in DK za regalna skladišča, ki niso SIT. Model temelji na naključnem skladiščenju, z upoštevanjem alternativnih V/I položajev in postavitve regalnega dvigala v regalnem hodniku. V analitičnih modelih nista upoštevala vpliva pospeševanja in pojemanja. Na podlagi naključnega skladiščenja in odpreme PPPP so določena statistična povprečja za različne oblike skladiščnega opravila, sledi [13]:

- Izračun izmer skladiščnega regala v času

returning and deposing the TUL at the I/O location [10].

Many formulas for the cycle-time calculation of the AS/RS can be found in the literature. In what follows the expressions of Bozer and White [2] and Gudehus [6] will be presented.

Bozer and White [2] have extended the analytical expressions that were previously presented by Hausman at al. [8] and Graves at al. [5]. They developed analytical models for the expected single and dual command cycles for the non-SIT racks. The models are based on randomized storage, where the alternative I/O locations and various dwell-point strategies for the S/R machine were considered. In the analytical expressions the influences of acceleration and deceleration were not considered. According to randomized storage and FCFS retrieval requests, the expected travel-time estimation for different kinds of operation are determined as follows [13]:

- Computation of the dimensions for the SR in time

$$t_x = \frac{L}{v_x} \qquad t_y = \frac{H}{v_y} \qquad (1).$$

Naj bo T faktor velikosti in b faktor oblike skladiščnega regala:

Let T be the scaling factor and b the shape factor for the SR:

$$T = \text{maks}(t_x, t_y) \qquad b = \min\left(\frac{t_x}{T}, \frac{t_y}{T}\right) \qquad (2).$$

- Izračun statističnega povprečja za različne delovne kroge

Statistično povprečje časa vožnje regalnega dvigala za eno smer v skladiščnem regalu:

- Computation of the expected travel times for different cycles

Expected one-way travel time:

$$E(T(SA))=\left[\frac{1}{2}+\frac{b^2}{6}\right]\cdot T \qquad (3).$$

Statistično povprečje časa vožnje regalnega dvigala pri enojnem delovnem krogu:

Expected single command travel time:

$$E(T(SC))=\left[1+\frac{b^2}{3}\right]\cdot T \qquad (4).$$

Statistično povprečje časa vožnje regalnega dvigala med dvema skladiščnima položajema:

Expected travel between time component for dual command cycle:

$$E(T(TB))=\left[\frac{1}{3}+\frac{b^2}{6}-\frac{b^3}{30}\right]\cdot T \qquad (5).$$

Statistično povprečje časa vožnje regalnega dvigala pri dvojnem delovnem krogu:

Expected dual command travel time:

$$E(T(DC))=\left[\frac{4}{3}+\frac{b^2}{2}-\frac{b^3}{30}\right]\cdot T \qquad (6).$$

Vpliva razmerja pospeševanja in pojemanja sta upoštevana v analitičnih izrazih Gudehus [6]. Predstavljeni analitični modeli veljajo samo za skladiščne regale, pri katerih je faktor oblike b enak 1

The influence of acceleration and deceleration rate on the analytical expressions are considered by Gudehus [6]. The presented analytical models are valid only for the SR shape factor b = 1

$$b=\frac{v_x}{v_z}\cdot\frac{H}{L} \qquad (7).$$

S spodnjimi izrazi lahko določimo statistično povprečje za različne delovne kroge. Statistično povprečje časa vožnje regalnega dvigala za eno smer v skladiščnem regalu:

The expected travel time estimations for different cycles are calculated using the following expressions. Expected one-way travel time:

$$E(T(SA))=\frac{1}{2}\left(\frac{v_x}{a_x}+\frac{v_y}{a_y}\right)+\frac{2}{3}\cdot\frac{L}{v_x} \qquad (8).$$

Statistično povprečje časa vožnje regalnega dvigala pri enojnem delovnem krogu:
.

Expected single command travel time:

$$E(T(SC))=\left(\frac{v_x}{a_x}+\frac{v_y}{a_y}\right)+\frac{4}{3}\cdot\frac{L}{v_x} \qquad (9).$$

Statistično povprečje časa vožnje regalnega dvigala med dvema skladiščnima položajema:

Expected travel time between two randomly selected points:

$$E(T(TB))=\frac{1}{2}\left(\frac{v_x}{a_x}+\frac{v_z}{a_z}\right)+\frac{14}{30}\frac{L}{v_x} \qquad (10).$$

Statistično povprečje časa vožnje regalnega dvigala pri dvojnem delovnem krogu:

Expected dual command travel time:

$$E(T(DC))=\frac{3}{2}\left(\frac{v_x}{a_x}+\frac{v_y}{a_y}\right)+\frac{4}{3}\frac{L}{v_x}+\frac{14}{30}\frac{L}{v_x} \qquad (11).$$

1.2 AS/RS z večpomičnimi mizami

V predloženem prispevku temelji analiza AS/RS z večpomičnimi mizami na pristopu diskretnih simulacij. Analitične modele za ŠK in ŠEK za AS/RS z več-pomičnimi mizami so predstavili avtorji Meller in Mungwatana [13] ter Keserla in Peters [10]. Z namenom, da bi dosegli največje zmogljivost AS/RS (npr. kratki časi vožnje regalnega dvigala), moramo uporabiti ustrezno domiselno metodo. V nadaljevanju bo predstavljena domiselna metoda “strategija x” za

1.2 Multi-shuttle AS/RS

In the presented study of multi-shuttle AS/RS, the analysis is based on the discrete event simulations approach. Analytical models for the QC and STC of multi-shuttle AS/RS operation were developed by Meller and Mungwatana [13] and Keserla and Peters [10]. In order to achieve the maximum efficiency of the AS/RS (e.g., short travel times) the proper heuristics strategy should be used. The use of heuristics “Strategy x”, for the case of primera AS/RS z dvojnopomično in trojnopomično mizo, ki je bila uporabljena v predloženem prispevku.

1.2.1 AS/RS z dvojnopomično mizo

V primeru AS/RS z dvojnopomično mizo se uporablja posebna tehnična izvedba regalnega dvigala, ki lahko prenaša dve TSE hkrati. Poenostavljena oblika regalnega dvigala (glej sl. 2) sestoji iz pomičnega okvira, ki vodi in podpira dvižno mizo. Dve pomični mizi ali teleskopski napravi na dvižni mizi neodvisno vodita TSE v položaj v skladiščnem regalu in iz njega.

AS/RS z dvojno pomično mizo se nanaša na ŠK in določa regalnemu dvigalu, da obišče dva skladiščna in dva odpremna položaja v skladiščnem regalu. Učinkovit način za izvedbo omenjene določitve je, da sledimo zaporedju zahtev po uskladiščenju in odpremi z namenom, da bo čas prazne vožnje regalnega dvigala najmanjši [13]. Zaporedje zahtev za uskladiščenje in odpremo je mogoče natančno določiti z uporabo domiselne metode - "strategije x".

Algoritem za izvedbo te domiselne metode lahko zapišemo na naslednji način. Naj predstavlja S_n množico n začetnih praznih položajev in R_m množico n odprem, primernih za izvedbo zaporedja v skladiščnem regalu.

Algoritem "strategije x" v primeru AS/RS z dvojno pomično mizo:

1) Izbira dveh skladiščnih položajev v SR

$$(S_1, S_2, ..., S_n \in S) \quad (S_1, S_2) \in S$$

2) Izbira dveh odpremnih položajev v SR

$$(R_1, R_2, ..., R_n \in R) \quad (R_1, R_2) \in R$$

3) Določitev zaporedja za obisk dveh skladiščnih in dveh odpremnih položajev

$$(S_1, S_2)^{\text{Naraščajoča "strategija x"}} \quad (R_1, R_2)^{\text{Padajoča "strategija x"}}$$

4) Izvedba skladiščne operacije štirikratnega delovnega kroga

Skladiščno opravilo - uskladiščenje TSE (naraščajoča "strategija x")

1. uskladišči S_1, če velja pogoj $x_{S_1} < x_{S_2}$,
2. uskladišči S_2.

Skladiščno opravilo - odprema TSE (padajoča "strategija x")

1. odpremi R_1, če velja pogoj $x_{R_1} > x_{R_2}$,
2. odpremi R_2.

5) Določitev pretočnih zmogljivosti pri enem delovnem krogu

$$\lambda_{QC} = (2 \cdot S + 2 \cdot R) = 4 \left[\frac{TSE}{cikel} \right] \qquad (12).$$

Statistično povprečje časa vožnje regalnega dvigala pri štirikratnem delovnem krogu je enako statističnemu povprečju časa vožnje regalnega

dual-shuttle and triple-shuttle AS/RS, is discussed in the following study.

1.2.1 Dual-shuttle AS/RS

In the case of dual-shuttle AS/RS, a special design of S/R machine, which can carry two TULs simultaneously, is used. The simplified configuration of the S/R machine (see Fig. 2) consists of the traveling structural frame, which guides and supports a hoisted carriage. Two shuttles or extraction devices on the hoisted carriage manipulate the TULs into and out of the SR position independently [12].

The dual-shuttle AS/RS corresponds to the QC and requires the S/R machine to visit two storage and two retrieval locations in the SR. An efficient way to perform this command is to sequence storage and retrieval requests with the condition that the empty travel of the S/R machine will be minimised (see also Meller and Mungwatana [13]). The possibility to sequence storage and retrieval requests is to follow the heuristics, which will be further presented.

The algorithm for performing "Strategy x" can be written with the following procedure. Let S_n be the set of n initial open locations and R_m the set of m retrievals available for sequencing in the SR.

The "Strategy x" in the case of dual-shuttle AS/RS operates as follows:

1) Selection of two storage locations in the SR

$$(S_1, S_2, ..., S_n \in S) \quad (S_1, S_2) \in S$$

2) Selection of two retrieval locations in the SR

$$(R_1, R_2, ..., R_n \in R) \quad (R_1, R_2) \in R$$

3) Determination of the sequence for visiting two storage and two retrieval locations

$$(S_1, S_2)^{\text{Increasing "Strategy x"}} \quad (R_1, R_2)^{\text{Decreasing "Strategy x"}}$$

4) Performance of the storage operation under quadruple command cycle

Storage operation-storage of TULs (increasing "Strategy x")

1. Storage S_1, if the condition $x_{S_1} < x_{S_2}$ is true,
2. Storage S_2.

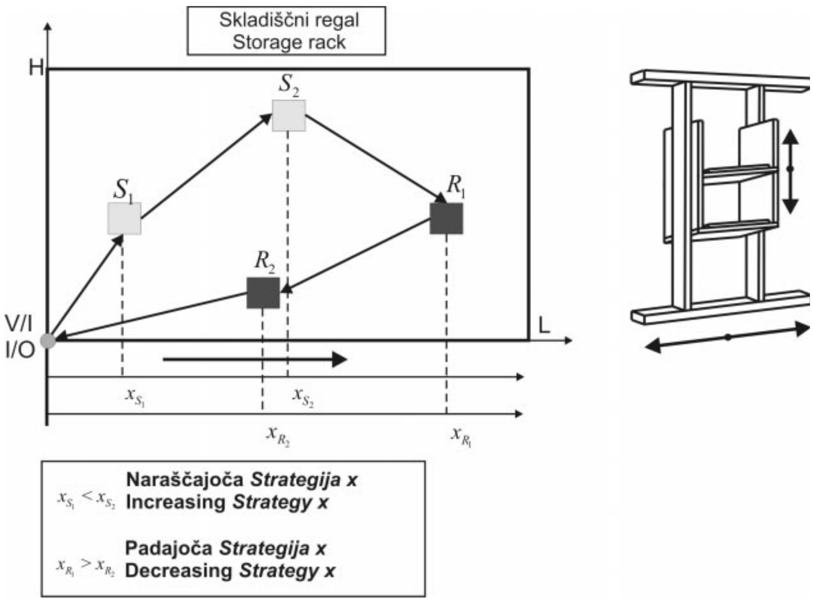
Storage operation-retrieval of TULs (decreasing "Strategy x")

1. Retrieve R_1, if the condition $x_{R_1} > x_{R_2}$ is true,
2. Retrieve R_2.

5) Determination of the throughput capacity in a quadruple command cycle

$$\lambda_{QC} = (2 \cdot S + 2 \cdot R) = 4 \left[\frac{TUL's}{cycle} \right] \qquad (12).$$

The expected quadruple command travel time consists of the expected single command travel time E(T(SC)) and three expected travel



Sl. 2. *Štirikratni delovni krog*
Fig. 2. *Quadruple command cycle*

dvigala pri enojnem delovnem krogu E(T(SC)) ter trem statističnim povprečjem časa vožnje regalnega dvigala med dvema skladiščnima položajema E(T(TB)) v skladiščnem regalu.

times between the time components E(T(TB)) in the SR.

$$E(T(QC)) = E(T(SC)) + 3 \cdot E(T(TB)) \quad (13).$$

Statistično povprečje časa za izvedbo štirikratnega delovnega kroga povečamo za vrednost vseh rokovanj, ki nastanejo pri izvedbi skladiščnega opravila (nalaganje in odlaganje TSE, razpoznavanje TSE itn.).

The expected quadruple command cycle time is enlarged for all the manipulations related to the TUL's handling (pickup and deposit of TULs, identification of TULs etc.)

$$E(QC) = E(T(QC)) + \sum T_m \quad (14).$$

1.2.2 AS/RS s trojno pomično mizo

V primeru AS/RS s trojno pomično mizo se uporablja posebna konstrukcijska izvedba regalnega dvigala, ki lahko prenaša tri TSE hkrati. Regalno dvigalo (sl. 3) se sestoji iz pomičnega okvira, ki vodi in podpira dvižno mizo. Tri pomične mize ali teleskopske naprave na dvižni mizi vodijo neodvisno TSE v položaj v skladiščnem regalu in iz njega.

AS/RS s trojno pomično mizo se nanaša na ŠEK in določa regalnemu dvigalu, da obišče tri skladiščne in tri odpremne položaje v skladiščnem regalu. Prav tako kakor v AS/RS z dvema pomičnima mizama je učinkovit način za izvedbo omenjene zahteve, da sledimo zaporedju zahtev po uskladiščenju in odpremi z namenom, da bo čas prazne vožnje regalnega dvigala najmanjši.

Naj predstavlja S_n množico n začetnih praznih položajev in R_m množico n odprem, primernih za izvedbo zaporedja v SR.

Algoritem "strategije x" v primeru AS/RS s trojno pomično mizo:

1.2.2 Triple-shuttle AS/RS

In the case of the triple-shuttle AS/RS, a special design of the S/R machine, which can carry three TULs simultaneously, is used. The S/R machine (see Figure 3) consists of the travelling structural frame, which guides and supports a hoisted carriage. Three shuttles or extraction devices on the hoisted carriage manipulate the TULs into and out of the SR position independently [12].

The triple-shuttle AS/RS corresponds to STC and requires the S/R machine to visit three storage and three retrieval locations in the SR. As well as in the dual-shuttle AS/RS, an efficient way to perform this command is to sequence storage and retrieval requests with condition that the empty travel of the S/R machine will be minimal.

Let S_n be the set of n initial open locations and R_m the set of m retrievals available for sequencing in the SR.

The "Strategy x" in case of triple-shuttle AS/RS operates as follows:

1) Izbira treh skladiščnih položajev v SR

$$(S_1, S_2, S_3 ..., S_n \in S)\ (S_1, S_2, S_3) \in S$$

2) Izbira treh odpremnih položajev v SR

$$(R_1, R_2, R_3, ..., R_n \in R)\ (R_1, R_2, R_3) \in R$$

3) Določitev zaporedja za obisk treh skladiščnih in treh odpremnih položajev

$$(S_1, S_2, S_3)^{\text{Naraščajoča "strategija x"}}\quad (R_1, R_2, R_3)^{\text{Padajoča "strategija x"}}$$

4) Izvedba skladiščnega opravila šestkratnega delovnega kroga

Skladiščno opravilo - uskladiščenje TSE (naraščajoča "strategija x")

1. Uskladišči S_1, če velja pogoj $x_{S_1} < x_{S_2} < x_{S_3}$.
2. Uskladišči S_2, če velja pogoj $x_{S_2} < x_{S_3}$.
3. Uskladišči S_3.

Skladiščno opravilo odprema TSE (padajoča "strategija x")

1. Odpremi R_1, če velja pogoj $x_{R_1} > x_{R_2} > x_{R_3}$.
2. Odpremi R_2, če velja pogoj $x_{R_2} > x_{R_3}$.
3. Odpremi R_3.

5) Določitev pretočnih zmogljivosti pri enem delovnem krogu

$$\lambda_{STC} = (3 \cdot S + 3 \cdot R) = 6 \left[\frac{TSE}{cikel}\right] \quad (15).$$

Statistično povprečje časa vožnje regalnega dvigala pri šestkratnem delovnem krogu je enako statističnemu povprečju časa vožnje regalnega dvigala pri enojnem delovnem krogu E(T(SC)) ter petim statističnim povprečjem časa vožnje regalnega dvigala med dvema skladiščnima položajema E(T(TB)) v skladiščnem regalu.

1) Selection of three storage locations in the SR

$$(S_1, S_2, S_3 ..., S_n \in S)\ (S_1, S_2, S_3) \in S$$

2) Selection of three retrieval locations in the SR

$$(R_1, R_2, R_3, ..., R_n \in R)\ (R_1, R_2, R_3) \in R$$

3) Determination of the sequence for visiting three storage and three retrieval locations

$$(S_1, S_2, S_3)^{\text{Increasing "Strategy x"}}\quad (R_1, R_2, R_3)^{\text{Decreasing "Strategy x"}}$$

4) Performance of the storage operation under sextuple command cycle

Storage operation-storage of TULs (increasing Strategy x)

1. Storage S_1, if the condition $x_{S_1} < x_{S_2} < x_{S_3}$ is true.
2. Storage S_2, if the condition $x_{S_2} < x_{S_3}$ is true.
3. Storage S_3.

Storage operation-retrieval of TULs (decreasing "Strategy x")

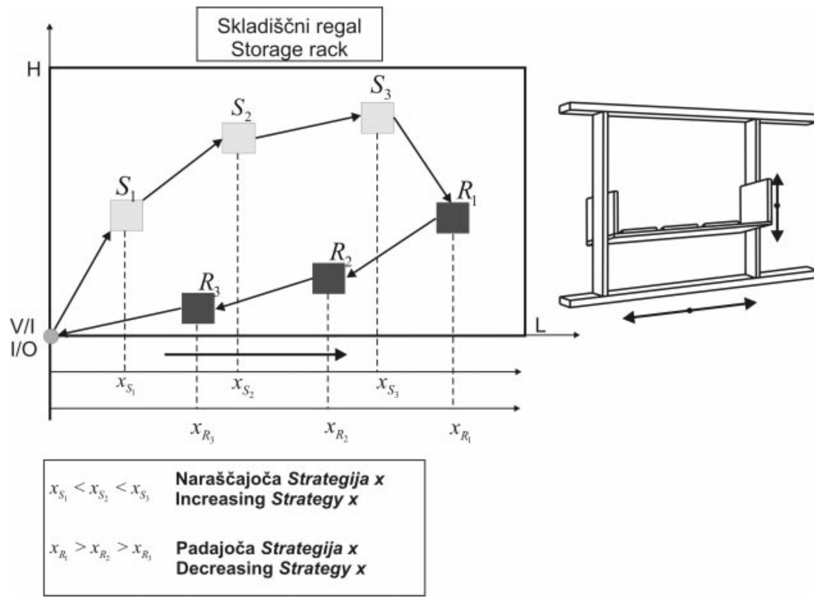
1. Retrieve R_1, if the condition $x_{R_1} > x_{R_2} > x_{R_3}$ is true.
2. Retrieve R_2, if the condition $x_{R_2} > x_{R_3}$ is true.
3. Retrieve R_3.

5) Determination of throughput capacity in one cycle

$$\lambda_{STC} = (3 \cdot S + 3 \cdot R) = 6 \left[\frac{TULs}{cycle}\right] \quad (15).$$

The expected sextuple command travel time consists of the expected single command travel time E(T(SC)) and five expected travel times between time components E(T(TB)) in the SR.

$$E(T(STC)) = E(T(SC)) + 5 \cdot E(T(TB)) \quad (16).$$



Sl. 3. *Šestkratni delovni krog*
Fig. 3. *Sextuple command cycle*

Statistično povprečje časa za izvedbo šestkratnega delovnega kroga, povečamo za vrednost vseh rokovanj, ki nastanejo pri izvedbi skladiščnega opravila (nalaganje in odlaganje TSE, razpoznavanje TSE itn.).

The expected sextuple command cycle time is enlarged for all the manipulations related to TUL's handling (pickup and deposit of TULs, identification of TULs).

$$E(STC) = E(T(STC)) + \sum T_m \qquad (17).$$

2 SIMULACIJSKI MODEL AS/RS

2 SIMULATION MODEL OF THE AS/RS

Za ovrednotenje zmogljivosti AS/RS z enojno pomično mizo, v primerjavi z večpomičnimi mizami, smo uporabili metodo diskretnih simulacij. Simulacijski model AS/RS je sestavljen iz dveh delov skladiščnih regalov, regalnega dvigala, V/I položaja in zveznega transporterja. Model je bil izdelan in analiziran s programskim paketom "AutoMod" [3].

Na podlagi pregleda literature in praktičnih izkušenj smo ugotovili, da pomenijo (i) različne oblike skladiščnih regalov, (ii) zmogljivosti regalnega dvigala in (iii) upravljalna strategija velik vpliv na povprečen čas vožnje regalnega dvigala. Zatorej smo uporabili v simulacijski analizi pet različnih tipov skladiščnih regalov, ki so predstavljeni v preglednici 1.

Glede na zmogljivost regalnega dvigala smo uporabili devetnajst najpogosteje uporabljenih hitrostnih profilov za pomik regalnega dvigala v vodoravni in pomične mize v navpični smeri. V

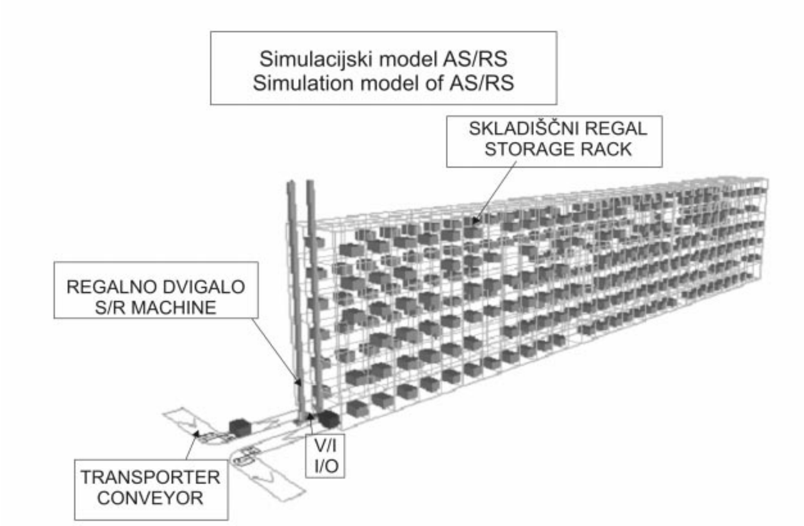
To facilitate the performance evaluation and comparison of the single-shuttle AS/RS versus multi-shuttle AS/RS, a discrete event simulation was employed. The simulation model of the AS/RS consists of two lines of SR, S/R machine, I/O location and accumulating conveyors, and was defined using the "AutoMod" computer software [3].

From the literature and practical experiences it has been found that (i) different layouts of the SR (ii) the efficiency of the S/R machine and (iii) the control policies have a tremendous influence on the average travel time. Therefore, five different layouts of the SR were used in the simulation analyses, which are presented in Table 1.

According to the efficiency of the S/R machine, nineteen different velocity profiles were used for the translation in the horizontal and vertical directions. Therefore, two completely independent

Preglednica 1. *Pet različnih tipov skladiščnih regalov*
Table 1. *Five different layouts of the SR*

Skladiščni regal Storage rack	L (m)	H (m)	Zalogovna velikost Rack capacity
SR 30/6	30	6	360
SR 20/13	20	13	520
SR 45/10	45	10	900
SR 60/13	60	13	1560
SR 80/20	80	20	3200



Sl. 4. *Simulacijski model AS/RS z enojno pomično mizo*
Fig. 4. *Simulation model of the single-shuttle AS/RS*

Preglednica 2. *Zmogljivost regalnega dvigala*
Table 2. *The efficiency of the S/R machine*

Zmogljivost regalnega dvigala The S/R machine efficiency	Vodoravno gibanje regalnega dvigala Horizontal movement of the S/R machine		Navpično gibanje dvižne mize Vertical movement of the hoisting carriage	
	v_x (m/s)	a_x (m/s^2)	v_y (m/s)	a_y (m/s^2)
V_1	2	1	1,5	0,75
V_2	2	1	1,5	1,5
V_3	2	2	1,5	0,75
V_4	2	2	1,5	1,5
V_5	4	1	1,5	0,75
V_6	4	1	1,5	1,5
V_7	4	2	1,5	0,75
V_8	4	2	1,5	1,5
V_9	4	3	1,5	0,75
V_{10}	4	3	1,5	1,5
V_{11}	4	1	3	0,75
V_{12}	4	1	3	1,5
V_{13}	4	1	3	2,25
V_{14}	4	2	3	0,75
V_{15}	4	2	3	1,5
V_{16}	4	2	3	2,25
V_{17}	4	3	3	0,75
V_{18}	4	3	3	1,5
V_{19}	4	3	3	2,25

preglednici 2 sta s parametrom zmogljivosti V_i predstavljena dva popolnoma neodvisna mehanska pogona za vodoravno in navpično gibanje. Upoštevali smo tudi pospeševanje in pojemanje regalnega dvigala.

Prav tako kakor oblika skladiščnega regala in zmogljivost regalnega dvigala ima tudi upravljalno pravilo pomemben vpliv na povprečni čas vožnje regalnega dvigala. V primeru AS/RS z enojno pomično mizo smo za uskladiščenje TSE uporabili strategijo naključnega skladiščenja, medtem ko smo za odpremo TSE uporabili strategijo po pravilu PPPP. V primeru AS/RS z večpomičnimi mizami smo za uskladiščenje in odpremo uporabili predhodno omenjeno "strategijo x". Za vsak posamezen tip AS/RS (oblika skladiščnega regala, zmogljivost regalnega dvigala in sistem z enojno pomično v primerjavi z več-pomičnimi mizami) smo osnovni simulacijski model AS/RS primerno prilagajali.

2.1 Izdelava osnovnega AS/RS

V nadaljevanju bo prikazana določitev postopka za AS/RS z enojno pomično in večpomičnimi mizami.

2.1.1 Postopek izvedbe simulacije za AS/RS z enojno pomično mizo

Simulacija AS/RS se prične s postopkom, ki na podlagi določenih spremenljivk označi vsa prosta mesta v skladiščnem regalu. Ko je določen

mechanical drives (horizontal and vertical), which are presented with the efficiency parameter V_i, are presented in Table 2. The acceleration and deceleration of the S/R machine have also been considered.

Like the layout of the SR and the efficiency of the S/R machine, the control policy also has a significant share on the average travel time. For the single-shuttle AS/RS, the general randomized storage policy and the FCFS order picking assignment policy were applied; however, for the multi-shuttle AS/RS, the heuristics storage and order picking assignment policy, "Strategy x", were applied. For every single type of AS/RS (the layout of the SR, the efficiency of the S/R machine and the single in comparison with multi-shuttle AS/RS) the general simulation model of AS/RS has been suitably modified.

2.1 Development of the general AS/RS

In the following, the determination of the simulation procedure for the single and multi-shuttle AS/RS will be presented.

2.1.1 Single-shuttle AS/RS

The simulation of the AS/RS starts with the process of indicating all the storage locations in the SR, on the basis of definite variables. After creating seznam prostih skladiščnih mest, se prične simulacija prihoda TSE. Po končanem transportu s tekočim trakom je TSE na V/I položaju, ki leži v spodnjem levem robu regalnega skladišča. TSE sprejme oznako, ki ji določa skladiščni položaj v skladiščnem regalu. Regalno dvigalo prevzame TSE na V/I položaju, jo naloži s pomično mizo na dvižno mizo in jo dostavi na določen skladiščni položaj v skladiščnem regalu. Za opravilo uskladiščenja je bila uporabljena strategija naključnega skladiščenja. Vsako TSE, ki je bila uskladiščena, zapišemo na čakalno listo. Skladiščenje TSE se izvaja tako dolgo, dokler se skladišče ne zapolni do določene stopnje (npr. 80 %). Ob prekoračitvi stopnje napolnjenosti se sproži postopek odpreme TSE. Pri opravilu odpreme smo uporabili pravilo PPPP. V nadaljevanju potuje regalno dvigalo na odpremni položaj TSE, ki jo s pomično mizo naloži na dvižno mizo ter jo dostavi na V/I položaj. Pri izvedbi skladiščnega opravila deluje regalno dvigalo na temelju DK.

2.1.2 Postopek izvedbe simulacije za AS/RS s trojno pomično mizo

Podobno kakor pri AS/RS z enojno pomično mizo, se tudi v tem primeru simulacija prične s postopkom, ki označi vsa prosta mesta v skladiščnem regalu. Po končanem transportu z zveznim transporterjem se TSE na V/I položaju, ki leži v spodnjem levem robu regalnega skladišča. V nadaljevanju TSE sprejmejo oznako, ki ji določa skladiščni položaj v skladiščnem regalu. Regalno dvigalo prevzame TSE na V/I položaju, jih naloži s pomičnimi mizami na dvižno mizo in jih dostavi na določen skladiščni položaj v skladiščnem regalu. S tremi praznimi položaji (S_1, S_2, S_3) potuje regalno dvigalo od V/I položaja do najbližjega skladiščnega položaja, na primer S_1. Po uskladiščenju prve TSE potuje regalno dvigalo do drugega skladiščnega položaja S_2, saj je le-ta bližje S_1 kakor S_3. Dalje potuje regalno dvigalo do zadnjega skladiščnega položaja S_3(sl. 7). Za opravilo uskladiščenja je bila uporabljena naraščajoča "strategija x". TSE, ki so bile uskladiščene, so vpisane na čakalno listo. Skladiščenje se izvaja tako dolgo, dokler se skladišče ne zapolni do določene stopnje (npr. 80 %). Ob prekoračitvi stopnje napolnjenosti se sproži nov postopek odpreme. Iz zadnjega skladiščnega položaja S_3 potuje regalno dvigalo do najbližjega od treh odpremnih položajev (R_1, R_2, R_3), na primer R_1. Dalje, s prvega odpremnega položaja R_1 potuje regalno dvigalo do najbližjega od preostalih odpremnih položajev R_2, saj je le-to bližje k R_1 kakor R_3. Po odpremi druge TSE potuje regalno dvigalo k zadnjemu odpremnemu položaju R_3. Nazadnje se regalno dvigalo vrne na V/I položaj kjer so TSE pripravljene, da zapustijo AS/RS. Pri opravilu odpreme je bila uporabljena padajoča "strategija x". Pri izvedbi

the list of free storage locations, the AS/RS's first TULs are entered. Through concluded transport with accumulating conveyor, the TULs are situated in the I/O location, which lies at the lower left-hand corner of the SR. Next, the TULs receive a sign, which is dedicated to the storage location in the SR. The S/R machine picks up the TUL from the I/O location, loads it into the shuttle at the hoisting carriage and moves it to the prescribed storage location in the SR. For the storage operation, randomized storage assignment policy was used. Each TUL that has been stored in the SR is then recorded by a computer on a waiting list. The storage operation is performed until the warehouse does not reach a certain degree of fullness (e.g., 80 %). In the case of overriding the degree of fullness, a new retrieval process starts. For the retrieval operation the FCFS request selection rule was used. Next, the S/R machine travels to the retrieval location of the TUL, loads it into the shuttle and delivers it to the I/O location. In performing the storage operation, the S/R machine operates on the dual command cycle.

2.1.2 Multi-shuttle AS/RS (triple-shuttle AS/RS)

Like for the single-shuttle AS/RS, the simulation of the AS/RS starts with the process that indicates all the storage location in the SR. After the concluded transport with an accumulating conveyor the TULs are situated in the I/O location, which lies at the lower left-hand corner of the SR. Next, the TULs receive the signs, which are dedicated to the storage locations in the SR. The S/R machine picks up the TULs from the I/O location, loads them into the shuttles, and moves them to the prescribed storage locations in the SR. With three open locations (e.g., S_1, S_2, S_3), the S/R machine moves from the I/O location to the closest storage location, for example, S_1. After storing the first TUL, the S/R machine moves to the second storage location, which is S_2 since it is closer to S_1 than S_3. Next, the S/R machine moves to the last storage location S_3. For the storage operation the increasing "Strategy x" storage assignment policy was used. TULs that have been already stored are then recorded by a computer on the waiting list. The storage operation is performed until the warehouse does not reach a certain degree of fullness (e.g., 80 %). In the case of overriding the degree of fullness, a new retrieval process starts. From the last storage location S_3, the S/R machine moves toward to the closest of three retrieval locations (e.g., R_1, R_2, R_3), for instance R_1. Next, from the first retrieval location R_1, the S/R machine moves to the closest of the remaining two retrieval locations, which is R_2, since it is closer to R_1 than R_3. After the retrieval of the second TUL, the S/R machine moves to the last retrieval location R_3. Finally, the S/R machine returns to the I/O location when the TULs are ready to depart from the system. For the retrieval operation the decreasing "Strategy x" request skladiščnega opravila deluje regalno dvigalo na podlagi ŠEK.

Povprečni čas vožnje regalnega dvigala glede na AS/RS z večpomičnimi mizami je daljši v primerjavi z AS/RS z enojno pomično mizo. Kljub temu, da je povprečni čas vožnje regalnega dvigala daljši, dosežemo večje pretočne zmogljivosti, saj regalno dvigalo omogoča uskladiščenje in odpremo več TSE hkrati. Za vsak posamezen tip AS/RS je bil izdelan poseben simulacijski model, tako da smo lahko prilagajali osnovni simulacijski model.

selection rule was used. In performing storage operation, the S/R machine operates on the sextuple command cycle.

The average travel time, according to the multi-shuttle AS/RS, is longer than the single-shuttle AS/RS. Despite a longer average travel time, higher throughput capacities are achieved, since the S/R machine manipulates several TULs simultaneously. For every single type of AS/RS a special simulation model was performed in such a way that the general simulation model was supplemented.

2.2 Izvajanje in rezultati simulacij

S programskim modulom "AutoStat" smo za vsako posamezno izvedbo AS/RS analizirali povprečne čase vožnje regalnega dvigala. Pred začetkom simulacijske analize smo določili vhodne podatke za izvedbo simulacije.

V uporabljenem simulacijskem modelu pomeni T povprečen čas vožnje regalnega dvigala, definiran z "*v_Time*", ki je enak vsoti časov T_i, potrebnih za uskladiščenje in odpremo TSE.

2.2 Performance and the results of the simulations

For every single realization of the AS/RS the average travel times were analysed using the program module "Auto Stat" [3]. Before starting the simulation analysis, the input data were determined.

In the present simulation model, T represents the average travel time, defined with "*v_Time*", which consist of the sum of times T_i, necessary for the storage and retrieval of TULs.

$$T = \sum_i T_i \quad (18).$$

Za AS/RS z enojno-pomično mizo pomeni "*v_Time*" vsoto povprečnega časa vožnje regalnega dvigala za enojni delovni krog in vožnjo regalnega dvigala med dvema skladiščnima položajema, kar pomeni dvojni delovni krog. Za AS/RS z večpomičnimi mizami pomeni "*v_Time*" vsoto povprečnega časa vožnje regalnega dvigala za enojni delovni krog in tri ali pet voženj regalnega dvigala med dvema skladiščnima položajema, kar pomeni štirikratni oziroma šestkratni delovni krog. Povprečni čas vožnje regalnega dvigala za AS/RS z enojno pomično in večpomičnimi mizami pomeni razmerje med vsoto časov vožnje regalnega dvigala in številom izvedenih krogov:

For the single-shuttle AS/RS represents the variable "*v_Time*", the sum of the average travel time for a single command cycle T(SC) and the average travel lines between the time component T(BT), which gives us the necessary average travel time for the dual command cycle T(DC). For the multi-shuttle AS/RS represents the variable "*v_Time*", the sum of the average travel time for the single command cycle T(SC) and three or five average travel times between the time components T(BT), which gives us the necessary time for the average travel time for quadruple T(QC) and sextuple command cycle T(STC). The average travel time for the single and multi-shuttle AS/RS represents the relation between the sums of the travel times with the number of performed cycles

$$T(DC)_{average} = \frac{\sum_i^m T(DC)}{m} \quad (19)$$

$$T(QC)_{average} = \frac{\sum_i^m T(QC)}{m} \quad (20)$$

$$T(STC)_{average} = \frac{\sum_i^m T(STC)}{m} \quad (21).$$

Preglednica 3. *Vhodni podatki za izvedbo simulacije*
Table 3. *Input data for the simulation analysis*

SR 30/6 – V_1	
Frekvenca prihoda (s^{-1}) / Arrival frequency (s^{-1})	45
Ogrevanje modela (ure) / Warmup period (hours)	5
Čas izvajanja simulacij (ure) / Simulation time (hours)	40
Število zaporednih simulacij / Number of successive simulations	5

Pri določitvi celotnega povprečnega časa delovnega kroga moramo upoštevati dodatne čase T_m, ki nastanejo pri rokovanju TSE (razpoznava TSE, nalaganje in odlaganje TSE itn.). Povprečni čas dvojnega, štirikratnega in šestkratnega delovnega kroga je tako:

The additional time T_m, which is associated with the manipulation of the TULs, must also be considered in the determination of the average cycle time (identification of TULs, pickup and deposit times for TULs etc.). Therefore, the average cycle time now becomes:

$$T(DC) = T(DC)_{average} + \sum_i T_m \qquad \sum_i T_m = 10\,\text{sec} \tag{22}$$

$$T(QC) = T(QC)_{average} + \sum_i T_m \qquad \sum_i T_m = 22\,\text{sec} \tag{23}$$

$$T(STC) = T(STC)_{average} + \sum_i T_m \qquad \sum_i T_m = 30\,\text{sec} \tag{24}.$$

Glede na izračunan povprečni čas delovnega kroga lahko določimo pretočno zmogljivost λ (TSE/uro) posamezne izvedbe AS/RS. Pretočna zmogljivost AS/RS z enojno pomično in večpomičnimi mizami je določena z naslednjimi izrazi:

The throughput capacity λ (TUL's/hour) of the individual variant of AS/RS can be determined according to the computed average cycle time. The throughput capacities for single and multi-shuttle AS/RS are determined with the following expressions;

$$\lambda_{DC} = \left[\left[\frac{3600}{T(DC)}\right] \cdot 2\right] \tag{25}$$

$$\lambda_{QC} = \left[\left[\frac{3600}{T(QC)}\right] \cdot 4\right] \tag{26}$$

$$\lambda_{STC} = \left[\left[\frac{3600}{T(STC)}\right] \cdot 6\right] \tag{27}.$$

Glavni namen simulacijske analize AS/RS z enojno pomično in več pomičnimi mizami je določitev odvisnosti med povprečnim časom delovnega kroga in pretočnih zmogljivosti za vsak določen AS/RS. Podrobna pojasnitev simulacijske analize je prikazana v naslednjem poglavju.

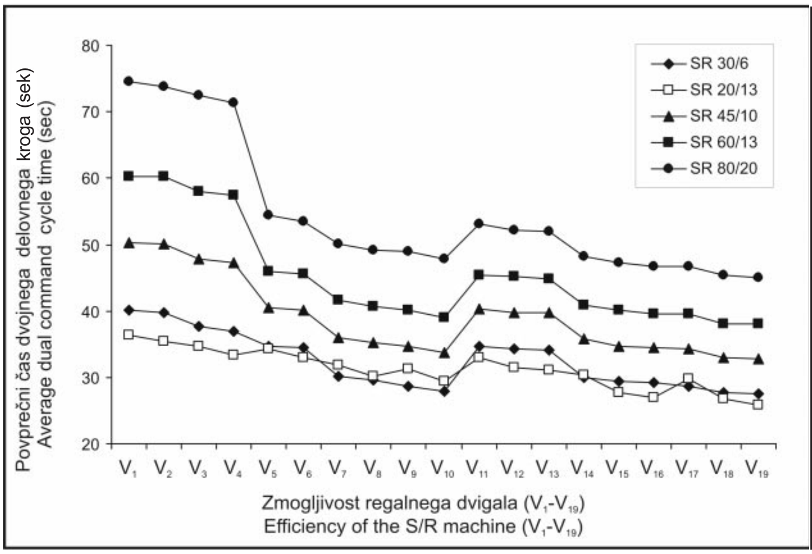
The main purpose of the simulation analysis of the single and multi-shuttle AS/RS is a determination of the relationship between the average cycle times and the throughput capacities for each defined AS/RS. A detailed explanation of the simulation analyses is presented in the next section.

2.3 Analiza rezultatov

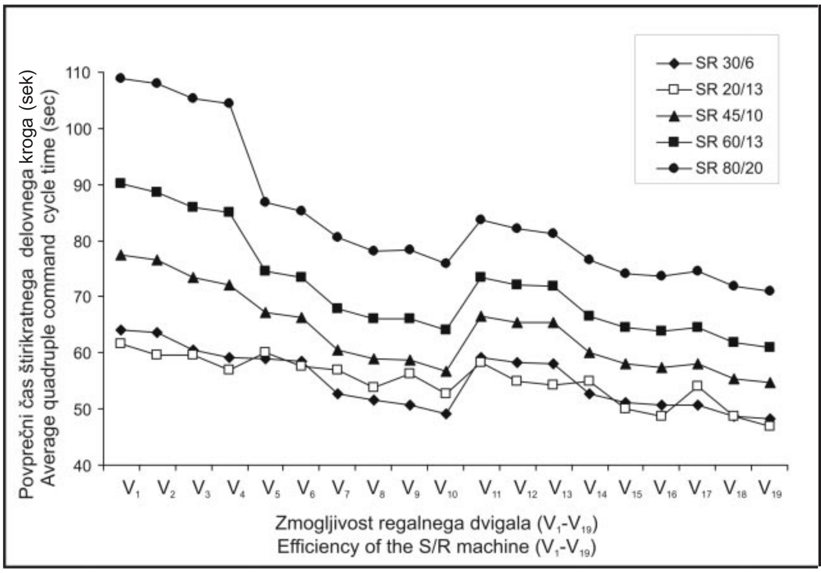
2.3 Analysis of the results

Povprečni časi delovnega kroga in pretočne zmogljivosti za AS/RS z enojno pomično in več-

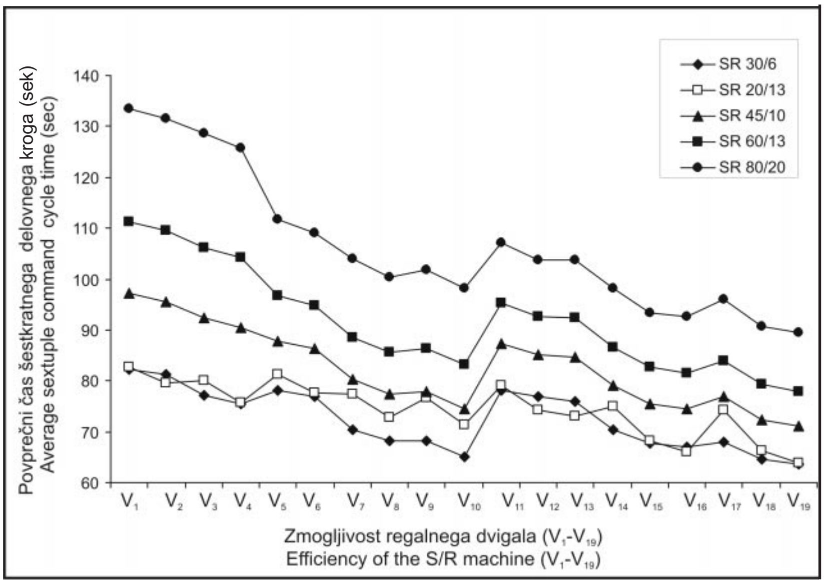
Average cycle times and throughput capacities for the single and multi-shuttle AS/RS,



Sl. 5. *Porazdelitev povprečnega časa dvojnega delovnega kroga*
Fig. 5. *Distribution of the average dual command cycle time*



Sl. 6. *Porazdelitev povprečnega časa štirikratnega delovnega kroga*
Fig. 6. *Distribution of average quadruple command cycle time*



Sl. 7. *Porazdelitev povprečnega časa šestkratnega delovnega kroga*
Fig. 7. *Distribution of average sextuple command cycle time*

pomičnimi mizami, ki so predstavljeni na slikah 5, 6, 7, so podani na temelju izvedene simulacijske analize. Analize so bile izvedene za pet različnih oblik skladiščnih regalov in devetnajst različnih zmogljivosti regalnega dvigala.

2.3.1 Povprečni čas delovnega kroga

(i) Geometrija skladiščnega regala
Glede na porazdelitev povprečnega časa dvojnega, štirikratnega in šestkratnega delovnega kroga za pet različnih oblik skladiščnih regalov (sl. 5, 6, 7) je očitno, da ima geometrija skladiščnega regala bistveni vpliv na povprečni čas delovnega kroga. Najnižji povprečni čas delovnega kroga, glede na tip AS/RS, pripada

which are presented in the following figures 5, 6, 7, are given on the basis of the performed simulation analyses. The analyses were conducted for five different layouts of the SR and nineteen different efficiencies of the S/R machine.

2.3.1 Average cycle times

(i) The SR geometry
According to the distribution of the average dual, quadruple and sextuple command cycle times for five different layouts of the SR (Figures 5, 6, 7), it is obvious that the SR geometry has a significant impact on the average cycle time. The lowest average cycle times according to the types of AS/RS belong to the

tipu regalnega skladišča SR 20/13 in SR 30/6. Najdaljšji povprečni rokovalni čas delovnega cikla pripada regalnemu skladišču SR 80/20. Poudariti je treba, da ima SR 80/20 šestkrat večjo zalogovno velikost od SR 20/13. Glavni sklep je, da ima geometrijska oblika skladiščnega regala (dolžina *L* in višina *H*) velik vpliv na povprečni čas delovnega kroga. Torej, pri določitvi tipa AS/RS pomeni geometrijska oblika skladiščnega regala pomemben podatek.

(ii) Zmogljivost regalnega dvigala

Drugi pomembni dejavnik je zmogljivost regalnega dvigala (preglednica 2), ki smo jo analizirali glede na pet različnih oblik skladiščnih regalov in tipov AS/RS. Izrazit vpliv povprečnega časa delovnega kroga, glede na spremembo zmogljivosti regalnega dvigala, velja za SR 80/20. V prvih štirih točkah lahko opazimo razmeroma majhne spremembe na povprečnem času delovnega kroga (sl. 5, 6, 7), kar prikazuje nepomemben vpliv pospeševanja, pojemanja in navpični hitrosti glede na obliko skladiščnega regala. Zmanjšanje povprečnega časa delovnega kroga se pojavi v točki V_5, v kateri naraste hitrost v vodoravni smeri, hitrost v navpični smeri pa ostane enaka, kar potrdi domnevo, da je komponenta hitrosti v_x za omenjene skladiščne regale najpomembnejša. Sledi padanje rokovalnega časa, vse do točke V_{11}, kjer vrednost hitrost v vodoravni smeri v_x ponovno doseže vrednost hitrosti v točki V_5, medtem ko se poveča hitrost v navpični smeri v_y. Povečanje hitrosti v vodoravni in navpični smeri povzroči ponovno padanje povprečnega časa delovnega kroga (sl. 5, 6, 7). Skladiščni regal 80/20 ima izrazit vpliv na povprečni čas delovnega kroga glede na obliko skladiščnega regala (dolgi SR $L/v_x >> H/v_y$). Kljub veliki hitrost (v_x = 4 m/s) ima vožnja regalnega dvigala pogosto hitrostno-časovno odvisnost pospeševanja, vožnje z ustaljeno hitrostjo in pojemanja (sl. 8).

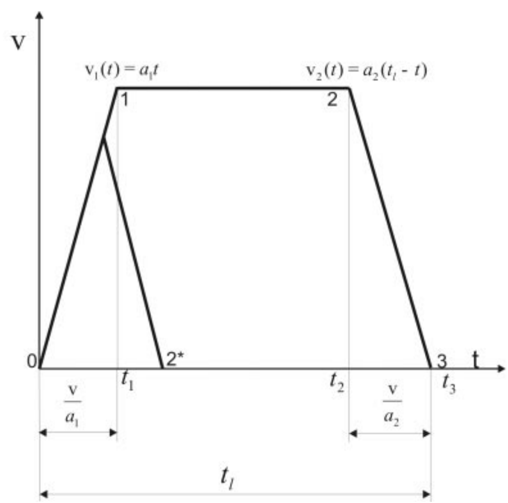
Drugače velja za SR 20/13, ki ima neizrazito težnjo glede na zmogljivost regalnega dvigala in kjer

type of storage rack SR 20/13 and SR 30/6, while the largest average cycle times belong to the type of storage rack SR 80/20. It must be emphased that the SR 80/20 has a six-times-greater capacity than the SR 20/13. The main conclusion is that the SR geometry (length *L* and height *H* of the SR) has a great influence on the average cycle times. Therefore, when determining the type of AS/RS, the SR geometry represents significant information.

(ii) The efficiency of the S/R machine

Another significant factor is the efficiency of the S/R machine (Table 2), which was analysed according to the five different layouts of the SR and types of the AS/RS. An expressive tendency, due to the change of efficiency of the S/R machine, is shown by storage rack SR 80/20. Relatively small changes in the average cycle times are observed for the first few points (Figures 5, 6, 7), which shows the insignificant influence of acceleration, deceleration and vertical velocity due to the layout of the SR. A decrease of the average cycle time arises at point V_5, where the horizontal velocity is increased, while the vertical velocity remains the same, which just confirms that for such a SR v_x is the most important. The decreasing tendency of the average cycle times continues until point V_{11}. The value of the horizontal velocity (V_{11}) again becomes equal to velocity at point V_5, while vertical velocity is increased. Increased vertical and horizontal velocities cause once again a decreasing tendency of average cycle times (Figures 5, 6, 7). The SR 80/20 has an expressive tendency according to the layout of the SR (long SR $L/v_x >> H/v_y$). Despite the high velocity travels (v_x = *4 m/s*), the S/R machine usually with velocity-time relationship according to acceleration, uniform velocity and deceleration (Figure 8).

In other cases, for the storage rack SR 20/13, the relationship of the average command cycle



Sl. 8. *Hitrostno-časovna odvisnost regalnega dvigala*
Fig. 8. *Velocity-time relationship of the S/R machine*

odvisnost povprečnega časa delovnega kroga ni tako bistvena. Kljub povečanju hitrosti v vodoravni smeri (točka V_5 na sliki 5, 6, 7), ne dosežemo večjega vpliva na vrednost povprečnega časa delovnega cikla zaradi oblike skladiščnega regala (kratki SR $L/v_x \geq H/v_y$). Kljub veliki zmogljivosti regalnega dvigala dosežemo največjo hitrost le v redkih primerih, zaradi razmeroma kratkih razdalj v skladiščnem regalu. Vožnja regalnega dvigala ima pogosto hitrostno-časovno odvisnost, ki obsega vpliv pospeševanja in pojemanja (sl. 8).

Na splošno lahko opazimo, da dosežemo najboljše rezultate pri izvedbi regalnega dvigala, ki ima najzmogljivejše pogone za vožnjo v vodoravni in navpični smeri. Sklepamo lahko, da se izrazite razlike vrednosti povprečnega časa delovnega kroga pojavijo zaradi posledice spremembe hitrosti v horizontalni smeri in manj v vertikalni smeri.

(iii) Odvisnost med AS/RS z enojno-pomično in večpomičnimi mizami

Primerjava med T(DC), T(QC) in T(STC) kaže na veliko povečanje povprečnega časa delovnega kroga za AS/RS z večpomičnimi mizami. Slednje lahko razložimo z dejstvom, da regalno dvigalo potrebuje več časa za obisk skladiščnih položajev pri ŠK in ŠEK glede na DK. Poudariti moramo, da bi bil povprečni čas delovnega kroga še večji, če ne bi za AS/RS z več-pomičnimi mizami uporabili domiselno metodo - "strategijo x". Kljub daljšim povprečnim časom delovnega kroga za AS/RS z večpomičnimi mizami dosežemo večje pretočne zmogljivost, saj sprejme regalno dvigalo več TSE hkrati.

Sklenemo lahko, da so geometrijska oblika skladiščnega regala, zmogljivost regalnega dvigala in vrsta upravljalne strategije najpomembnejši

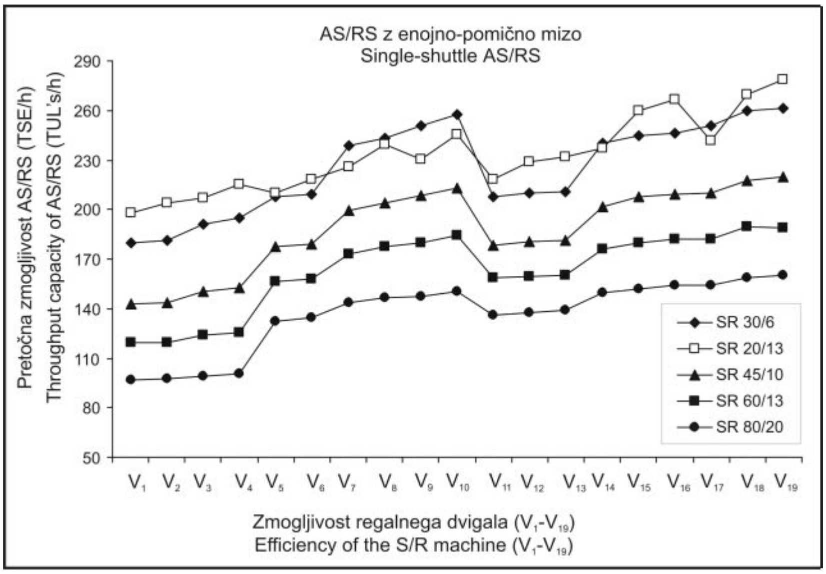
time is not so essential, which has inexpressive tendency according to the efficiency of the S/R machine. Due to the increasing horizontal velocity (point V_5 on Figures 5, 6, 7), major changes in the average cycle times are not achieved because of the layout of the SR (short SR $L/v_x \geq H/v_y$). In spite of the great efficiency of the S/R machine the maximum velocity hardly reached, due to the relatively short distances in the SR. The S/R machine travels in many instances on the basis of velocity-time relationship, which is associated with the acceleration and deceleration (Figure 8).

Generally, the best results are achieved with the S/R machine, which has the efficient drives for horizontal and vertical travelling. It can be concluded that the expressive differences in the average cycle times originate as a result of changing the horizontal velocity v_x and less as a result of changing the vertical velocity v_y.

(iii) The relationship between the single and multi-shuttle AS/RS

A comparison of the T(DC), T(QC) and T(STC) shows a large increase in the average cycle times. This can be explained by the fact that the S/R machine requires more time to visit all the storage locations under QC and STC, due to DC. It must be emphasised that the average travel time would be even higher if heuristics "Strategy x" in the multi-shuttle AS/RS had not been used. Despite the longer average cycle times for the multi-shuttle AS/RS, higher throughput capacities are achieved, since the S/R machine manipulates several TULs simultaneously.

The conclusion is that the SR geometry, the efficiency of the S/R machine and the type of control policy are the most significant parameters and that



Sl. 9. *Porazdelitev pretočne zmogljivosti za AS/RS z enojno pomično mizo*
Fig. 9. *Distribution of throughput capacities under single-shuttle AS/RS*

parametri v AS/RS in imajo velik vpliv na povprečni čas delovnega kroga.

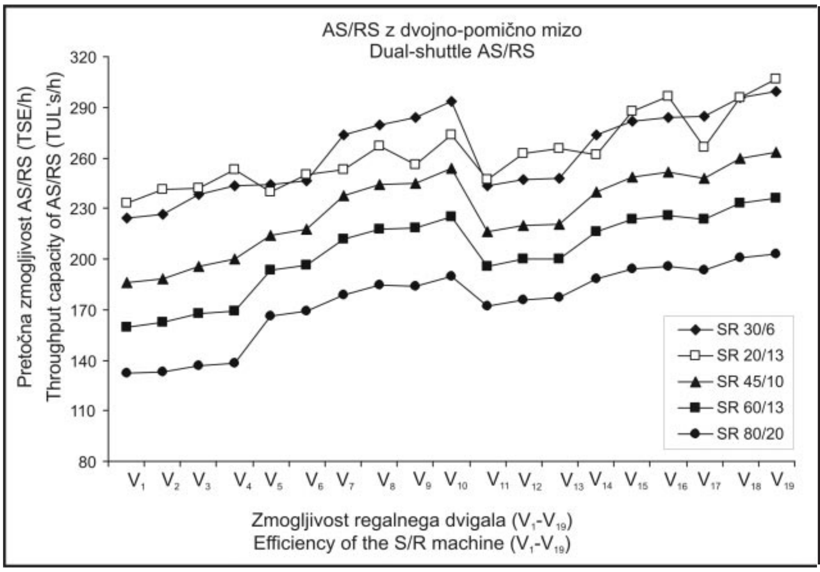
2.3.2 Pretočna zmogljivost

Na slikah 9, 10, 11 so prikazane porazdelitve pretočne zmogljivosti za AS/RS z enojno-pomično in večpomičnimi mizami, glede na različne oblike skladiščnih regalov in zmogljivosti regalnega dvigala. Po izvedenih analizah za T(DC), T(QC) in T(STC) in izrazov (25), (26), (27) (poglavje 2.2) je očitno, da imata SR 20/13 in SR 30/6 največje pretočne zmogljivosti. Najmanjše pretočne zmogljivosti lahko opazimo za SR 80/20. Očitno je, da sta povprečni čas delovnega kroga in pretočna zmogljivost obratno sorazmerna.

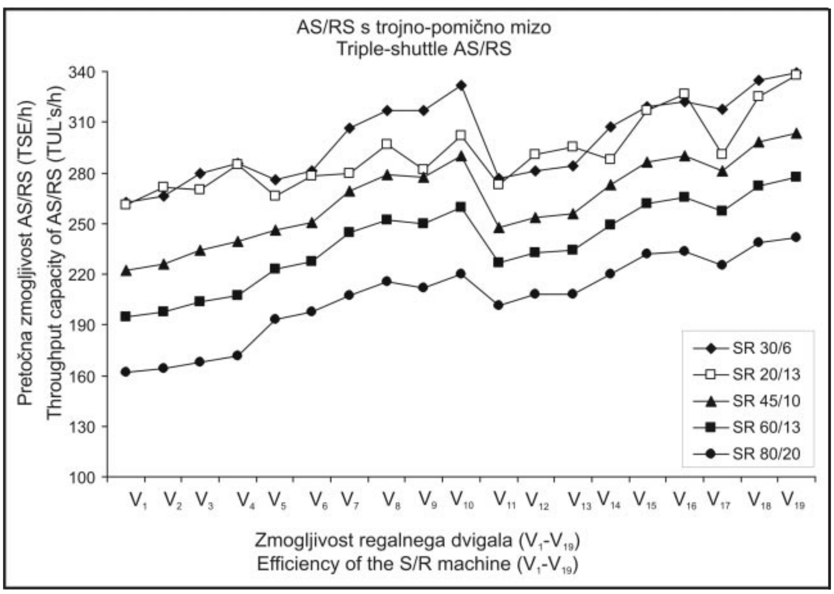
they have a major influence on the average cycle time.

2.3.2 Throughput capacities

Distributions of the throughput capacities under the single and multi-shuttle AS/RS according to different layouts of the SR and the efficiency of the S/R machine are presented in Figures 9, 10, 11. On the basis of the performed analyses for T(DC), T(QC) and T(STC) and the equations 25, 26, 27 (section 2.2) it is evident that the storage racks SR 20/13 and SR 30/6 have the highest throughput capacities. The lowest throughput capacities are observed for the storage rack SR 80/20. It is obvious that the average cycle times and throughput



Sl. 10. *Porazdelitev pretočne zmogljivosti za AS/RS z dvojno pomično mizo*
Fig. 10. *Distribution of throughput capacities under dual-shuttle AS/RS*



Sl. 11. *Porazdelitev pretočne zmogljivosti za AS/RS s trojno pomično mizo*
Fig. 11. *Distribution of throughput capacities under triple-shuttle AS/RS*

Pri majhnih vrednostih povprečnega časa delovnega kroga so pretočne zmogljivosti visoke in nasprotno, pri večjih vrednostih povprečnega časa delovnega kroga so pretočne zmogljivosti manjše.

Na splošno izkazujejo AS/RS z večpomičnimi mizami v primerjavi z AS/RS z eno pomično mizo pomembno izboljšanje pretočnih zmogljivosti. Izboljšanje pretočnih zmogljivosti glede na ŠEK je vidno v primerjavi z DK in bo podrobno predstavljeno za naslednji primer.

2.3.2.1 Primerjava med AS/RS z enojno pomično in večpomičnimi mizami

Primerjava med AS/RS z enojno pomično in večpomičnimi mizami je predstavljena za naslednji primer. Analiza se nanaša na SR 30/6 in zmogljivost regalnega dvigala - V_1.
Pri čemer so:
- T povprečni čas vožnje regalnega dvigala,
- SD standardni odmik,
- $max.\ T$ največji čas vožnje regalnega dvigala,
- $min.\ T$ najmanjši čas vožnje regalnega dvigala,
- ΣT_m časi, ki so povezani z rokovanjem TSE,
- λ pretočna zmogljivost.

(i) Povprečni čas delovnega kroga za DK, ŠK in ŠEK:

capacities are inversely dependent. With lower values of the average cycle times, the throughput capacities are higher, and inversely, with the higher values of the average cycle times, the throughput capacities are lower.

In general, the multi-shuttle AS/RS in comparison with the single-shuttle AS/RS shows significant improvements in the throughput capacity. The throughput-capacity improvement according to the STC is evidential in comparison with the DC, and will be presented in detail in the following case.

2.3.2.1 Comparison of the single and multi-shuttle AS/RS

A comparison of single-shuttle versus multi-shuttle AS/RS is presented for the following case. The analysis relates to the storage rack SR 30/6 and the efficiency of the S/R machine V_1.
Where:
- T average travel time,
- SD standard deviation,
- $max.\ T$ maximum travel time,
- $min.\ T$ minimum travel time,
- ΣT_m times associated with manipulation of the TULs,
- λ throughput capacity.

(i) Average cycle times for DC, QC and STC:

$$T(DC) = T(DC)_{average} + \sum_i T_m = 40{,}044\,\text{s} \quad (28)$$

$$T(QC) = T(QC)_{average} + \sum_i T_m = 64{,}125\ \text{s} \quad (29)$$

$$T(SxC) = T(STC)_{average} + \sum_i T_m = 82{,}308\ \text{s} \quad (30).$$

(ii) Pretočna zmogljivost za DK, ŠK in ŠEK:

(ii) Throughput capacities for DC, QC and STC:

$$\lambda_{DC} = \left[\left[\frac{3600}{T(DC)}\right]\cdot 2\right] = 180\left[\frac{\text{TSE/TUL}}{\text{h}}\right] \quad (31)$$

$$\lambda_{QC} = \left[\left[\frac{3600}{T(QC)}\right]\cdot 4\right] = 225\left[\frac{\text{TSE/TUL}}{\text{h}}\right] \quad (32)$$

$$\lambda_{STC} = \left[\left[\frac{3600}{T(STC)}\right]\cdot 6\right] = 262\left[\frac{\text{TSE/TUL}}{\text{h}}\right] \quad (33).$$

(iii) Izboljšanje pretočne zmogljivosti za AS/RS z večpomičnimi mizami, glede na AS/RS z enojno pomično mizo:

(iii) Throughput-capacity improvement of multi-shuttle AS/RS in comparison with single-shuttle AS/RS:

Preglednica 4. *Rezultati simulacijske analize*
Table 4. *Results of the simulation analysis*

SR 30/6 – V_1	T (s)	SD (s)	$max.\ T$ (s)	$min.\ T$ (s)	ΣT_m (s)	λ (TSE/h) (TUL/h)
T(DC)	30,044	9,49	66,45	11,95	10	180
T(QC)	42,125	7,58	74,80	23,13	22	225
T(SC)	52,308	6,20	78,78	34,37	30	262

$$\mu_{QC}^{DC} = \frac{Q_{QC} - Q_{DC}}{Q_{DC}} \cdot 100 = 25\% \quad (34)$$

$$\mu_{STC}^{QC} = \frac{Q_{STC} - Q_{QC}}{Q_{QC}} \cdot 100 = 16,45\% \quad (35)$$

$$\mu_{STC}^{DC} = \frac{Q_{STC} - Q_{DC}}{Q_{DC}} \cdot 100 = 45,56\% \quad (36).$$

Izboljšanje pretočne zmogljivosti glede na AS/RS z večpomičnimi mizami (QC-25 %) in (STC-45 %) je očitno v primerjavi z AS/RS z enojno pomično mizo. Izboljšanje pretočne zmogljivosti lahko izloči enega ali več regalnih hodnikov, s čimer dosežemo velike prihranke pri investiciji. Čeprav so AS/RS z večpomičnimi mizami dražji od AS/RS z enojno pomično mizo, je lahko omenjeno povečanje manjše od povečanja pri varčevanju glede na izločitev regalnega hodnika. Podobne ugotovitve sta predstavila tudi Keserla in Peters [10]. Kljub povečanju pretočne zmogljivosti za AS/RS z večpomičnimi mizami, priporočamo dodatno gospodarnostno analizo obravnavanega sistema. Torej, predstavljeni rezultati lahko na splošno pomagajo načrtovalcem skladišč pri začetnih odločitvah projekta o izbiri tipa AS/RS, glede na pretočno zmogljivost TSE.

The throughput-capacity improvement according to the multi-shuttle AS/RS (QC–25 %) and (STC–45 %) is evident in comparison to the single-shuttle AS/RS. The improvement of the throughput capacity could eliminate one or more aisle and therefore large savings can be achieved. Even though a multi-shuttle AS/RS is more expensive than a single-shuttle AS/RS, this increase may be less than the increase in the savings due to the elimination of the aisles. Similar conclusions have also been presented by Keserla and Peters [10]. Hence, in spite of the increased throughput capacity of the multi-shuttle AS/RS, an additional economic analysis of these systems is recommended. Therefore, the presented results could, generally, help warehouse planners to decide in the early stage of the project, which type of AS/RS will be installed due to the TUL's turnover.

3 PRIMER NAČRTOVANJA AS/RS Z UPORABO REZULTATOV SIMULACIJSKE ANALIZE

3 EXAMPLE OF THE DESIGN PROCESS OF THE AS/RS USING THE RESULTS OF SIMULATION ANALYSES

V nadaljevanju je prikazan primer načrtovanja AS/RS, pri katerem smo uporabili rezultate, predstavljene v poglavju 2.

In the following an example of the design process of the AS/RS, using results obtained in section 2, of the simulation analyses of the single and multi-shuttle AS/RS, is presented.

3.1 Načrtovanje AS/RS

Pri načrtovanju AS/RS sta pomembna parametra zalogovna velikost Q in pretočna zmogljivost λ. Podatke za zalogovna velikost in pretočna zmogljivost dobimo z opazovanjem in statistično analizo predhodnega poslovanja podjetja. Naj obsega želena zalogovna velikost 3200 regalnih mest, pri čemer moramo zagotoviti zahtevano pretočno zmogljivost $\lambda_{V/I}$ = 180 TSE/uro. Izhodiščni parametri:
- $Q = 3200$ *TSE*,
- $\lambda_{Vhod} = 90$ *TSE/uro*,
- $\lambda_{Izhod} = 90$ *TSE/uro*.

3.1 Design process of the AS/RS

In the design process of the AS/RS rack the capacity Q and throughput capacity λ represent important information. Data for the Q and λ is acquired from the observation and statistical analyses of previous company operation. Let the required Q contain 3200 pallet places, from which are desired throughput capacity $\lambda_{I/O} = 180$ *TUL's/hour* has to be ensured. The starting-point parameters:
- Q = 3200 TULs,
- λ_{Input} = 90 TULs/hour,
- λ_{Output} = 90 TULs/hour.

3.2 Določitev izmer SR (oblika SR)

Pri načrtovanju AS/RS se pogosto srečujemo z omejitvami, ki jih moramo upoštevati pri določitvi izmer skladiščnega regala. Glede na podani tloris in višino skladiščnega prostora, moramo izbrati ustrezno obliko skladiščnega regala. V nadaljevanju se odločimo za tip skladiščnega regala SR 80/20 dolžine (L = 80 m) in višine (H = 20 m). Zalogovna velikost omenjenega skladiščnega regala znaša 3200

3.2 Determination of the SR dimensions (layout of the SR)

In the design process of the AS/RS, the restrictions that have to be considered when determining the SR layout, have to be fulfilled. The suitable shape of the SR has to be determined according to the given ground plan and the height of the warehouse. In the presented case a storage rack SR 80/20 with length ($L = 80$ *m*) and height ($H = 20$ *m*) was chosen. The rack capacity Q is 3200 pallet regalnih mest, pri čemer je prostornina vsakega regalnega okna enaka 1 m^3 (1 m v dolžino, 1 m v višino in 1 m v širino).

3.3 Izbira AS/RS z enojno pomično ali večpomičnimi mizami

Pri izbiri AS/RS z enojno pomično in večpomičnimi mizami si pomagamo z odvisnostmi povprečnega časa delovnega kroga in pretočnih zmogljivosti. Predstavljena odvisnost povprečnega časa delovnega kroga in pretočnih zmogljivosti se nanaša na SR 80/20.

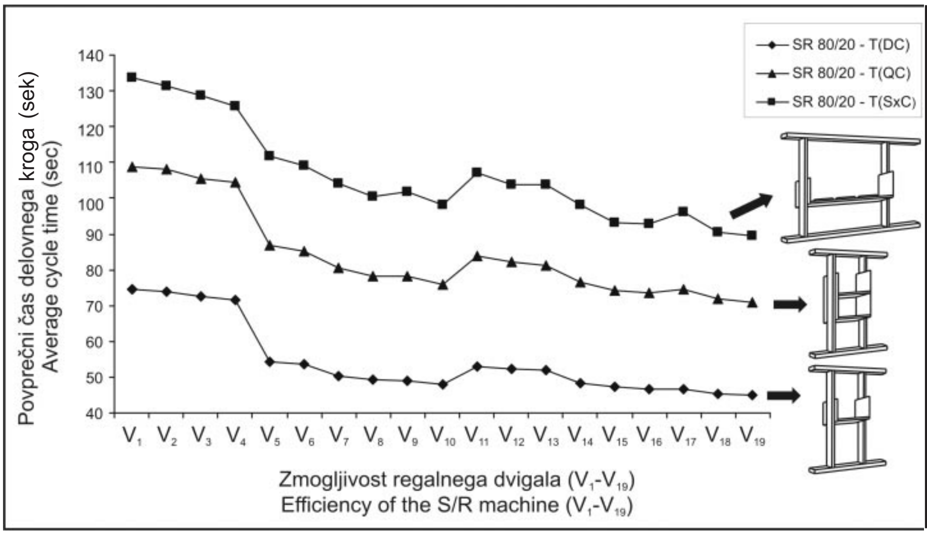
Glede na zahtevano pretočno zmogljivost ($\lambda_{V/I}$ = 180 TSE/uro), izberemo AS/RS s trojno pomično mizo in zmogljivostjo regalnega dvigala –

places. It was assumed that each rack opening is a cube that equals 1 m^3 (1 m in length, 1 m in height and 1 m in width).

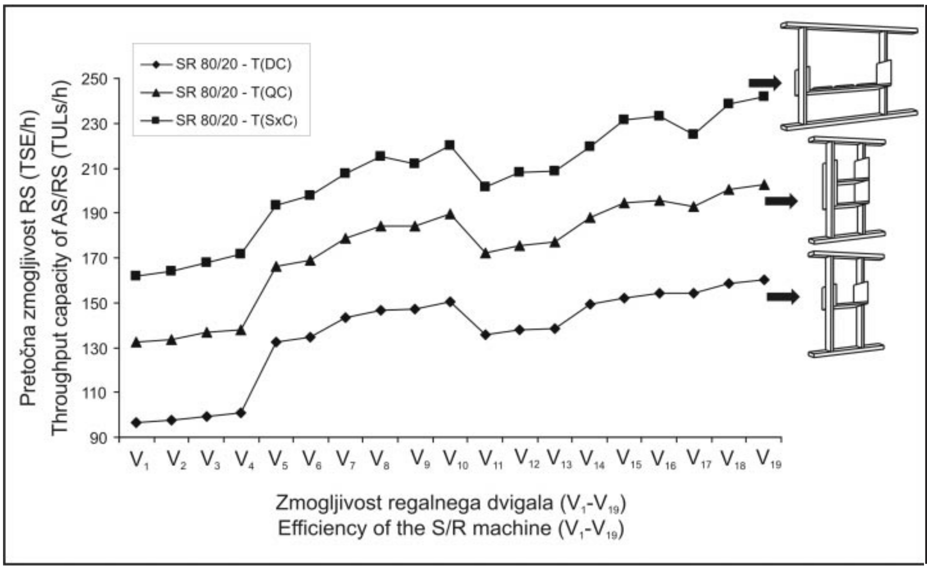
3.3 Selection of the AS/RS-SS or the AS/RS-MS

The relationships of average cycle times and throughput capacities helped when choosing single- or multi-shuttle AS/RS. The presented relationship of the average cycle times and throughput capacities are related to the storage rack SR 80/20.

According to throughput capacity ($\lambda_{I/O}$ = *180 TULs /hour*), the triple-shuttle AS/RS with the efficiency of the S/R machine V_{19} was chosen. For the chosen AS/RS the maximum throughput capacity



Sl. 12. *Porazdelitev povprečnega časa delovnega kroga AS/RS z enojno-pomično in večpomičnimi mizami*
Fig. 12. *Distribution of the average cycle times under single- and multi-shuttle AS/RS*



Sl. 13. *Porazdelitev pretočnih zmogljivosti AS/RS z enojno-pomično in večpomičnimi mizami*
Fig. 13. *Distribution of the throughput capacities under single- and multi-shuttle*

V_{19}. Največja pretočna zmogljivost za izbran AS/RS je enaka λ_{max} = 242 TSE/uro, ki pa ne upošteva omejitev pri obratovanju AS/RS. Le-ta se nanaša na okvare in popravila regalnega dvigala in preostale rokovalne opreme, vzdrževanje opreme, izpad električne energije ter druge dejavnike, ki bistveno vplivajo na zmogljivost AS/RS. Z namenom, da zajamemo in upoštevamo omenjene vplive, moramo določiti dejansko zmogljivost AS/RS, ki bo zadostovala izbrani vhodni in izhodni pretočni zmogljivosti.

is λ_{max} = *242 TULs/hour*, which does not take into account the restrictions when operating the AS/RS. This is related to the errors and repairs of the S/R machine and the remaining equipment, the maintenance of the equipment, the loss of the electrical power and other factors, which have a significant influence on the AS/RS's efficiency. With the goal to achieve the main influencing parameters, the real AS/RS efficiency has to be determined, which will be sufficient for the chosen input/output throughput capacity.

3.4 Zmogljivost AS/RS

3.4 The AS/RS efficiency

(i) Največja zmogljivost pri STC

(i) Maximum efficiency under STC

$$E_{f_{\max}} = 3600/89{,}376 = 40\ 1/\mathrm{h}$$
$$\mathrm{T(STC)} = 89{,}376\ \mathrm{s} \qquad (37).$$

Največja zmogljivost AS/RS s trojno pomično mizo znaša 40 krogov/uro, pri čemer niso upoštevani časi za odpravo morebitnih okvar in popravil opreme, vzdrževanje opreme, izpad električne energije ipd. Povprečen čas šestkratnega delovnega kroga T(STC) je bil določen s simulacijsko analizo (sl. 13).

The maximum efficiency of the triple-shuttle AS/RS is represented by 40 cycles/hour, in which the times for errors and repairs for equipment, the maintenance of equipment, and the loss of electrical power are not considered. The average sextuple command cycle time T(STC) was determined with a simulation analysis (see Figure 13).

(ii) Dejanska zmogljivost pri STC

(ii) Real efficiency under STC

$$E_{f_{real}} = 0{,}81 \cdot 40 = 32\ 1/\mathrm{h} \qquad (38).$$

* (0,61 - 0,81) – rezerva zmogljivosti / efficiency reserve

Pri največji zmogljivosti upoštevamo tudi rezervo zmogljivosti, ki upošteva zgoraj navedene omejitve. Z upoštevanjem rezerve zmogljivosti znaša dejanska zmogljivost pri šestkratnem delovnem krogu samo 32 krogov/uro.

The maximum efficiency is further multiplied by the efficiency reserve, which considers above mentioned restriction. By considering the coefficient of reserve efficiency, the real efficiency under sextuple command cycle is only 32 cycles/hour.

(iii) Povprečni čas šestkratnega delovnega kroga in dejanska pretočna zmogljivost

(iii) Average sextuple command cycle time and real throughput capacity

$$\mathrm{T(STC)} = 3600/32 = 112{,}5\ \mathrm{s} \qquad (39)$$

$$\lambda_{real} = (3600/112{,}5) \cdot 6 = 192\ 1/\mathrm{h} \qquad (40).$$

Glede na dejanske pretočne zmogljivosti λ_{real} lahko ugotovimo, da izbrano AS/RS s trojno pomično mizo ustreza načrtovani pretočni zmogljivosti. Izbrano regalno dvigalo doseže $\Delta\lambda^*$ = 6,67 % večjo zmogljivost glede na predpisano pretočno zmogljivost.

According to the real throughput capacity λ_{real}, the selected triple-shuttle AS/RS suit prescribed throughput capacity was found. The chosen S/R machine reached a $\Delta\lambda^*$ = 6.67 % higher efficiency due to the prescribed throughput capacity.

$$\Delta\lambda^* = \frac{192-180}{180} \cdot 100 \qquad (41).$$

4 SKLEP

4 CONCLUSION

V prispevku je predstavljen simulacijski model AS/RS z enojno pomično in večpomičnimi

A discrete event simulation model of single- and multi-shuttle AS/RSs for the support of the design mizami kot podpora postopku načrtovanja skladiščnih sistemov. Raziskani so različni elementi skladišča, kakor so oblika skladiščnega regala, zmogljivost regalnega dvigala in upravljalna strategija, z namenom določiti zmogljivost AS/RS z večpomičnimi mizami, glede na AS/RS z enojno pomično mizo. Za AS/RS z enojno pomično mizo smo uporabili strategijo naključnega skladiščenja in pravilo PPPP. Pri uporabi AS/RS z večpomičnimi mizami, strategija naključnega skladiščenja in pravilo PPPP več ne ustrezata načrtovanju, zato smo uporabili domiselno metodo "strategijo x". Največja prednost predstavljene metode je skrajšanje prazne vožnje regalnega dvigala pri ŠK in ŠEK.

Glede na odvisnost različnih oblik skladiščnih regalov v primerjavi z zmogljivostjo regalnega dvigala, smo ugotovili, da ima geometrijska oblika skladiščnega regala pomemben vpliv na povprečni čas delovnega kroga. Glede na zmogljivost regalnega dvigala, še posebej za skladiščne regale katerih oblika je ($L/v_x \geq H/v_y$), načrtovalci skladišč ne morejo povečati pretočne zmogljivosti samo s povečanjem hitrosti regalnega dvigala. V takšnih primerih sta pospešek in pojemek, skupaj z majhnimi razdaljami, mejna dejavnika, ki lahko imata pomemben vpliv na ustrezno načrtovanje AS/RS. Torej, če želimo doseči zmogljiv AS/RS, moramo upoštevali tako geometrijsko obliko skladiščnega regala kakor tudi zmogljivost regalnega dvigala.

Povečanje pretočne zmogljivosti v mejah od 25 do 46 % lahko dosežemo za AS/RS z večpomičnimi mizami v primerjavi z AS/RS z enojno pomično mizo. V tem primeru moramo pri AS/RS z večpomičnimi mizami uporabiti domiselno metodo - "strategijo x". Poudariti moramo, da so AS/RS z enojno pomično mizo v znanosti deležni velikega zanimanja in so prisotni že v mnogih znanstvenih prispevkih. Glede na to, da ni veliko objav na temo AS/RS z večpomičnimi mizami, lahko predstavljeni rezultati dajejo uporabnikom v praksi želene informacije povprečnega časa delovnega kroga in načine za povečanje pretočne zmogljivosti. Uporabnost modela ni omejena samo na AS/RS majhnih delov, temveč je model uporaben tudi za AS/RS, pri čemer je osnova za TSE predstavlja paleto, ki nam v inženirski praksi predstavlja najpogosteje uporabljeno izvedbo.

process of a warehouse is presented in this paper. Various elements of the AS/RS were examined, for example, the layout of the SR, the efficiency of the S/R machine and the control policy, in order to investigate the efficiency of the multi-shuttle AS/RS in comparison with the single-shuttle AS/RS. For the single-shuttle AS/RS, a randomized storage-assignment policy and the FCFS request selection rule were used. Using the multi-shuttle AS/RS randomized storage-assignment policy and the FCFS request selection rule does not satisfy the design any more, therefore the heuristics strategy called "Strategy x" was applied. The main advantage of the presented heuristics is in the minimization of the empty travel of the S/R machine within QC and STC.

According to the relationship of different layouts of the SR in comparison with the efficiency of the S/R machine, it was pointed out that the SR geometry has a significant influence on the average cycle times. Further, according to the efficiency of the S/R machine, especially for those SRs whose shape is ($L/v_x \geq H/v_y$), the designers could not increase throughput capacities simply by increasing the velocities of the S/R machine. In such cases the acceleration and deceleration along with small distances of the SR are the limiting factors, which could have a significant impact on the proper design of the AS/RS. Therefore, the designers should consider the SR geometry and the efficiency of the S/R machine simultaneously, in order to achieve an effective and efficient AS/RS.

The throughput-capacity improvements in the range 25 to 46 % for the multi-shuttle AS/RS could be achieved in comparison with the single-shuttle AS/RS. In this case, heuristics "Strategy x" must be used within the multi-shuttle AS/RS. It must be emphasized that the single-shuttle AS/RS is common in the engineering practice and is the subject of many research studies. However, since there are not so many publications on the multi-shuttle AS/RS, the presented results could give useful information on average cycle times and ways of increasing the throughput capacity. The practicability of the presented model is not limited only to the mini-load AS/RS but also to the AS/RS where the TUL is of a bigger size and a different shape.

5 OZNAKE
5 NOMENCLATURE

avtomatizirani regalni skladiščni sistemi	AS/RS	automated storage and retrieval systems
skladiščni regal	SR	storage racks
regalno dvigalo	RD / S/R	machine storage and retrieval machine
vhodni in izhodni položaj	V/I / I/O	input and output location
transportno skladiščna enota	TSE / TUL	transport unit load
pretočna zmogljivost	λ	throughput capacity
zalogovna velikost	Q	rack capacity

enojni delovni krog	EK/SC	single command cycle
kvadraten po času	SIT	square-in-time
dvojni delovni krog	DK/DC	dual command cycle
pravilo "prvi pride prvi odpremi"	PPPP/FCFS	"first-come-first-served" policy
pravilo "najbližji sosed"	NS/NN	"nearest neighbor" policy
štirikratni delovni krog	ŠK/QC	quadruple command cycle
šestkratni delovni krog	ŠEK/STC	sextuple command cycle
hitrost regalnega dvigala v vodoravni smeri.	v_x	velocity of the S/R machine in the horizontal direction
hitrost regalnega dvigala v navpični smeri.	v_y	velocity of the S/R machine in the vertical direction
pospeševanje/pojemanje regalnega dvigala v vodoravni smeri.	a_x	acceleration/deceleration of the S/R machine in the horizontal direction
pospeševanje/pojemanje regalnega dvigala v navpični smeri.	a_y	acceleration/deceleration of the S/R machine in the vertical direction
višina skladiščnega regala.	H	height of the SR
dolžina skladiščnega regala.	L	length of the SR
izmere skladiščnega regala po času	t_x, t_y	dimensions of the SR in time
faktor velikosti za skladiščni regal	T	the scaling factor for the SR
faktor oblike za skladiščni regal	b	the shape factor for the SR
statistično povprečje časa vožnje regalnega dvigala za eno smer v skladiščnem regalu	E(T(SA))	the expected one-way travel time
statistično povprečje časa vožnje regalnega dvigala pri enojnem delovnem krogu	E(T(SC))	the expected single command travel time
statistično povprečje časa vožnje regalnega dvigala pri dvojnem delovnem krogu	E(T(DC))	the expected dual command travel time
statistično povprečje časa vožnje regalnega dvigala pri štirikratnem delovnem krogu	E(T(QC))	the expected quadruple command travel time
statistično povprečje časa vožnje regalnega dvigala pri šestkratnem delovnem krogu	E(T(STC))	the expected sextuple command travel time
statistično povprečje časa za izvedbo štirikratnega delovnega kroga	E(QC)	the expected quadruple command cycle time
statistično povprečje časa za izvedbo šestkratnega delovnega kroga	E(STC)	the expected sextuple command cycle time
povprečen čas vožnje regalnega dvigala za enojni delovni krog	$T(DC)_{average}$	average dual command travel time
povprečen čas vožnje regalnega dvigala za štirikratni delovni krog	$T(QC)_{average}$	average quadruple command travel time
povprečen čas vožnje regalnega dvigala za šestkratni delovni krog	$T(STC)_{average}$	average sextuple command travel time
povprečen čas dvojnega delovnega kroga	T(DC)	average dual command cycle time
povprečen čas štirikratnega delovnega kroga	T(QC)	average quadruple command cycle time
povprečen čas šestkratnega delovnega kroga	T(STC)	average sextuple command cycle time
povprečen čas vožnje regalnega dvigala	T	average travel time
standardni odmik	SD	standard deviation
največji čas vožnje regalnega dvigala,	Max. T	maximum travel time
najmanjši čas vožnje regalnega dvigala,	Min. T	minimum travel time
časi, ki so povezani z rokovanjem TSE	ΣT_m	times associated with the manipulation of the TULs
pretočna zmogljivost za dvojni delovni krog	λ_{DC}	throughput-capacity for dual command cycle
pretočna zmogljivost za štirikratni delovni krog	λ_{QC}	throughput-capacity for quadruple command cycle
pretočna zmogljivost za šestkratni delovni krog	λ_{STC}	throughput-capacity for sextuple command cycle
izboljšanje pretočne zmogljivosti za ŠK glede na DK	μ_{QC}^{DC}	throughput improvement of QC in comparison with DC
izboljšanje pretočne zmogljivosti za ŠEK glede na ŠK	μ_{STC}^{QC}	throughput improvement of STC in comparison with QC
izboljšanje pretočne zmogljivosti za ŠEK glede na DK	μ_{STC}^{DC}	throughput improvement of STC in comparison with DC
največja zmogljivost AS/RS	$E_{f_{max}}$	maximum efficiency
dejanska zmogljivost AS/RS	$E_{f_{real}}$	real efficiency
dejanska pretočna zmogljivost	λ_{real}	real throughput capacity

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Zaporedje prevzema naročil: navadna hevristika, izboljšana hevristika in optimalni algoritem

Order-Picking Routing Policies: Simple Heuristics, Advanced Heuristics or Optimal Algorithm

Goran Dukić - Čedomir Oluić

Prevzem naročila je postopek zbiranja in priprave izdelkov v skladišču, glede na določeno naročilo kupca. Je najbolj težavna in draga dejavnost v skladišču. Za prevoz porabimo 50 odstotkov celotnega časa prevzema naročila. Zmanjšanje prevoznih poti je eden glavnih ciljev načrtovalca skladišča.V prispevku smo predstavili obširne simulacijske analize načrtovanja poti in razporeditve polic s primerjavami hevrističnih metod načrtovanja poti in optimalnim algoritmom

(Ključne besede: skladišča, prevzemi naročil, načrtovanja poti, skladiščenje)

Order-picking, the process of retrieving items from storage locations in response to a specific customer request, is the most laborious and the most costly activity in a typical warehouse. As 50% of the total order-picking time is spent on traveling, reducing travel distances is one of a warehouse designer's objectives. In this paper an extensive simulation analysis of routing and storage policies in order-picking systems is presented. The best combinations of routing and storage policies are defined with a comparison between routing heuristics and an optimal algorithm.

(Keywords: warehouses, order-picking, routing policies, storage policies)

0 INTRODUCTION

It is well known that logistic costs have an important influence on the overall success of any company. In western countries these costs are estimated to be about 10 to 15% of GDP. Mostly they are the result of the two main logistics activities: transportation and warehousing. The order-picking process, defined as the process of retrieving items from storage locations in response to a specific customer request, is the most laborious and the most costly activity in a typical warehouse, consisting of up to 55% of the warehouse's total operating costs [11]. The fact that about 50% of the total order-picking time is spent on traveling gives the potential to improve order-picking efficiency by reducing traveling distances. One way to reduce traveling times is an entirely new design (new equipment, new layout, automation of processes). Hopefully, there are also some less radical methods, that do not require large investment costs.

Using a specific routing policy in determining the sequences and routes of traveling is one way to reduce traveling distances. Assigning items to storage locations based on some rule, i.e., a storage policy, can also reduce traveling distances compared to a random assignment. Both have been proven, used separately or in combination, to improve the efficiency of the order-picking process. However, the performances of existing methods depend greatly on the layout and size of the warehouse, the size of orders and the picking volume of items. Additionally, the performance of a particular routing method depends on the chosen storage policy, and vice versa, the potential travelling- time savings using a particular storage policy are not the same for all routing policies. The purpose of this paper is to identify the performances of routing policies, depending on the given situation and the implemented storage policy. The analysis is restricted to conventional warehouses with the so-called basic warehouse layout. These are rectangular warehouses with parallel aisles, a central depot (pick up/delivery point), and two possibilities for changing aisles, at the front and at the rear of the warehouse. The picking aisles (the main aisles) are wide enough to allow two-way travel, but picking can be done from both sides of the aisle without a significant change in position. The location of a depot (pick-up/delivery point) is at the front corner of the warehouse. This is consistent with observations of several similar studies presented in the literature [2], [7] and [10].

1 ROUTING POLICIES IN ORDER-PICKING

There are several routing policies developed and used in practice. They range from the very simple to the slightly more complex. The performance of these heuristics depends on the particular operating conditions of the system under study, as a result of their definitions. The simplest routing heuristic is the S-shape policy. When this policy is used, the order-picker enters every aisle where an item has to be picked and traverses the entire aisle. Aisles where nothing has to be picked are skipped. An exception is made for the last aisle visited in the case that the number of aisles to be visited is odd. In this case a return travel is performed in the last aisle visited. Another very simple routing heuristic is the Return policy. The order-picker enters and leaves aisles containing item(s) to be picked from the front aisle. The midpoint routing policy, also one simple heuristics, looks like the return method on two halves of a warehouse. Only the first and the last aisle visited are traversed entirely. Similar to the last heuristic, with the Largest Gap policy all the aisles that contain even one item to be picked are also left at the same side as they were entered, except the first and the last visited, which are traversed entirely. The gap represents the separation between any two adjacent picks, between the first pick in the aisle and the front aisle, or between the last pick in the aisle and the back aisle. If the largest gap is between two adjacent picks, the picker performs a return route from both ends of the aisle. Otherwise, a return route from either the front or back aisle is used. The largest gap is therefore the portion of the aisle that the order-picker does not traverse. This policy is a slightly more complex routing heuristic than the first three mentioned. The resulting route is somehow similar, but definitely at least equal or better than the route defined by the Midpoint policy in all possible situations. Two relatively new policies developed are the Composite policy and the Combined policy. The Composite routing heuristic combines features of the S-shape and Return heuristics, minimizing the travel distance between the farthest picks in two adjacent aisles for each aisle individually. Combined heuristics is also a combination of S-shape and Return policies, but a small component of dynamic programming gives it a possibility to look one aisle ahead. The decision about the return or the traversal route in the aisle depend not only on minimized travel in that aisle, but also on a better starting point for the next aisle. This in turn leads to a better overall result than the Composite heuristic. All the routing policies described above by their definitions have some restrictions when if comes to creating a route. An optimal algorithm [9], combining a graph theory and dynamic programming, results in the shortest possible, i.e., the optimal, route. Examples of routes created by these routing heuristics and an optimal algorithm are given in Figure 1.

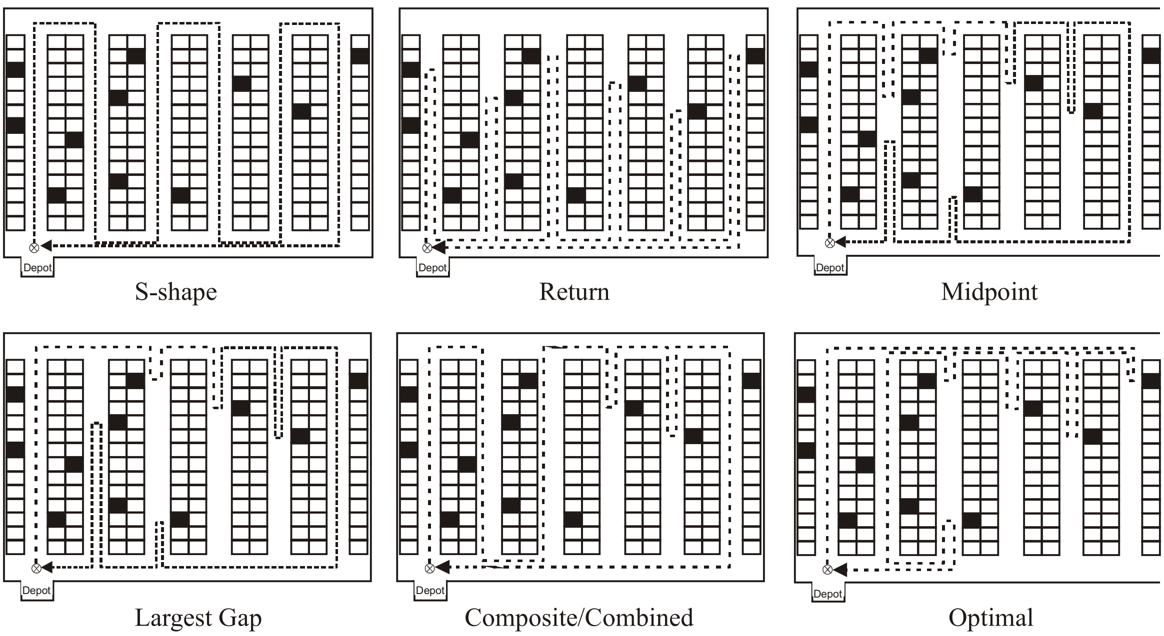


Fig. 1. *Examples of routes using routing heuristics and the optimal algorithm*

Even with the optimal algorithm developed, the majority of order-picking operations use heuristic routing policies [7]. The reason for this is that heuristic policies can provide near-optimal solutions and avoid the confusion inherent in optimal solutions [5]. It is true that a specific heuristic policy could in some situations result in a near-optimal route, but in some other situations it could perform badly. Therefore, it is important to know in which situations some heuristics are good or bad. Even more, which are better than others, and how much better in particular situations.

2 STORAGE POLICIES IN ORDER-PICKING

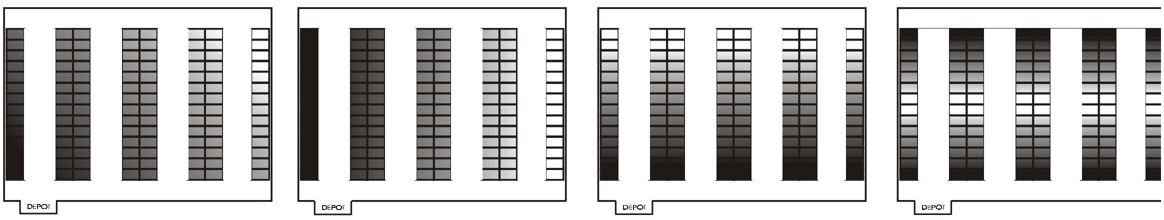
Storage policies assign items to warehouse storage locations, based on popularity, demand, size, hazard etc. In order-picking systems, storage policies are solely based on the rule of assigning the frequently accessed items to the locations near the depot [3]. With a volume-based storage policy items are assigned to storage locations based on the expected volume. Large savings in travel distances are possible with volume-based storage when compared to random storage [8]. The most effective storage policy in reducing the picking travel distance seems to be the cube-per-order-index-based storage policy [4]. The COI-based storage policy means assigning items with a low ratio of the required storage space to the order frequency to the locations nearest to the p/d point. With the assumption that each type of item is dedicated to only one location, volume-based storage and COI-based storage are the same. When warehouses are divided into forward and reserve areas (picking operations are in the forward area, items are replenished from the reserve area), such a situation is likely to occur. One can also use different types (patterns) of storage, as shown in Figure 2. Items with a higher volume (or smaller COI) are stored in the darker locations.

With diagonal storage, the highest volume item is stored in the location closest to the depot, while the lowest volume item is stored in the farthest location from the depot. Tompkins et al., 1996, states that this type of storage is optimal. Within-aisle storage means that high-volume items are stored in the aisle closest to the depot and the low-volume items are stored in the aisle farthest from the depot. Jarvis & McDowell [6] proposed this type of storage for an S-shape routing policy, which was confirmed by Petersen & Schmenner [8]. In along-front-aisle (across-aisle) storage, the high-volume items are stored along the front aisle and the low-volume items along the rear aisle. Caron et al. [1] used this type of storage with a Return routing policy. As the Midpoint and Largest Gap routing policies are characterized by return traveling from both the front and rear aisles, a potentially good type of storage for these routing policies could be along-front and rear-aisle storage.

3 THE COMPARISON OF ROUTING POLICIES

The comparison of routing policies and their interactions with storage policies is based on an extensive analysis made by simulation. The pick size varied from 5, 10, 15, 20, 30 and 40 picks per route. Two different warehouses, with respect to their size (small and large), with four different layouts, with respect to the shape (the ratio of width and depth were 2:1, 1:1, 1:2 and 3:1, for more explanation readers are referred to [7]) were analysed. This gives 48 different situations examined for each combination of routing and storage policy. In order to explain the potential savings using the storage policies, we first present an analysis of the routing policies with random storage. The results are partly illustrated in Figure 3.

The graph shows the performances of routing policies depending on the pick-list size for one examined layout. Two routing policies, Midpoint heuristic and Composite heuristic, are excluded from the presentation because they are very similar, but slightly worse, than two other analysed policies, Largest Gap and Combined heuristic, respectively. Note that despite the fact that the Composite heuristic is outperformed by the Combined heuristics, it is still generally better than simple heuristics. The Return routing policy was outperformed by all the other routing policies in all the simulated situations, while the difference increases as the pick-list size increases



a) diagonal type b) within aisle type c) along front aisle type d) along front and rear aisle type

Fig. 2. *The types of volume-based storage*

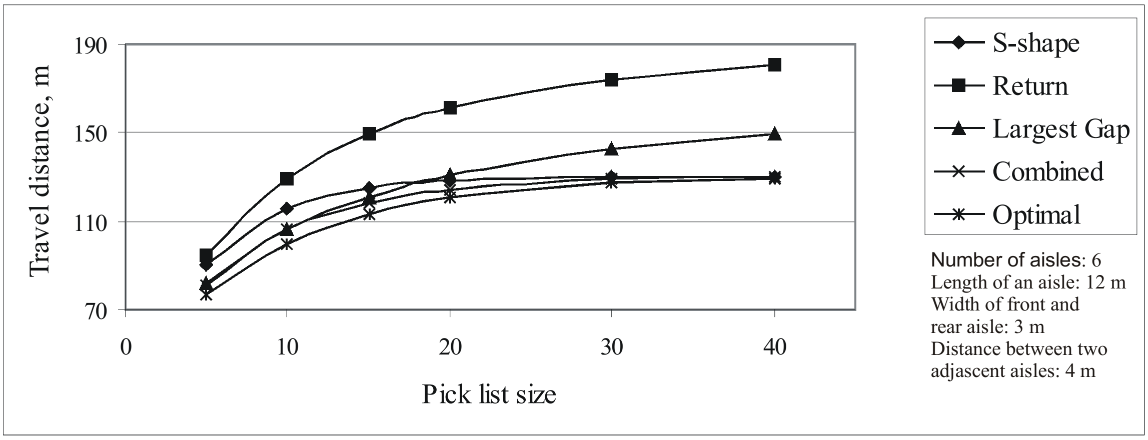


Fig. 3. *Comparison of routing policies and the interaction with pick-list size for random storage*

(but note that this policy could be beneficial in terms of some other aspects, for instance, the total space required, as there is no need for a rear aisle). The S-shape routing policy is just a few percent over the optimal in the case of a large number of picks, but does not perform well with small pick-list sizes. In contrast, the Largest Gap policy performs well with small pick sizes (about 5% over the optimal policy), while it is not so good in the case of a large number of picks. The Combined policy is, in general, the best heuristic policy. It is slightly outperformed only by Largest Gap policy in situations with a very small number of picks in a large warehouse (long aisles). For a small number of picks per tour, the best heuristic policy for a given situation is only 5–10% over the optimal policy, depending on the shape of the warehouse. The difference between the optimal and the best heuristics in the case of a large number of picks per tour is neglected.

To compare the routing policies with volume-based storage, the best type of storage for a particular routing policy should be determined. The simulation analysis included four different volume-based ABC curves, denoted as 50/20, 60/20, 70/20, 80/20 (the first number indicates the percentage of the total activity corresponding to items indicated in the percentage by the second number). Caron et al. [1] presented a simple function that describes well the COI-based ABC curve

$$F(x) = \frac{(1+s)\cdot x}{s+x} \qquad (1)$$

where x indicates the ratio of the required storage space to total storage space, corresponding to the items whose order frequency represents a fraction $F(x)$ of the total warehouse activity. The function above depends on a single parameter – the shape factor s. Note that with each type of items stored in only one location, the COI-based ABC curve is identical to the volume-based ABC curve.

For an S-shape routing policy, where the order-picker entirely traverses each aisle containing a pick location(s), it is obvious that within-aisle storage will minimize the travel distance – minimizing both the “within-aisles” travel component (minimizing the visited number of aisles) and the “across-aisle” component (minimizing the furthest aisle visited). With Return policy, to minimize the “within-aisle” travel component an across-aisle storage is used. Within-aisle storage minimizes the “across aisle” travel component and the expected number of visited aisles, but due to the increased number of picks per visited aisle (increased travel per visited aisle) the total amount of travel distance reduction with the Return policy is questionable. Finally, somewhere between is diagonal storage, decreasing to the some degree the “across-aisle” component, expected travel within the visited aisles and the number of visited aisles. Petersen & Schmenner [8] proposed this type of storage for the Return policy. To determine the best type of storage for Return routing policy all three mentioned types were analyzed. The results showed that the within-aisle type of storage is outperformed either by diagonal or across-aisle storage, depending on the pick-list size, the skewness of the ABC curve and the size of the warehouse. With a large number of picks and a less-skewed ABC curve one should prefer across-aisle storage, while for smaller orders and a more-skewed ABC curve the diagonal storage is preferable. As the size of a warehouse increases, the preference region for across-aisle storage increases. With the Largest Gap routing policy, within-aisle storage also minimizes the “across-aisle” travel component and the expected number of visited aisles. Like the Return policy, an increased number of picks per visited aisle leads to a reduced largest gap in the aisle, and therefore increased travel within such aisles. Travel within aisles could be reduced using an across aisle type of storage. As the order-picker enters the aisles from the front and rear aisles, depending on the position of the largest gap, it is logical to expect that along the front and rear aisle type of storage will result in better performance. However, these two types of storage have no influence on the number of visited aisles and the "across-aisle" travel component. Diagonal storage is again a good candidate, influencing both the "across-aisle" travel and travel within the visited aisle. The simulation results have confirmed that storing "fast movers" along front and rear aisles is better than storing them along just the front aisle. However, the diagonal storage policy generally performed better. The best type was, in any case, within-aisle storage, in all the examined situations. The routes created by Combined and Optimal routing policies are a mix of traversal and return travel (from one or both ends, respectively). Therefore, the within-aisle type seems to be the best storage type for those routing policies [8]. Additionally, diagonal storage was analyzed too. With the Combined routing policy, within-aisle storage is preferable in the case of a larger number of picks, irrespective of the skewness of the ABC curve. With just a few picks per tour, diagonal storage performs better. For the optimal algorithm the best type of storage is definetely within-aisle storage.

The simulation results, partly illustrated in Figure 4., showed that all volume-based storage methods provide travel savings over random storage.

Large savings (45 to 55%) are possible in the case of a small number of picks and more-skewed ABC curves, while for less-skewed curves and large pick lists the advantage of using volume-based storage is diminished (only a few to 15%, depending on the routing policy). The Return routing policy is no longer inferior to other heuristics in all situations. With a small number of picks and more-skewed curves it could outperform the S-shape and the Largest Gap policies. Also, the decision factor between using the S-shape or the Largest Gap routing policy is no longer only the average number of picks per (visited) aisle, but also the skewness of the ABC curve. For an 80/20 ABC curve, the Largest Gap routing performs as well as the Combined heuristic, even for a very large number of picks. Generally, the Combined policy is still the best routing heuristic. The correctly selected simple heuristic with an appropriate type of volume-based storage results in travel distances that are only 4–8% over the optimal route. Combined heuristics is even better, with only 1–5% over the optimal travel, depending on the pick-list size and the skewness of the ABC curve.

4 CONCLUSIONS

Even with the optimal algorithm developed, many manual warehouses apply very simple rules for routing order-pickers [10]. The performance of such methods heavily depends on the situation, regarding the size and the shape of the warehouse and the size of the pick lists. The correctly selected routing heuristic could result in routes that are only a few percents over the optimal route. On the other hand, bad decisions regarding routing policy could lead to very inefficient order-picking. With storage assignment involved, the right selection is even more complex. Even though all volume-based storage methods reduce the travel distances of order-pickers, each routing policy has its own best type of storage for a particular situation. Choosing the best combination of routing and storage policies is therefore a crucial task in improving order-picking efficiency. The optimal algorithm with within-aisle storage is definitely the best choice. However, it one seeks to avoid the possible confusions of order-pickers following the optimal routes, the near-optimal solutions are also available. Even the simplest routing heuristics in combination with a "belonging" type of storage could, in some situations, result in routes that are not more than a few percent over the optimal.

Finally, it should be noted that the analysis was restricted to the manual, narrow-aisle warehouses with only one block. Having one or more cross-aisles

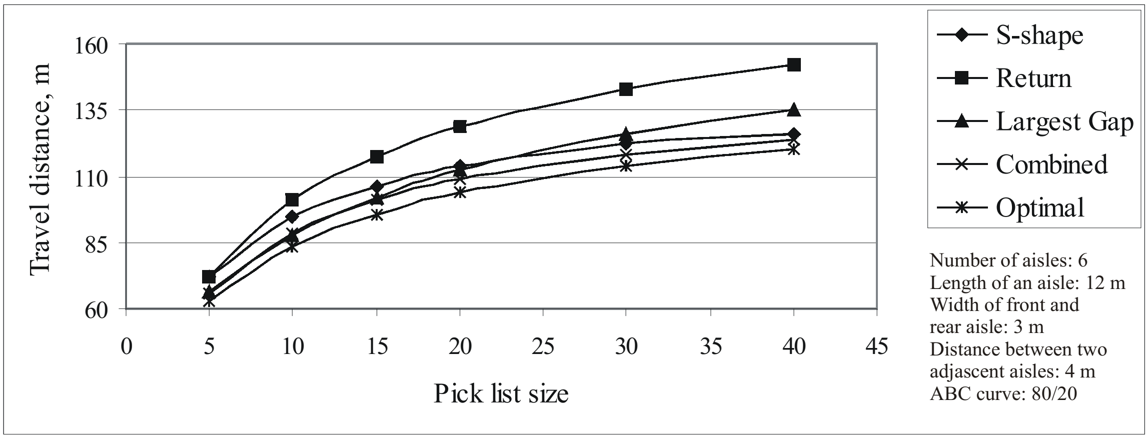


Fig. 4. *Comparison of routing policies with volume-based storage and the interaction with pick-list size*

(two or more blocks) in some situations could decrease travel distances. If the aisles are wide, the traversal travel has to include crossovers from one side of the aisle to the other. As a consequence, the preferences of some routing policies (and combinations with storage policies) could be changed with respect to other. Also, the paper was focused on only two order-picking methods: routing and storage. Batching, grouping the customer orders into one picking order; and zoning, dividing the picking area into zones, are also proven to improve the order-picking efficiency. If used, one should be aware of the possible interactions of order-batching and zoning methods with routing and storage policies.

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Vpliv oskrbe z energijo na sonaravno uravnotežen razvoj Slovenije v obdobju do leta 2020

The Influence of Energy Supply on the Sustainable Development of Slovenia up to year 2020

Štefan Žun - Sašo Medved

Spoznanja o pretiranem črpanju neobnovljivih naravnih virov in neenakost kakovosti življenja ljudi je privedlo do spoznanja po nujnih omejitvah energijskih in snovnih tokov, ki jih ustvarja človeštvo. Torej k ravnanju, ki ga imenujemo sonaravno uravnotežen razvoj[1]*. Tudi Slovenija se je zavezala k takemu ravnanju. Stopnjo približevanje željenemu cilju pa lahko ugotavljamo le, če uporabimo metodo s katero postane razvoj merljiv. V zadnjih letih se je kot ena od metod uveljavila metoda ekoloških sledi. V delu opisujemo metodo in jo prvič uporabljamo v Sloveniji. Ugotovimo, da je v sedanjem trenutku za Slovenijo značilen netrajnostni razvoj, saj ekološke sledi povprečnega prebivalca Slovenije presegajo lokalno (v Sloveniji) in globalno (na planetu) razpoložljivo bioproduktivno površino. Ugotovimo pomen oskrbe prebivalcev Slovenije z energijo in z upoštevanjem napovedane rabe energije, ki je ocenjena v najpomembnejših državnih razvojnih dokumentih in direktivah EU, napovemo spreminjanje ekoloških sledi v odbobju do leta 2020.*

(Ključne besede: Slovenija, razvoj uravnotežen, oskrba z energijo, sledi ekološke)

Knowing that humans overexaggerated extracting nonrenewable natural sources which caused nonequal quality of life lead to the awareness that energy and mass flows generated by mankind should be decreased drastically. Only than the sustainable development on the planet could be achieved. Slovenia also expresses commitment to the sustainable development. The grade approaching to the final goal can be measured only by an appropriate method. In the last years the environmental footprints become wide used. In the paper the method is described and first time used for calculation of environmental footprints of Slovenian inhabitance. It was found out that current development is non sustainable because environmental footprints of Slovenian's are greater than local and global bio-productive space. The influence of the current energy use on the environmental footprints is analyzed and prediction of the future environmental footprints caused by the use of energy predicted in most important national strategic documents and EU Directives up to year 2020 are presented.

(Keywords: Slovenia, sustainable development, energy supply, ecological footprint)

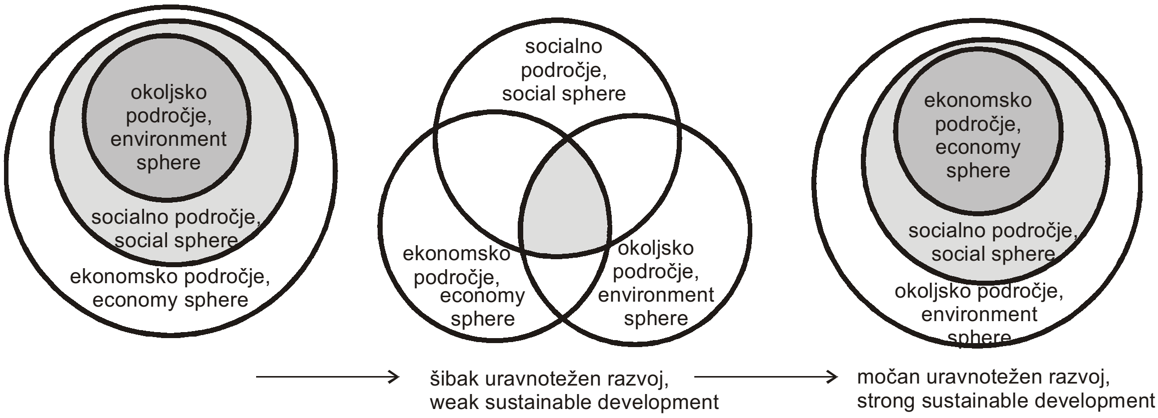
0 UVOD

Za razvoj zadnjih dvesto let je značilna neprestana gospodarska rast. Povečalo se je število prebivalstva, še bolj pa količina in kakovost proizvodnje. To je obdobje, za katero je značilna vera v možnost nezadržne rasti, ki ji lahko postavlja meje edino človek sam. Leta 1987 je v okviru Svetovne komisije za okolje in razvoj potekala konferenca, ki je v skupnem poročilu z naslovom "Naša skupna prihodnost" napovedala največje grožnje človeštvu

0 INTRODUCTION

The history of the past two hundred years has been characterised by continuous economic growth. The quantity and quality of production has increased even more than the population. This has been an era characterised by a faith in the possibility of ever-increasing growth, which only mankind can control. In 1987 there was a conference organised under the umbrella of the World Commission on Environment and Development, which defined in the

[1]Opomba: v slovenskem okolju je izraz "sustainable development" prevajan različno – trajnostni razvoj, sonaravni, vzdržni, samovzdržni; v našem delu uporabljamo definicijo Sveta za varstvo okolja Republike Slovenije "sonaravno uravnotežen razvoj".



Sl. 1. *Proces preoblikovanja vrednot v procesu približevanja sonaravno uravnoteženemu razvoju ([1] in [2])*
Fig. 1. *The process of value change within the process of approximation to sustainable development ([1] and [2])*

v prihodnosti - množično revščino, povečevanje števila prebivalstva, spreminjanje podnebja, zmanjšanje kakovosti okolja. Sklepi konference pomenijo temelje dejavnosti, ki jih dandanes s skupnim izrazom imenujemo sonaravno uravnotežen razvoj. Tedaj so oblikovali tudi relativno suhoparno definicijo tega postopka, ki se glasi: "sonaravno uravnotežen razvoj zadovoljuje potrebe sedanjih generacij, ne da bi pri tem zmanjševali možnosti prihodnjih generacij pri zadovoljevanju njihovih lastnih potreb". Reševanje teh problemov zahteva sočasno opazovanje treh področij družbe - ekonomskega, socialnega in okoljskega. Interesi in zahteve posameznih področij se med seboj prepletajo. Ko opazujemo postopek ocenjevanja vrednot v časovni lestvici, lahko sledimo prevladi ekonomskega področja, prek enakopravnosti ekonomskega, socialnega in ekonomskega področja (šibak sonaravno trajnostni razvoj) do prevlade okoljskega področja (močan sonaravno trajnostni razvoj). Ta postopek h končnemu cilju - sonaravno uravnoteženemu razvoju prikazuje slika 1.

Zavezanost približevanju sonaravno uravnoteženemu razvoju je tako mednarodna skupnost kakor Slovenija izrazila v številnih mednarodnih deklaracijah in razvojnih listinah. Hkrati z razvojnimi strategijami so bile razvite tudi metode, s katerimi ocenjujemo približevanje končnemu cilju. V zadnjih letih med njimi izstopa metoda okoljskih sledi.

1 MERJENJA SONARAVNO URAVNOTEŽENEGA RAZVOJA Z OKOLJSKIMI SLEDMI

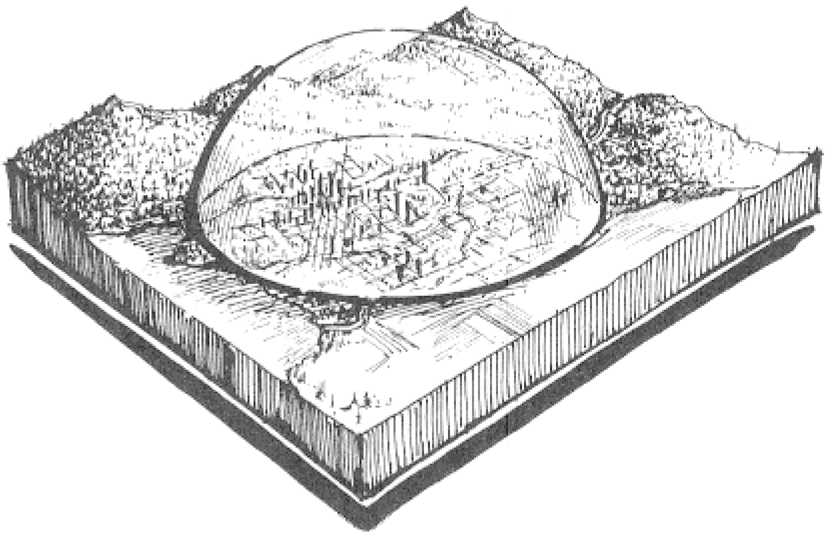
V zadnjem desetletju razvita teorija merjenja sonaravno uravnoteženega razvoja z okoljskimi sledmi temelji na podlagi velikosti prostora, ki si ga »prisvoji«, za zadovoljevanje lastnih potreb, nek sistem (človeštvo, država, lokalna skupnost, posameznik). Velikost prostora merimo s površinskimi enotami, ki ponazarjajo

frame of a joint report under the title "Our Common Future", the biggest threats to future humanity: mass poverty, population increase, change of climate and environmental degradation. The conference's conclusions are the background to activities that are nowadays referred to as sustainable development. The definition of sustainable development that was formed at this conference is as follows: "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs". Solving such problems requires the constant monitoring of three areas in society: economic, social and environmental. There is, of course, an interplay of interests and requirements for these individual areas. When the process of value evaluation is observed in relation to time scale, one may note either a predominance of the economic area or an equivalence between the economic, the social and the environmental areas (weak sustainable development), or a dominance of the environmental area (strong sustainable development). The process to achieve the final goal of sustainable development is presented in Figure 1.

The international community – including Slovenia – has expressed its commitment to sustainable development in numerous international declarations and developmental documents. The methods necessary to measure the degrees of success in achieving the final goals were developed in parallel with the developmental strategies. In recent times the environmental footprint method has gained more prominence.

1 THE ENVIRONMENTAL FOOTPRINT: A TOOL FOR MEASURING SUSTAINABLE DEVELOPMENT

The theory of measuring sustainable development with environmental footprints was developed during the past decade. The theory is based on the amount of environmental space occupied by a particular system – human race, country, local community, individual – in order for that system to provide for its own needs. The amount of space is measured in units of area, which are



Sl. 2. *Shematski prikaz okolja, na katerem neki sistem zadovoljuje svoje življenjske in razvojne potrebe – kolikostno in kakovostno ocenjena površina tega prostora ponazarja okoljske sledi sistema [1]*
Fig. 2. *Schematic representation of an environmental space where a particular system covers its living and developmental needs – the quantitatively and qualitatively appraised area of this space indicates the environmental footprint of a system [1]*

okoljske sledi (ES). Z njimi torej merimo kolikost in kakovost okoljskega prostora, ki je nujno potreben za stalno proizvodnjo in oskrbo z viri in asimilacijo odpadkov (v vseh pojavnih oblikah), ki jih proizvede opazovan sistem. Metoda okoljskih sledi torej temelji na oceni nosilne zmogljivosti okolja.

Metoda je bila razvita v okviru projekta Uravnotežena Evropa ([3] in [4]). Leta 1992 jo je kot metodo merjenja sonaravno uravnoteženega razvoja uveljavila skupina Prijatelji Zemlje na Nizozemskem. Od uvedbe se je metoda uveljavila v svetovnem merilu za presojo sistemov zelo različnih velikosti. Uveljavitev metode je posledica dveh izrazitih primerjalnih prednosti te metode:

– okoljske sledi so celostni kazalnik
– ker jih merimo s površinskimi enotami so nazorno predstavljive in izražene z absolutnimi vrednostmi, ter imajo neko končno planetarno vrednost

Velikost prostora, ki ga ima na voljo opazovani sistem znotraj svojih meja, imenujemo biološko proizvodna površina (BP). Sistem na tej površini zagotavlja potrebne vire in ponore energijskih in snovnih tokov, ki tečejo prek meja ali znotraj opazovanega sistema. Biološko proizvodne površine razdelimo v več vrst. Prikazuje jih preglednica 1. Dodamo jim tudi energijsko površino, ki je namišljena površina in določena bodisi kot:

– površina za biološko asimilacijo plinov, ki nastajajo pri sežigu fosilnih goriv in jih ovrednotimo s toplogrednim ekvivalentom CO_2,
– površina, na kateri bi prirastek lesne biomase

then expressed in terms of environmental footprints (EFs). Environmental footprints measure the quantity and the quality of an environmental space that is required to consistently produce and supply the resources and to assimilate the wastes (in all forms) generated by a given system. The method of environmental footprints is based on an appraisal of the environmental carrying capacity.

The method of environmental footprints has been developed within the Sustainable Europe project ([3] and [4]). It was established as a method of measuring sustainable development in 1992 by a group called Friends of the Earth – Netherlands. Since its establishment, the method has become accepted around the world as a method for appraising systems of various sizes. The wide acceptance of the method is mainly due to its two comparative advantages:

– environmental footprints are an integral indicator;
– since they are measured in area units, they are easily imagined, expressed in absolute values, and have some kind of final global value.

The amount of space that a given system has within its limits is its bio-productive space (BP). Within this space the system ensures all the necessary resources as well as the source/sinks of energy and material flows running across or within the limits of the given system. A bio-productive space can be classified into many categories. These categories are presented in Table 1, together with the energy space, which is fictitious and determined as one of the following:

– the space for the biological assimilation of gases resulting from burning fossil fuels measured by a greenhouse carbon-dioxide equivalent;
– the space where an increment of wood biomass

nadomestil fosilna goriva,
- površina, ki bi zadoščala za proizvodnjo biometanola, bioetanola in biodizla v količini, ki bi nadomestila fosilna goriva.

V našem prispevku bomo uporabili metodo asimilacije ekvivalenta toplogrednih plinov. Za različne vrste bioproizvodnih površin so značilne različne lastnosti. Zato fizično velikost posamezne vrste dogradimo s povprečno svetovno proizvodnostjo, ki jo imenujemo enakovredni faktor. Ebakovredne površine merimo v globalnih hektarih ([1], [4] do [6]). Rodovitnost in absorpcijska zmožnost različnih vrst površin se razlikuje tudi geografsko. Razlike med svetovnim povprečjem in značilnicami sistema, ki ga opazujemo, ovrednotimo s faktorjem pridelka. Ker si ljudje delimo planet z drugimi organizmi, del prostora ohranimo za njihov razvoj. Mnenja raziskovalcev o potrebni površini za ohranjanje biotske raznovrstnosti so različna – od 3,5 do 50% glede na celotno biološko proizvodni prostor. Najpogosteje ([2] in [5]) se upošteva vrednost 12%. Ta površina zmanjšuje površino prostora, ki jo za svoje potrebe lahko izkoriščajo ljudje. Ker je zadovoljevanje potreb neke populacije odvisno tudi od njenega števila, izračunamo delež celotne enakovredne bioproizvodne površine, ki pripada posamezniku v opazovanem sistemu. Prav tako okoljske sledi opazovanega sistema opredelimo glede na populacijo.

would replace fossil fuels;
- the space that would suffice for the production of bio-methanol, bio-ethanol and bio-diesel in an amount sufficient to replace fossil fuels.

In this paper the method of assimilating greenhouse-gas equivalents is used. Each bio-productive space is unique. Therefore, the amount of physically existing space for a particular category is adjusted for the world's average productivity, i.e., the equivalence factor. The equivalent areas of space are measured in global hectares ([1], [4] to [6]). The fertility and absorption capacity of various types of spaces vary geographically too. The difference between the world average and the characteristics of a given system is expressed with a yield factor. Since people share the planet with other species, some spaces have to be preserved for the development of these species. Researchers' opinions on the amount of space necessary to preserve biodiversity vary – from 3.5 to 50% of the entire bio-productive space. However, an value of 12% is generally accepted ([2] and [5]). This space reduces the amount of space that might otherwise be used by people to satisfy their needs. Because satisfying the needs of a particular population depends on the size of this population, a share of the equivalent bio-productive space appertaining to an individual in a given system is calculated. Similarly, the environmental footprints of a given system are defined in terms of a given population.

2 BIOLOŠKO PROIZVODNE POVRŠINE V SLOVENIJI

Slovenija, katere površina je 20.273 km^2, je imela v letu 2002 1.990.272 prebivalcev. Preglednica 1 navaja izračunano velikost biološko proizvodne površine na področju Slovenije. Površino Slovenije, ki jo zasedajo posamezne vrste biološko proizvodnih površin, povzamemo po uradnih statističnih virih [7] Enakovredni faktorji pomenijo svetovno povprečje ([3] in [4]), medtem ko je faktor pridelka lokalnega značaja. Faktorji pridelka za Slovenijo so določeni za leto 2002 ([7] do [9]) glede na količine pridelkov in svetovno povprečje. Splošno skupno biološko proizvodno površino v sistemu določimo z izrazom:

2 BIO-PRODUCTIVE SPACE IN SLOVENIA

Slovenia measures 20,273 km^2 and has a population of 1,990,272 (in 2002). Table 1 presents the calculated amount of bio-productive space in the region of Slovenia. The Slovenian space, composed of relevant bio-productive areas, is adopted from the official statistical source [7]. The equivalence factors represent the world average [3] and [4], while the yield factors are local. The yield factors for Slovenia for 2002 [7] to [9] are defined in terms of the harvest quantity and the world average. The total area of bio-productive space in a system is defined by the following equation:

$$BP = \sum_{j=1}^{5} A_j ef_j fp_j \quad (1),$$

kjer so:
- BP biološko proizvodna površina sistema (gha),
- j vrsta biološko proizvodne površine (1),
- ef enakovredni faktor posameznega tipa biološko proizvodne površine (gha/ha),
- fp faktor pridelka posameznega tipa biološko proizvodne površine (1).

Ocena sonaravno uravnoteženega razvoja opazovanega sistema temelji na primerjavi razpoložljive biološko proizvodne površine in

where:
- BP the bio-productive space of a system (gha);
- j the type of bio-productive space (1);
- ef the equivalence factor of the individual type of bio-productive space (gha/ha);
- fp the yield factor of the individual type of bio-productive space (1).

An appraisal of the sustainable development of a given system is based on a comparison between the available bio-productive space and the deter-

Preglednica 1. *Velikost biološko proizvodnih površin v Sloveniji na prebivalca v letu 2002*
Table 1. *The amount of bio-productive space per capita in Slovenia in 2002*

Vrsta bioproizvodnih površin Type of bio-productive space	**indeks j index j**	**površina (ha/preb) space (ha/capita)**	**enakovredni faktor equivalence factor (gha/ha)**	**faktor pridelka yield factor (1)**	**globalni hektari (gha/preb) global hectares (gha/capita)**
kmetijske površine crop land	1	0,13	2,11	1,69	0,46
pašniki grazing land	2	0,22	0,47	3,60	0,37
gozdovi kot vir gradbenega lesa forests as a source of timber	3	0,63	1,35	2,42	2,06
sladko in slanovodna področja kot vir morske hrane fresh- and salt-water areas as a source of seafood	4	0,01	0,35	1,00	0,00
pozidane površine naselij, prometnih poti, infrastrukturne površine built-up areas for accommodation, transportation and infrastructure	5	0,004[1]	1,35	1,00	0,01
energijske površine, kot vir/ponor toplogrednih plinov s CO_2 ekvivalentom energy space, as source/sink of greenhouse gases expressed as a carbon-dioxide equivalent	6	-	1,00	-	-
skupaj total					**2,90**
potreben prostor za zagotavljanje biotske raznovrstnosti space required to ensure bio-diversity					**0,35**
preostanek difference					**2,55**

[1]Opomba: pri pozidanih površinah ocenjujemo delež zelenih površin kot 10%.
[1]Note: within the category named "built-up areas", green plots are estimated to cover 10% of the area.

ugotovljenih okoljskih sledi, ki jih povzroča njegova populacija. Razlika opredeljuje okoljski presežek ali primanjkljaj, značilen za opazovani sistem.

mined environmental footprints generated by its population. The difference gives the environmental surplus or deficit for a given system.

$$\Delta ED = BP - ES = BP - \left(ES_E + ES_H + ES_S + ES_G\right) \quad (2),$$

kjer so:

- ΔED presežek ali primanjkljaj okoljskih sledi (gha/preb),
- ES_E okoljske sledi, nastale pri oskrbi z energijo (gha/preb),
- ES_E okoljske sledi, nastale pri proizvodnji in oskrbi s hrano (gha/preb),
- ES_S okoljske sledi zaradi rabe snovi in ravnanja z odpadki (gha/preb),
- ES_G okoljske sledi grajenega okolja (gha/preb).

Če je razlika določena zgolj glede na lastno biološko proizvodno površino opazovanega sistema, ocenjujemo lokalni sonaravno uravnotežen razvoj;

where:

- ΔED environmental surplus or deficit (gha/capita);
- ES_E environmental footprints resulting from the energy supply (gha/capita);
- ES_E environmental footprints resulting from production and food supply (gha/capita);
- ES_S environmental footprints resulting from material consumption and waste handling (gha/capita);
- ES_G environmental footprints resulting from a built-up environment (gha/capita);

The difference determined on the basis of the bio-productive space of a given system gives an estimation of the local sustainable development; how-če okoljske sledi populacije v sistemu primerjamo s planetarno biološko proizvodno površino, ugotavljamo globalni sonaravno uravnotežen razvoj. Po podatkih ([1], [3] in [4]) je trenutna velikost planetarnih biološko proizvodnih površin 1,9 gha na prebivalca Zemlje. Torej lahko sklepamo, da biološko proizvodne površine v Sloveniji (pregl. 1) pomembno presegajo svetovno povprečje.

Kljub mednarodni uveljavljenosti metode okoljskih sledi smo ugotovili, da metoda v Sloveniji še ni bila uporabljena. Zato je namen tega prispevka tudi prenos metode v slovensko okolje ter določitev resničnega okoljskega presežka ali primanjkljaja v sedanjem trenutku.

3 METODOLOGIJA IZRAČUNA OKOLJSKIH SLEDI

Okoljske sledi določimo po dveh osnovnih metodah – celovito ali komponentno. Celostna metoda sledi bilanci energijskih in snovnih tokov na lupini in v notranjosti opazovanega sistema, pri komponentni metodi pa analiziramo dejansko rabo energije in snovi posameznika v opazovanem sistemu. Za statistično dobro vrednotene in z jasno mejo definirane sisteme praviloma, tako kakor v tem delu, uporabljamo celostno metodo. Pri obeh metodah z uvedbo utežnih faktorjev tokov energentov in snovi postanejo okoljske sledi primerljive z biološko proizvodnimi površinami. Slika 3 prikazuje energijske tokove, ki jih obravnavamo pri celoviti metodi izračuna energijskih okoljskih sledi.

Okoljske sledi, ki so posledica rabe energije, določimo z izrazom:

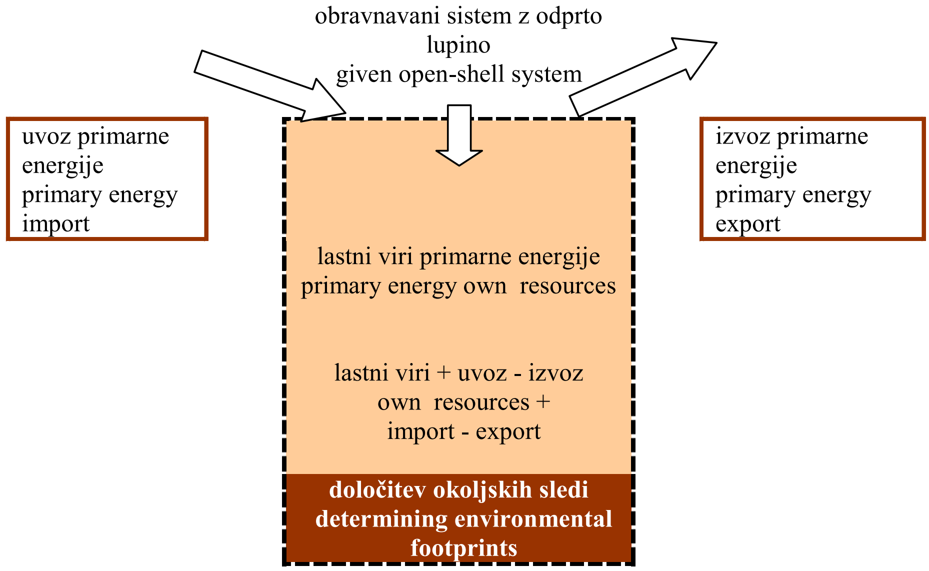
ever, when the environmental footprints of a population in a system are compared to the world's bio-productive space, then global sustainable development is estimated. According to the data available ([1], [3] and [4]), the current amount of planetary bio-productive space equals 1.9 gha per person. Therefore, it can be concluded that the bio-productive space in Slovenia (Table 1) significantly exceeds the world average.

Although the environmental footprints method has been internationally recognised, it has not been used in Slovenia yet. Therefore, the aim of this paper is to apply this method to the Slovenian environment and determine Slovenia's current, real environmental surplus or deficit.

3 METHODOLOGY FOR CALCULATING ENVIRONMENTAL FOOTPRINTS

Environmental footprints are determined with two basic methods: the integral method and the component method. The integral method follows the balance of the energy and material flows on the shell as well as inside a given system, while the component method aims at analysing the actual energy and material consumption of an individual in a given system. The integral method is used for statistically well-evaluated and clearly defined systems, such as those used in this article. With both methods, the environmental footprints become comparable with the bio-productive space by initiating a weighting factor for the energy and material flows. Figure 3 presents the energy flows used for calculating the energy footprints with the integral method.

Environmental footprints caused by energy consumption are determined with the following equation:



Sl. 3. *Shematski prikaz določitve okoljskih sledi, ki so posledica rabe energije nekega sistema s celostno metodo*

Fig. 3. *Schematic representation of the method for determining the environmental footprints caused by energy consumption in a system using the integral method*

$$ES_E = \sum_{m=1}^{n} \sum_{j=1}^{6} (k_{j,m} u_m + k_{j,m} v_m - k_{j,m} e_m) \quad (3),$$

kjer so:

ES_E energijske okoljske sledi (gha/ leto),
m vrsta energenta (1),
j vrsta biološko proizvodne površine (1),
u_m količina primarne energije, ki jo v sistem uvozimo z energentom m (GWh/leto),
v_m notranji vir primarne energije energenta m (GWh/leto),
e_m količina primarne energije, ki jo iz sistema izvozimo z energentom m (GWh/leto),
$k_{j,m}$ utežni faktor za j vrsto biološko proizvodne površine in energent m (gha/GWh).

Utežne faktorje energentov določimo glede na vgrajeno energijo v sisteme za spremembo energije ter emisije, ki nastajajo pri spremembi energije. Navajajo jih dela [1], [6] in [9].

Pri izračunu okoljskih sledi, ki so posledica proizvodnje hrane, porabe snovi in ravnanja z odpadki, se moramo pri celostni metodi dosledno izogibati dvojnemu štetju okoljskih sledi. Zato je treba paziti, da vgrajeno energijo upoštevamo samo pri snoveh, ki jih uvozimo, ter da pri okoljskih sledeh ne upoštevamo snovi, ki jih iz sistema izvozimo. Vgrajeno energijo v teh snoveh in energijo, ki je potrebna za prevoz do meje sistema, odštejemo od skupnih okoljskih sledi sistema:

where:

ES_E energy footprints (gha/year);
m type of energy product (1);
j type of bio-productive space (1);
u_m the amount of primary energy imported in a system by energy product m (GWh/year),
v_m internal source of primary energy of energy product m (GWh/year),
e_m the amount of primary energy exported from a system by energy product m (GWh/year),
$k_{j,m}$ weighting factor for j type of bio-productive space and energy product m (gha/GWh).

The weighting factors of the energy products are determined based on embodied energy in the systems used for energy conversion and based on emissions resulting from such energy conversion. They are cited in sources [1], [6] and [9].

When calculating the environmental footprints caused by food production, material consumption and waste handling using the integral method, double accounting of the environmental footprints should be consistently avoided. Therefore, one must pay attention and recognise embodied energy only in the materials being imported. Further, the materials that are exported from the system should not be taken into account when calculating the environmental footprints. The embodied energy in such materials and the energy needed for transport to the system border is subtracted from the total environmental footprints of the system:

$$ES_S = \sum_{i=1}^{n} \sum_{j=1}^{5} (k_{j,i} p_i + k_{j,i} u_i - k_{j,i} e_i) + \sum_{i=1}^{n} (k_{6,i} u_i - k_{6,i} e_i) + \sum_{i=1}^{n} (k_{6,h,i} s_{h_i} u_i - k_{6,h,i} s_{h_i} e_i) \quad (4),$$

kjer so:

ES_s okoljske sledi, ki so posledica rabe snovi (gha/leto),
i vrsta snovi (1),
j vrsta bioproizvodne površine (1),
h prevozno sredstvo,
u_i količina uvožene snovi *i* (t/leto),
e_i količina izvožene snovi *i* (t/leto),
p_i količina proizvedene snovi *i* (t/leto),
k_i spreminjevalni faktor za snov *i* (gha/t leto),
k_h spreminjevalni faktor za vrsto prevoza *h* (gha/kmt leto),
s prevožena razdalja snovi, ki jih uvozimo ali izvozimo, med mestom proizvodnje in mejo sistema (km).

Vrste živil in snovi, ki jih vključimo v obravnavo, izberemo tako, da zagotovimo mednarodno primerljivost raziskave [9].

where:

ES_s environmental footprints caused by material consumption (gha/year),
i type of material (1);
j type of bio-productive space (1);
h transport;
u_i amount of imported material *i* (t/year);
e_i amount of exported material *i* (t/year);
p_i amount of produced material *i* (t/year);
k_i conversion factor for material *i* (gha/t year);
k_h conversion factor for type of transport *h* (gha/kmt year);
s the distance covered between the production site and system's border with material being imported or exported (km).

The type of food and material taken into consideration must be selected in such a way that the research is comparable in international terms [9].

4 OKOLJSKE SLEDI PREBIVALCEV SLOVENIJE IN VPLIV OSKRBE Z ENERGIJO

Okoljske sledi prebivalcev Slovenije določimo po letni bilanci energijskih in snovnih tokov z enačbama (3) in (4). Posebno razlago

4 ENVIRONMENTAL FOOTPRINTS OF SLOVENIAN CITIZENS AND THE INFLUENCE OF ENERGY SUPPLY

The environmental footprints of Slovenian citizens are determined on the basis of the annual balance of energy and material flows with Equations (3) and (4).

Preglednica 2. *Okoljske sledi, ki so posledica oskrbe in rabe energije ter goriv (2002)*
Table 2. *Ecological footprints caused by energy and fuel supply and consumption (2002)*

	količina energije energy amount	**energijske površine energy space**	**kmetijske površine crop land**	**pašniki grazing land**	**gozdovi forests**	**vodne površine water space**	**pozidane površine built-up land**
	GWh/leto GWh/year	**(gha/prebivalca) (gha/capita)**					
zemeljski plin natural gas	10150	0,21					
UNP	1006	0,02					
motorni bencin[1] petrol[1]	9477	0,28					
dizelsko gorivo, EL kurilno olje[1] diesel fuel. EL fuel oil[1]	5925	0,26					
premog[2] coal[2]	2543	0,09					
lesna biomasa wood biomass	3060				0,02		
geotermalna energija geothermal energy	333						
sončna energija solar energy	28						
deponijski in bio plin depot and bio gas	52						
el. energija iz TE el. energy from thermal power plants	4815	0,39					
el. energija iz HE el. energy from hydroelectric power plants	3741						0,04
el. energija iz JE el. energy from nuclear power plants	5036	0,41					
uvoz el. energije import of el. energy	4232	0,34					
izvoz el. energije export of el. energy	5553	- 0,45					
vgrajena energija izvoženim izdelkom[3] embodied energy in exported products[3]		- 0,19					
skupaj total		**1,36**			**0,02**		**0,04**
	1,42						

Opomba: v preglednici prikazane vrednosti so zaokrožene na dve decimalni mesti
[1] vrednost je razlika med uvozom in izvozom energenta
[2] upoštevana le poraba za proizvodnjo toplote
[3] podatek, določen na podlagi količin prepeljanih snovi in povprečne razdalje 550 km [12]
Note: The values presented in the table are rounded up to two decimal points
[1] the value represents the difference between the import and export of energy product
[2] only the consumption for heat production is recognised
[3] datum determined on the basis of transported material over an average distance of 550 km [12]

izračuna okoljskih sledi zahteva primer ponovne uporabe snovi. Tako je na primer, glede na letno proizvodnjo, uvoz in izvoz izdelkov iz aluminija, komponenta energijskih površin okoljskih sledi izdelkov 297.889 gha (ali 0,15 gha/prebivalca). V viru [10] zasledimo, da v Sloveniji 16 % završenih

However, the presence of material re-use requires an additional explanation for the environmental-footprint calculation. For example, according to annual production, the import and export of aluminium products, the component of energy footprints for such products is equal to 297,889 gha (or 0.15 gha/capita). However,

Preglednica 3. *Okoljske sledi povprečnega prebivalca Slovenije v letu 2002*
Table 3. *Ecological footprints of an average Slovenian citizen in 2002*

ekološke sledi ecological footprints	**energijske površine (gha/preb) energy space (gha/capita)**	**kmetijske površine (gha/preb) crop land (gha/capita)**	**pašniki (gha/preb) grazing land (gha/capita)**	**gozdovi (gha/preb) forests (gha/capita)**	**vodne površine (gha/preb) water space (gha/capita)**	**grajeno okolje (gha/preb) built-up land (gha/capita)**	**skupaj (gha/preb) total (gha/capita)**
energije ES_E energy ES_E	1,36			0,02		0,04	**1,42**
hrane ES_H food ES_H	0,004 (0,15)[1]	0,88	0,38				**1,26**
snovi in odpadki ES_S material and waste ES_S	0,02 (0,95)[1]	0,04		0,83		0,19	**1,08**
grajenega okolja ES_G built-up land ES_G						0,08	**0,08**
skupaj total	1,38	0,92	0,38	0,85		0,31	**3,85**

[1]Opomba: Okoljske sledi zaradi rabe energije, ki pa so pri celostni metodi že upoštevane pri energijskih okoljskih sledeh.
[1]Note: Ecological footprints caused by energy consumption – with the integral method they are already recognised in the context of energy footprints

izdelkov iz aluminija recikliramo, pri tem se raba energije in tako tudi potrebne površine za asimilacijo toplogrednih plinov zmanjšajo za 95 % [11]. Zato se navidezno energijske površine pri oskrbi z izdelki iz aluminija zmanjšajo za 45.279 gha. To zmanjšanje okoljskih sledi pa upoštevamo zgolj pri komponentni metodi in ne tudi pri celostni, saj je raba energije že vključena v skupno energijsko bilanco. Preglednica 2 navaja energijske okoljske sledi prebivalcev Slovenije v letu 2002, skupne okoljske sledi pa navaja preglednica 3.

Iz preglednice 3 je razvidno, da raba energijske in energetske spremembe najpomembneje zmanjšujejo naravne neobnovljive vire in obremenujejo okolje, saj največ prispevajo k skupnim okoljskim sledem prebivalcev Slovenije. To potrjuje potrebo tako po zmanjšanju rabe energije kakor tudi nadomeščanju fosilnih goriv z obnovljivimi viri energije, katerih uporaba povzroča manjše okoljske pritiske. Predvsem zaradi velikega faktorja pridelka, ki je značilen za slovenske gozdove (2,42) predstavljajo ti pomemben ponor CO_2. Ob upoštevanju industrijske uporabe lesa pa znaša primanjkljaj ponora tega najpomembnejšega toplogrednega plina 0,21 gha na prebivalca. Dolgoročno bi utegnil biti za Slovenijo kritičen tudi primanjkljaj biološko proizvodnih površin za proizvodnjo hrane, ki znaša na prebivalca kar 0,43 gha. Izračun okoljskih sledi prebivalca Slovenije in primerjava z razpoložljivimi biološko proizvodnimi površinami pokaže, da je trenutno za Slovenijo značilen tako globalno (ΔED = - 1,95 gha/preb) kakor tudi lokalno (ΔED = - 1,3 gha/preb) neuravnotežen

within the references of this article [10], one can find that in Slovenia, 16% of thrown-away aluminium products are recycled; therefore, the energy consumption as well as the necessary areas for the assimilation of greenhouse gases decreases by 95% [11]. This results in an apparently decreased energy space, i.e., by 45,279gha, when aluminium products are used. Such a decrease in the environmental footprint is only recognised when using the component method, the integral method only accounts for the energy consumption in a total energy balance. Table 2 presents the energy footprints of Slovenian citizens in 2002, while Table 3 gives the total environmental footprints.

Table 3 clearly demonstrates that energy consumption as well as energy-conversion processes drastically reduce non-renewable natural resources and detrimentally affect the environment by contributing the most to the total environmental footprints of Slovenian citizens. This confirms the need to decrease energy consumption as well as to replace fossil fuels with renewable sources of energy, the usage of which would reduce the pressure on the environment. Slovenian forests are characterised by a high yield factor (2.42), which means they present a significant carbon-dioxide source/sink. However, when industrial wood consumption is taken into the account, the source/sink deficit of this most significant greenhouse gas amounts to 0.21gha per capita. In the long run, the deficit of bio-productive space intended for food production might be critical too, since it amounts to 0.43gha. A calculation of the environmental footprints of Slovenian citizens and a comparison with the available bio-productive space shows that, currently, Slovenia can be characterised by imbalanced development, both globally (ΔED = -1.95 gha/capita) and razvoj. Postavlja se vprašanje, ali lahko s smotrno rabo energije in večjim izkoriščanjem obnovljivih virov energije spremenimo trenutni primanjkljaj okoljskih sledi v presežek. Analizirali bomo obdobje do leta 2020, to je obdobje, ki ga vrednotijo najpomembnejši sprejeti razvojni dokumenti Republike Slovenije [18].

5 VPLIV OSKRBE IN RABE ENERGIJE NA OKOLJSKE SLEDI PREBIVALCEV SLOVENIJE V LETU 2020

5.1 Izbira vplivnih parametrov

Za napoved spreminjanja okoljskih sledi prebivalcev Slovenije je treba določiti vplivne parametre in napovedati njihove vrednosti ob koncu obdobja vrednotenja.

Spreminjanje števila prebivalcev v naslednjih dvajsetih letih ocenimo na podlagi populacijske napovedi. Ugotovimo, da se bo število prebivalcev Slovenije v opazovanem obdobju le malenkostno spremenilo - v letu 2020 naj bi v Sloveniji živelo 2,019.399 prebivalcev. Torej število prebivalcev Slovenije pri napovedi ne bo vplivni parameter.

Energijski in snovni tokovi v obdobju do leta 2020 ne bodo ostali nespremenjeni. Za napoved njihovega časovnega spreminjanja uporabimo oceno naraščanja industrijske rasti [18]. Posledično bo naraščanje industrijske proizvodnje in BDP povzročilo tudi povečevanje specifične površine stanovanj, kar bo vplivalo na rabo energije v splošnem sektorju. Pričakovane vrednosti navaja preglednica 4.

Napoved industrijske rasti bomo uporabili kot utežni faktor za napoved rabe energije in snovi, napoved naraščanja stanovanjskih površin pa za napoved rabe energije v stavbah. Pri tem bo šlo za linearno uteženje, na katerem bomo kasneje opazovali predlagane ukrepe energetske politike. Ekološke sledi, ki sledijo zgolj zaradi povečane rabe ob nespremenjenem ravnanju z energijo v letu 2020 navaja preglednica 5. To stanje vzamemo kot “ničelno stanje”.

locally (ΔED = -1.3 gha/capita). The question is whether rational energy consumption and a more extensive use of renewable energy sources can change the current environmental deficit into a surplus. Below is an analysis of the period up to 2020 – a period characterised by some of the most significant developmental documents adopted by the Republic of Slovenia [18].

5 THE INFLUENCE OF ENERGY SUPPLY AND CONSUMPTION ON THE ENVIRONMENTAL FOOTPRINTS OF SLOVENIAN CITIZENS IN 2020

5.1 Selection of the influential parameters

In order to forecast the changes in the environmental footprints of Slovenian citizens, one must define the influential parameters and forecast their values at the end of the evaluation period.

The change in the number of inhabitants in the next twenty years can be estimated on the basis of a population forecast. It is likely that the number of inhabitants of Slovenia will not change significantly during the observed period – in 2020, Slovenia should have about 2,019,399 inhabitants. In other words, the number of Slovenian citizens should not be an influential parameter in any environmental forecast.

Energy and material flows in the period up to 2020 will not remain unchanged. In order to forecast their change over time, an estimation of the increase in industrial growth needs to be employed [18]. An increase in industrial production and GDP will result in an increase in the specific housing space, which will further influence the energy consumption in the general sector. The expected values are presented in Table 4.

The forecast of industrial growth is also used as a weighting factor when forecasting energy and material consumption, while the forecasted increase in the housing space serves as a forecast for the energy consumption in buildings. Linear weighting will be employed, based on which the suggested measures of energy policy can be subsequently observed. The environmental footprints caused only by increased consumption, accompanied by unchanged energy handling in 2020, are presented in Table 5. This state will be referred to as the “zero state”.

Preglednica 4. *Napovedane stopnje industrijske rasti in specifične stanovanjske površine v Sloveniji za obdobje do 2020 [18]*

Table 4. *Forecasted levels of industrial growth and specific housing space in Slovenia during the period up to 2020 [18]*

	1997	2000	2005	2010	2015	2020
stopnja rasti fizičnega obsega proizvodnje level of growth in the physical volume of production	0,95	1	1,09	1,18	1,28	1,45
stanovanjska površina na prebivalca (m^2) housing space per capita (m^2)	24,7	25,5	26,5	27,1	27,5	29

Preglednica 5. *Pričakovane okoljske sledi kot posledica rabe energije ob nespremenjenem ravnanju*
Table 5. *Expected environmental footprints as a result of energy consumption and unchanged handling*

	2000	2020
	gha/prebivalca / gha/capita	
fosilna goriva fossil fuels		
kapljevita fosilna goriva liquid fossil fuels	0,54	0,78
plinasta fosilna goriva gas fossil fuels	0,23	0,33
trdna fosilna goriva solid fossil fuels	0,09	0,13
od tega v stavbah in buildings	0,26	0,30
električna energija electric energy		
iz fosilnih goriv from fossil fuels	0,39	0,57
vodni potencial water potential	0,04	0,06
jedrska energija nuclear energy	0,41	0,59
od tega v stavbah in buildings	0,25	0,29
lesna biomasa wood biomass	0,02	0,03
uvoz električne energije import of electrical energy	0,34	0,49
izvoz električne energije export of electrical energy	-0,45	-0,65
vgrajena energija izvoženim izdelkom embodied energy in exported products	-0,19	-0,28
skupaj total	1,42	2,06

Preglednica 6. *Pričakovane okoljske sledi snovnih tokov in oskrbe s hrano prebivalcev Slovenije*
Table 6. *Expected environmental footprints in terms of material flow and the food supply of Slovenian inhabitants*

	2000	2020
	gha/prebivalca gha/capita	gha/prebivalca gha/capita
hrana food	1,26	1,34
snovi in odpadki materials and waste	1,08	1,57

Opomba: Vrednosti ne upoštevajo rabo energije, saj je že upoštevana v preglednici 5.
Note: Energy consumption is not included in these values, because it is already included in Table 5.

Za oceno snovnih tokov prav tako uporabimo napovedi industrijske rasti. Torej bo za ničelno stanje veljalo, da se bo tok surovin do leta 2020 povečal za 1,45-krat. Izjema je oskrba s hrano. Za razvite države, kamor prištevamo tudi Slovenijo, velja napoved, da se bo naraščanje potreb po hrani spreminjalo bistveno manj intenzivno kakor v nerazvitih [13]. Energijska vrednost zaužite hrane naj bi se v razvitih državah do leta 2020 povečala le za 6 %. Okoljske sledi prebivalcev Slovenije v letu 2020 kot posledico snovnih tokov in potreb po hrani navaja preglednica 6.

An industrial growth forecast is also used when estimating material flows. The zero state in this sense means that the flow of raw materials will increase by 1.45 times in the period up to 2020. An exception is food supply. The forecast for the group of developed countries, which includes Slovenia, suggests that food consumption will increase less significantly in the developed than in the undeveloped countries [13]. Up to 2020, the energy value of the consumed food should increase by only 6% in developed countries. The environmental footprints of Slovenian citizens in 2020 as a result of material flows and the need for food are presented in Table 6.

5.2 Napoved okoljskih sledi prebivalcev Slovenije do 2020

Glede na sprejete mednarodne obveznosti Slovenije in državne razvojne dokumente lahko oblikujemo različne scenarije, ki bodo v prihodnosti vplivali na zmanjšanje okoljskih sledi, ki so posledica rabe energije. Njihove cilje oblikujemo v tri scenarije: A, B in C. Ti vključujejo povečevanje učinkovitosti energijskih sprememb, zmanjšanje rabe energije in povečano izkoriščanje obnovljivih virov energije.

5.2 Forecast of the environmental footprints of Slovenian inhabitants up to 2020

Based on the adopted international obligations of Slovenia and the national developmental documents, various scenarios on a future decrease of environmental footprints caused by energy consumption can be shaped. Based on their goals, three scenarios can be envisaged, i.e., A, B and C, which include the increased efficiency of energy conversions, decreased energy consumption and the increased exploitation of renewable sources of energy.

Preglednica 7. *Napoved okoljskih sledi ob podvojitvi energije, pridobljene iz OVE [14]*
Table 7. *Forecast of the environmental footprints when doubling the energy from renewable sources [14]*

Vir energije **Energy source**	**dodatna pridobljena energija na leto (GWh/leto)** **additionally acquired energy per year (GWh/year)**	**okoljske sledi (gha/prebivalca)** **environmental footprints (gha/capita)**
podvojena uporaba trdne biomase double use of solid biomass		
proizvodnja toplote thermal production	3.060	0,02
proizvodnja električne energije production of electrical energy	306	$4{,}59 \cdot 10^{-3}$
podvojena proizvodnja električne energije iz malih hidroelektrarn double production of electrical energy from small hydro-electric power plants	305	$2{,}75 \cdot 10^{-3}$
uvajanje bioetanola kot dodatek neosvinčenemu bencinskemu gorivu; uporabili bi 18 % opuščenih kmetijskih površin v zadnjih letih introduction of bio-ethanol as an additive to unleaded petrol; 18% crop lands, not cultivated during past years, would be used .	556	$4{,}45 \cdot 10^{-3}$
uvajanje biodizelskega goriva; uporabili bi 3% opuščenih kmetijskih površin v zadnjih letih introduction of bio-diesel fuel; 3% crop lands, not cultivated during past years, would be used	83	$0{,}66 \cdot 10^{-3}$
proizvodnja bioplina, kar je okvirno 4% glede na ocenjen potencial živalske biomase biogas production – app. 4%, based on estimated potential of animal biomass	277	$2{,}8 \cdot 10^{-3}$
izkoriščanje vetra; 12 vetrnic z imensko močjo 1,3 MW, v_{letno} =8m/s wind exploitation; 12 sails of windmill with maximum net power 1.3 MW, v_{yearly} = 8m/s	72	$0{,}14 \cdot 10^{-3}$
potrojen delež izkoriščanja geotermalne energije triple share of geo-thermal energy exploitation		
električne energije iz geotermalnega vodonosnika Termal II electrical energy from "Termal II" geothermal aquifer	83	0
toplota geotermalnega vodonosnika Termal II heat from "Termal II" geothermal aquifer	83	0
sončna energija solar energy		
energija, ki predstavlja 100 % energije za pripravo tople sanitarne vode v vsako leto novo zgrajenih individualnih stavbah (5000 objektov na leto) energy representing 100% of the energy needed for heated sanitary water in new, individual buildings (5000 buildings per year)	139	$8{,}36 \cdot 10^{-6}$
ogrevanje individualnih stavb in industrijskih objektov z nizko in srednjetemperaturnimi solarnimi sistemi heating of individual and industrial buildings with solar systems working with low and medium temperature	72	$4{,}32 \cdot 10^{-6}$
skupaj / total	**5.175**	**0,04**

5.2.1 Scenarij A: Podvojitev energije, pridobljene iz obnovljivih virov energije (OVE)

Podvojitev energije, pridobljene iz obnovljivih virov, je strateški cilj EU, ki ga opredeljuje "Bela knjiga". Za Slovenijo bi to pomenilo povečanje deleža primarne energije iz obnovljivih virov energije s 6% na 12 %. Možen scenarij [14] in nastale okoljske sledi navaja preglednica 7.

Z načrtovanim povečanjem izkoriščanja OVE bi bilo mogoče pridobiti letno 5.175 GWh energije. Okoljske sledi, ki jih povzročajo te tehnike, znašajo 0,04 gha/prebivalca, medtem ko so energijske okoljske sledi enake količine »fosilne« energije 0,21 gha/prebivalca. Pri tem smo upoštevali, da z OVE nadomestimo tisto energijo, pridobljeno iz fosilnih goriv, ki povzroča največje okoljske sledi. Celoten učinek scenarija A je torej zmanjšanje okoljskih sledi za 0,17 gha na prebivalca.

5.2.1 Scenario A: Doubling of the energy from renewable sources

Doubling of the energy from renewable source is a strategic goal of the EU, determined in the "White Book". For Slovenia it means an increase in the share of primary energy from renewable sources from 6 to 12%. A possible scenario [14] and the resulting environmental footprints are presented in Table 7.

The planned increase in the exploitation of renewable sources of energy would bring 5,175GWh of energy each year. The environmental footprints resulting from such technologies amount to 0.04gha/capita, while the energy footprints resulting from the same amount of fossil-fuel energy amount to 0.21 gha/capita. Also, it was taken into account that fossil-fuel energy, which causes the largest environmental footprints, is replaced with a renewable source of energy. Based on the above, the outcome of scenario A is a decrease in the environmental footprints by 0.17 gha per capita.

Preglednica 8. *Raba energije in okoljske sledi po scenariju B ([15] do [17])*
Table 8. *Energy consumption and environmental footprints according to Scenario B ([15] to [17])*

Ukrep **Measure**	**GWh/leto** **GWh/year**	**okoljske sledi (gha/prebivalca)** **environmental footprints (gha/capita)**
Napotilo o energijski učinkovitosti stavb - Napotilo 2002/91/ES Evropskega parlamenta in sveta, 2000 [33] predvideva, da bo uvajanje presoje rabe energije v stavbah posredno pripomoglo k 20 % zmanjšani rabi energije v stavbah Directive on the energy performance of buildings – Directive 2002/91/EC of the European Parliament and of the Council, 2000 [33] anticipates that the introduction of judgement of energy use in buildings would indirectly contribute to decreased energy use in the buildings by 20%	4.444 (prihranjena energija) (saved energy)	- 0,13
Napotilo o proizvodnji električne energije iz OVE - Napotilo 2001/77/ES Evropskega parlamenta in sveta, 2001, [32] sprejeta obveza Slovenije je povečanje sedanjega deleža proizvedene električne energije iz 33% na 36% Directive on electricity production from renewable energy sources – Directive 2001/77/EC of the European Parliament and of the Council, 2000 [32]; Slovenia adopted an obligation to increase the current share of electricity produced from 33% to 36%	1.480 (zamenjava fosilnih goriv) (replacing fossil fuels)	0,01
Napotilo o biogorivih - Napotilo 2003/30/ES Evropskega parlamenta in sveta, 2000, [34] predvideva do leta 2020 20% zamenjavo fosilnih tekočih goriv z gorivi proizvedenimi iz biomase ali vodika, ki bi bil proizveden z uporabo OVE Directive on bio-fuels – Directive 2003/30/EC of the European Parliament and of the Council, 2000 [34] anticipates that by 2020, 20% of liquid fossil fuels should be replaced with fuels produced from biomass or hydrogen produced by using renewable sources of energy	3.634 (zamenjava fosilnih goriv) (replacing fossil fuels)	0,03
skupaj **total**	**4.444 prihranjeno/saved** **5.114 pridobljeno/acquired**	**- 0,13** **- 0,19**

5.2.2 Scenarij B: Uveljavitev navodil EU s področja varčne rabe energije in izkoriščanja OVE

V zadnjih letih je EU sprejela vrsto navodil, katerih cilj je zmanjšanje rabe energije in s tem tudi odvisnosti od zunanjih energetskih virov. Dosledna uveljavitev sprejetih napotil EU s področja varčne rabe energije in izkoriščanja OVE ([15] do [17]) v Sloveniji drugi scenarij (B), ki ga ocenjujemo. V preglednici 8 so predstavljeni pričakovani učinki sprejetih in uveljavljenih navodil.

Glede na scenarij B bi lahko v stavbah prihranili letno 4444 GWh energije ob hkratnem zmanjšanju okoljskih sledi za 0,13 gha/prebivalca. Energija, pridobljena iz obnovljivih virov, (0,04 gha/prebivalca) pa pomeni zamenjavo »fosilne« energije (0,23 gha/prebivalca). Celoten učinek scenarija B je zmanjšanje okoljskih sledi za 0,32 gha/prebivalca, glede na napovedano ničelno stanje.

5.2.3 Scenarij C: Resolucija o državnem energetskem programu

Tretji scenarij povzamemo po dokumentu Predlog Resolucije o državnem energetskem

5.2.2 Scenario B: Implementation of EU directives in the area of the economical use of energy and the exploitation of renewable sources of energy

In recent years the EU has adopted a variety of directives with the aim of decreasing energy consumption and the dependency on external sources of energy. A consistent implementation of adopted EU directives in the area of the economical use of energy and the exploitation of renewable sources of energy ([15] to [17]) in Slovenia represents the second scenario, B, which is evaluated below. Table 8 presents the expected outcomes resulting from adopted and implemented directives.

According to scenario B we might save 4,444 GWh of energy per year; at the same time, the environmental footprints would decrease by 0.13 gha/capita. The energy produced from renewable sources (0.04 gha/capita) represents the replacement of fossil-fuel energy (0.23gha/capita). Based on the above, the overall outcome of scenario B is a decrease in the environmental footprints by 0.32 gha per capita, based on the proposed zero state.

5.2.3 Scenario C: The national energy programme resolution

The third scenario is based on the document entitled National Energy Programme Resolution Proposal,

Preglednica 9. *Okoljske sledi ob upoštevanju scenarija C [18]*
Table 9. *Environmental footprints based on scenario C [18]*

	2000	**2020**
	gha/prebivalca / gha/capita	
fosilna goriva fossil fuels		
kapljevita fosilna goriva liquid fossil fuels	0,54	0,59
plinasta fosilna goriva gas fossil fuels	0,23	0,31
trdna fosilna goriva solid fossil fuels	0,09	0,04
električna energija electrical energy		
termoelektrarne thermal power plants	0,39	0,50
hidroelektrarne hydroelectric power plants	0,04	0,05
jedrska elektrarna nuclear power plant	0,41	0,46
elektrarne na biomaso biomass power plants		0,01
lesna biomasa - toplota wood biomass heat	0,02	0,03
uvoz električne energije import of electrical energy	0,34	0
neto izvoz električne energije net export of electrical energy	- 0,45	- 0,22
vgrajena energija izvoženim izdelkom embodied energy in exported products	- 0,19	- 0,28
skupaj / total	**1,42**	**1,49**

programu [18], ki ga predlaga MOPE. Za izračun okoljskih sledi bomo povzeli podatke o energetskih bilancah, ki so objavljene v tem dokumentu in so prikazane v preglednici 9. Glede na scenarij C se bodo okoljske sledi zaradi rabe energije, glede na ničelno stanje, zmanjšale za 0,36 gha/prebivalca.

Velik delež energijskih površin pri oskrbi s snovmi in hrano, ki je prikazan v preglednici 2 poudarja pomen smotrne rabe snovi tudi v smislu oskrbe z energijo. Če bi v Sloveniji uspešno uvedli strategijo "brez odpadkov" ravnanja z naravnimi snovmi, ki jo uspešno uveljavljajo na primer v Canberri in Seattlu, bi občutno zmanjšali tudi energijske okoljske sledi. Pri analizi upoštevamo, da je možnost ponovne uporabe snovi količinsko omejena zaradi izgub pri predelavi in neustaljenih postopkov (kopičenja snovi), tako da lahko ponovno uporabimo 50 % zavrženih snovi. Učinek takega ravnanja navaja preglednica 10.

which was proposed by the Ministry of the Environment, Spatial Planning and Energy. In order to calculate the environmental footprints, the data on energy balances contained in this document will be summarized. The data are presented in Table 9. According to Scenario C, the environmental footprints caused by energy consumption would decrease by 0.36 gha/capita, based on the proposed zero state.

The large share of energy space for material and food supply, shown in Table 2, emphasises the importance of rational material use in the context of energy supply. If Slovenia managed to successfully implement the so-called "no waste" strategy in terms of handling natural materials, like, for example, Canberra or Seattle, our environmental footprints would significantly decrease. This analysis recognises the fact that material reuse is limited in terms of quantity due to the loss resulting from recovery and non-stationary processes (matter accumulation), which means that only 50% of thrown-away materials can be reused. The outcome of such handling is presented in Table 10.

Preglednica 10. *Zmanjšanje okoljskih sledi pri uvedbi strategije "brez odpadkov"*
Table 10. *The decrease of environmental footprints as a result of the implemented "no waste" strategy*

	energijske površine energy space	**kmetijske površine** crop land	**pašniki** grazing land	**gozdovi** forests	**pozidane površine** built-up land	**vodne površine** water space
	okoljske sledi (gha) / environmental footprints (gha)					
	- 0,52	- 0,009		- 0,60	- 0,13	
skupaj total	**- 1,26 gha/prebivalca gha/capita**					

Preglednica 11. *Predvidene okoljske sledi prebivalcev Slovenije v 2020 ob upoštevanju navedenih scenarijev in strategij*
Table 11. *Forecasted environmental footprints of Slovenian citizens in 2020 based on scenarios A, B and C.*

	Okoljske sledi (gha/prebivalca) / Environmental footprints (gha/capita)				
	stanje state in	**ničelno stanje zero state**	**scenariji smotrne rabe energije in snovi scenarios of rational energy and material consumption**		
	2002	**2020**	**2020**		
			A	**B**	**C**
energija energy	1,42	2,10	1,28	1,26	1,53
neposredna raba energije direct use of energy	1,39	2,06	2,06 + 0,04 – 0,21 – 0,13- 0,52	2,06 – 0,32 -0,52	1,49 – 0,52
energija, potrebna za oskrbo s snovmi, ki jih uvozimo energy necessary for supply from imported materials	0,03	0,04	0,04	0,04	0,04
hrana food	1,26	1,34	1,34	1,34	1,34
surovine in odpadki raw materials and waste	1,08	1,57	0,47	0,47	0,47
odstranjevanje odpadkov waste disposal	0,14	0,27	0,00	0,00	0,00
raba surovin use of raw material	0,94	1,34	0,47	0,47	0,47
grajeno okolje built-up land	0,08	0,09	0,09	0,09	0,09
skupaj / total	**3,85**	**5,10**	**3,28**	**3,26**	**3,01**

Napoved okoljskih sledi prebivalcev Slovenije v 2020 ob upoštevanju scenarijev A, B in C pri oskrbi z energijo ter predlaganega smotrnega ravnanja s snovmi navaja preglednica 11.

6 SKLEP

Namen dela je bil večplasten. Na teoretični ravni smo želeli ugotoviti omejitve in izbrati najprimernejšo metodo določitve okoljskih sledi kot metodo merjenja uravnoteženega razvoja nekega sistema. Glede na opravljeno raziskavo lahko povzamemo:

– Metodo okoljskih sledi odlikujejo številne lastnosti, ki jih morajo izpolnjevati celoviti kazalniki; gre za enopomensko vrednost, ki je predstavljiva; prva odločitev, ki jo moramo sprejeti pri uporabi te metode, pa je povezana z celostnim in komponentnim načelom; celostno načelo, ki smo ga uporabili za Slovenijo, je v osnovi laže uporabiti na statistično dobro obdelanih sistemih; pri delu pa smo ugotovili, da so energijski tokovi lahko merljivi, mnogo teže je slediti snovnim.
– Največjo težavo pri celostni metodi pomeni problem dvojnega štetja, še posebej pri analizi energijskih tokov.
– Naša ugotovitev je tudi, da z razpoložljivimi statističnimi podatki ni mogoče križno ugotavljanje (preverjanje) tokov snovi in odpadkov, kar bi izboljšalo natančnost metode.
– Ne glede na dejstvo, da osnovno pravilo metode upošteva največje znane vplive na okolje (za primer je izračun okoljskih sledi grajenega okolja, kjer predpostavimo, da to zaseda najkakovostnejše kmetijske površine) in dejstva, da so upoštevane vse pomembne snovi, so okoljske sledi praviloma podcenjene.

Na uporabni ravni pa smo želeli ovrednotiti okoljske sledi prebivalcev Slovenije v sedanjem trenutku in leta 2020 ob upoštevanju različnih scenarijev smotrne rabe energije, zamenjave fosilnih goriv in izkoriščanja obnovljivih virov energije. Gre za obdobje, ki ga obravnava večina razvojnih dokumentov. Naše ugotovitve lahko strnemo v naslednje:

– Trenutne okoljske sledi prebivalcev Slovenije (3,85 gha/preb) presegajo razpoložljivo biološko proizvodno površino (2,55 gha/preb) in bistveno presegajo planetarno razpoložljivo bioproizvodno površino (1,9 gha/preb), torej je za Slovenijo značilno tako lokalno kakor tudi globalno neuravnotežen razvoj.
– Primerjava z državami EU (sl. 4) pokaže, da so okoljske sledi prebivalcev Slovenije med najnižjimi; ob primerjavi okoljskih sledi držav Evropske zveze ugotovimo, da imajo samo Finska, Irska, Latvija in Švedska manjše okoljske sledi od njihove biološke

The forecast of environmental footprints for Slovenian citizens in 2020 based on scenarios A, B and C in terms of energy supply as well as the suggested rational material handling is presented in Table 11.

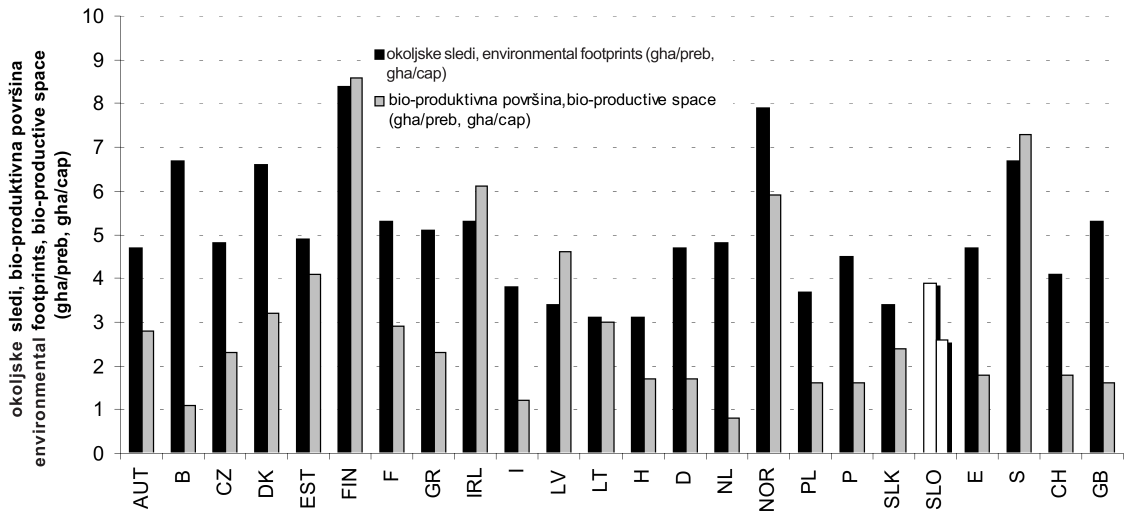
6 CONCLUSION

The purposes of this article are many fold. At the theoretical level, we wanted to find limits and choose the most appropriate method for determining environmental footprints – a method for measuring the sustainable development of a given system. Based on the performed research, the following can be concluded:

– the environmental footprints' method excels in many features that are mandatory for integral indicators; it presents a meaningful value that can be easily imagined; the first decision that has to be reached when using this approach involves a choice between the integral and component methods; the integral method that was used in the case of Slovenia is basically more applicable in systems that are statistically well analysed; our research found that energy flows are much easier to measure than material flows, which are more problematic in terms of tracking.
– the biggest problem when applying the integral method is double accounting, especially at the point where the energy flows are analysed;
– another finding is that the available statistical data do not allow the cross-sectional findings of material and waste flows, which would make the method more accurate.
– despite the fact that the basic rule of this method recognises the highest values in terms of influencing the environment (an example is the calculation of the environmental footprints of built-up land, where the assumption is that it occupies the most qualitative crop land) and the fact that all the significant materials are recognised, the environmental footprints are, as a rule, still underestimated.

At the applicable level we wanted to evaluate the current environmental footprints of Slovenian citizens as well as to forecast the environmental footprints in 2020 by considering various scenarios of the rational use of energy, the replacement of fossil fuels and the exploitation of renewable sources of energy. The period analysed is equal to a period mentioned in most developmental documents. Our findings may be summarized as follows:

– the current environmental footprints of Slovenian citizens (3.85 gha/capita) exceed the available bio-productive space (2.55 gha/capita) and significantly exceed the planetary bio-productive space (1.9gha/capita); therefore, Slovenia is characterised as a country with an imbalanced development, both locally and globally;
– a comparison with EU states (Figure 4) shows that the environmental footprints of Slovenian citizens are among the lowest; furthermore, the comparison of the environmental footprints of the EU states reveals that only Finland, Ireland, Latvia and Swe-



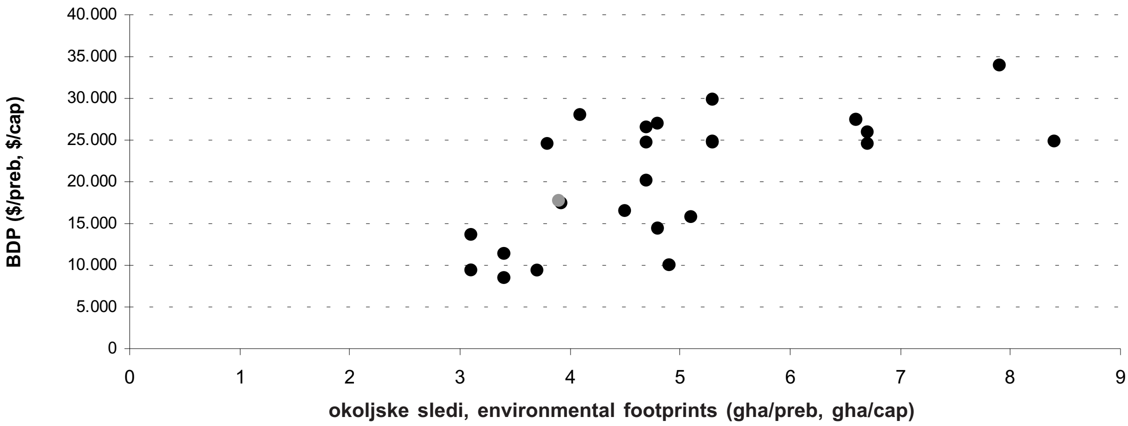
Sl. 4. *Ekološke sledi prebivalcev držav EU in velikost biološko-proizvodnih površin v teh državah ([3], [4] in [9])*
Fig. 4. *Environmental footprints of EU states and the amount of bio-productive space in these countries ([3], [4] and [9])*

proizvodnosti, torej presežek okoljskih sledi – v primeru Finske in Švedske je razlog v veliki površini gozda (7 oz. 5,4 gha/prebivalca), za Irsko so značilne velike vodne biološko proizvodne površine (1,66 gha/prebivalca), le za Latvijo velja, da ima razmeroma majhne okoljske sledi (3,1 gha/prebivalca) ob veliki površini za absorpcijo toplogrednih plinov (2,8 gha/prebivalca).

– Primerjava okoljskih sledi in najbolj značilnega ekonomskega kazalnika bruto domačega proizvoda (BDP) za države Evropske zveze pokaže opazno povezanost med naraščanjem okoljskih sledi in naraščanjem BDP (sl. 5); v območju okoljskih sledi med 3,5 in 5 gha na prebivalca pa opazimo velika odstopanja v BDP analiziranih držav (med 10.000 in 30.000 $). Torej je v tem področju, ki je tudi najbolj značilno, mogoče močno povečati BDP ob nespremenjenih okoljskih sledeh!

den have lower environmental footprints in comparison with their bio-productivity; however, the environmental surplus in the case of Finland and Sweden results from the extensive forests (7 and 5.4 gha/capita), while a huge water bio-productive space is characteristic for Ireland (1.66 gha/capita); only Latvia has a relatively low environmental footprint (3.1 gha/capita) and a large space for the absorption of greenhouse gases (2.8 gha/capita).

– the comparison between the environmental footprints and the GDP (the most significant economic indicator) of the EU countries reveals a significant, positive correlation (Figure 5); furthermore, one can see that for environmental footprints between 3.5 and 5 gha the per-capita GDP ranges between $10,000 and $30,000, which means that there is a possibility to increase GDP and still leave the environmental footprints unchanged.



Sl. 5. *Povezanost med BDP in okoljskimi sledmi držav Evropske zveze; poudarjena točka pomeni Slovenijo [9]*
Fig. 5. *Correlation between the GDP and the environmental footprints of EU countries; the highlighted point represents Slovenia [9]*

- Prizadevanja k smotrni rabi energije sicer vodijo k izpolnjevanju mednarodnih obvez Slovenije glede na zmanjšanje emisij toplogrednih plinov, vendar ne zadoščajo za zagotavljanje lokalno sonaravno uravnoteženega razvoja.
- Lokalno sonaravno uravnotežen razvoj Slovenije bo v naslednjih desetletjih mogoče doseči zgolj:
  - z doslednim upoštevanjem scenarijev o oskrbi z energijo, ki izhajajo iz sprejetih Napotil EU in opredelitev v državnih razvojnih dokumentih;
  - s smotrno rabo snovi in popolnoma spremenjenim upravljanjem z odpadki, pri čemer prevladuje zmanjšanje črpanja neobnovljivih virov in ne njihovo energijsko izkoriščanje;
  - s povečanjem faktorja pridelka hrane na raven, ki ga že dosegajo nekatere druge evropske države – na primer Irska in Belgija.

- Efforts directed towards the rational use of energy will lead to the fulfilment of the international obligations of Slovenia with regard to reducing the emission of greenhouse gases; however, they are not sufficient for sustainable development at the local level.
- the sustainable development of Slovenia at the local level will be possible, based on the following:
  - a consistent compliance with energy-supply scenarios, which originate in adopted EU directives, and definitions from national developmental documents;
  - a rational consumption of materials and a completely changed waste-handling process, where a policy of a reduced extraction of non-renewable sources should prevail over their exploitation for energy.
  - an increased level of food production, which should reach that of some European countries, e.g., Ireland and Belgium.

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Raziskava vpliva naprave za magnetno obdelavo vode na izločanje vodnega kamna v industrijskem stroju za pomivanje steklenic z uporabo vrstične elektronske mikroskopije

SEM Examination of the Influence of a Magnetic Water-Treatment Device on the Scale Precipitation in an Industrial Machine for Bottle Cleaning

Viljem Kozic - Lucija Črepinšek Lipuš - Jurij Krope

Testirana je bila tržna magnetna naprava za nadzor vodnega kamna v industrijskem stroju za pomivanje steklenic. Vzorci vodnega kamna, ki so se izločili na testnih ploščicah iz raznih materialov, so primerjani za magnetno obdelano in neobdelano vodo. Utežni rezultati in morfološko – kemični rezultati analize z elektronskim vrstičnim mikroskopom – so pokazali praktično enako kemijsko sestavo, vendar v primerih magnetno obdelane vode približno 20-odstotno zmanjšanje količine oblog, z manj trdimi, neadhezivnimi, prašnatimi strukturami. V primeru izločanja na korozivni jekleni ploščici je magnetna obdelava povzročila obilnejše nastajanje železovega hidroksida, vendar je bila čvrsta obloga prav tako manj strjena kakor v preostalih primerih.

(Ključne besede: obdelava vode magnetna, kamen vodni, mikroskopi elektronski, mikroskopi vrstični)

A commercial magnetic device for scale control was tested in an industrial machine for bottle cleaning. Scale samples, which had precipitated on test plates of different materials, were compared for magnetically treated and non-treated water. Gravimetrical results and morphological-chemical results from a scanning electron microscope analysis showed practically the same chemical composition, but an approximately 20% decrease in the amount of scale and less-compact, non-adhesive, powder-like structures in the cases of magnetically treated water. In the case of precipitation on a corrosive steel plate, the magnetic treatment caused the abundant formation of iron hydroxide, but the structure of the precipitate was also less compact than in the other cases.

(Keywords: magnetic water treatment, scale (deposits), scanning electron microscopy)

1 UVOD

1.1 Nastajanje vodnega kamna

Nastajanje vodnega kamna je pojav, pri katerem se minerali, prvotno raztopljeni v vodi, odlagajo na stenah cevi in površinah toplotnih izmenjav.

Obloge vodnega kamna so sestavljene iz mineralov, ki s povišanjem temperature postanejo manj topni. Med njimi je najpogostejši kalcijev karbonat [1]. Kalcijev karbonat ima tri polimorfe: kalcit, aragonit in vaterit; z romboedrično, ortorombsko oziroma šesterno strukturo [2].

Vaterit je najmanj stabilna faza, aragonit je metastabilna faza in kalcit je najstabilnejši. Kalcit je v splošnem manj topen kakor aragonit, vendar je

1 INTRODUCTION

1.1 Scale Formation

Scale formation is a process in which minerals, originally dissolved in water, are deposited on pipe walls and heat-exchanger surfaces.

Scale deposits are composed of minerals that become less soluble with increasing temperature, calcium carbonate being the most common [1]. Calcium carbonate has three kinds of polymorph: calcite, aragonite and vaterite, with rhombohedral, orthorhombic and hexagonal structures, respectively [2].

Vaterite is the least stabile phase, aragonite is metastable and calcite is the most stable. Calcite is generally less soluble than aragonite, but aragonite is often the first phase to precipitate out of solution aragonit pogosto prva faza, ki se izloči iz raztopine in nato sčasoma prekristalizira v kalcit. Hitrost prekristalizacije je odvisna od *pH*, temperature in nečistoč. Kalcit je večinoma v povezavi s trdim vodnim kamnom, medtem ko aragonit daje bolj mehke oblike, ki so laže odstranljive.

Mnogi avtorji so poročali, da imajo različni kovinski ioni, celo z milijonskimi deleži, vpliv na obliko izločanja polimorfov kalcijevega karbonata. Herzog je s sodelavci poročala o pozitivnem učinku ionov Fe^{2+}, ki so že z milijonskimi deleži zavirali nastajanje kalcita in pospeševali nastajanje aragonita [3]. Tudi prisotnost ionov Zn^{2+} daje celo z miljardinskimi deleži prednost nastajanju aragonita [4]. Ioni Mg^{2+} še posebej vplivajo na obliko kristalizacije in povzročajo spremembe v morfologiji kristalov kalcijevega karbonata [5]. Zaradi zapletenosti kristalizacije polimorfov in zapletenega vpliva primesi je v praksi nadzor kristalizacijskega procesa otežkočen.

1.2 Preprečevanje vodnega kamna

V uporabi so mnoge kemijske metode za preprečevanje ali nadzor izločanja kalcijevega karbonata [6]. Ena metoda je razgradnja hidrogen karbonatnih ionov v ogljikov dioksid z dodajanjem kislin, vendar znižanje *pH* povzroča težave s korozijo in razgradnjo konstrukcijskih materialov. Druga metoda je kationska izmenjava [7], katere stroški pa so zelo veliki.

Najbolje sprejeta metoda za nadzor vodnega kamna je obdelava s pragovnimi inhibitorji, med njimi dodatki polifosfatnih komponent, ki v zelo majhnih koncentracijah zavirajo rast kalcitnih kristalov. Mehanizem zaviranja še ni povsem razjasnjen. Ena možnost je, da adsorbirani fosfonatni ioni deaktivirajo mesta rasti na kalcitnih kristalih [8]. Polifosfonatni inhibitorji vodnega kamna so dragi in pod strogimi okoljevarstvenimi predpisi.

Običajne kemijske metode spremenijo kemijsko sestavo raztopine in se ne morejo uporabljati na nekaterih področjih, kakršni sta živilska industrija in industrija pijač, kjer so predpisane stroge zahteve glede kakovosti vode. Varovanje okolja in gospodarnost sta dva močna razloga za razvoj in uporabo različnih oblik nekemijskih metod za preprečevanje vodnega kamna.

Razvite in uporabljane so mnoge fizikalne metode za nadzor vodnega kamna. Na tržišču so različne naprave za električno obdelavo vode. Nova takšna naprava je Geno-K4 [9], ta sestoji iz elektrolitske celice, ki nepretrgoma proizvaja droben razpršen prah kristalov kalcijevega karbonata. Ta prah se dovaja v tok vode in vzpodbuja kristalizacijo kalcijevega karbonata v sredici vode, kar zmanjša obseg kristalizacije na površinah tehnološke opreme.

Druga nova metoda uporablja ultrazvočno polje, ki zavira kristalizacijo kalcitne kristalne oblike

and recrystallizes into calcite over time. The rate of the recrystallization depends on the *pH*, the temperature and the presence of impurities. Calcite is usually associated with hard scale, whereas aragonite gives rise to a softer type of scale that is easily removed.

Many authors have reported about various metallic ions that have an effect, even in ppm levels, on the precipitation behavior of calcium carbonate polymorphs. Herzog and coworkers reported about the influence of Fe^{2+} ions, which even in ppm levels inhibited the formation of calcite and promoted the formation of aragonite [3]. Also Zn^{2+} ions, even in ppb levels, can cause the preferential formation of aragonite [4]. Mg^{2+} ions have a strong influence on the crystallization behavior and induce a morphological change in the calcium carbonate crystals [5]. The complicated crystallization behavior of the polymorphs and the complicated effects of the additives make artificial control of the practical crystallization process very difficult.

1.2 Scale Prevention

Many chemical methods are used to prevent or control calcium carbonate precipitation [6]. One method involves the degradation of hydrogen carbonate ions into carbon dioxide by adding acids, but the resulting lowered *pH* causes problems with corrosion and the degradation of construction materials. Another method is cation exchange [7], but its costs can be very high.

The most popular scale-control method is treatment with threshold inhibitors, such as polyphosphonate compounds, which in very low concentrations act as agents for inhibiting the growth of calcite crystals. The inhibiting mechanism is however, not understood precisely, yet. One possibility is that the adsorbed phosphonate ions deactivate growth sites on the existing calcite crystals [8]. Polyphosphonate scale inhibitors are expensive and are subject to strict environmental regulations.

Traditional chemical methods change the solution chemistry and cannot be used in some fields, such as the food and drink industries, where strict requirements for water quality are demanded. Thus environmental protection and economic considerations are two strong motivations for developing and using various types of non-chemical scale-prevention methods.

Many physical methods for scale control have been developed and used, and various devices for electric water treatment are marketed. One new device is Geno-K4 [9], which consists of an electrolytic cell that continuously produces a fine dispersed powder of calcium carbonate crystals. This powder is supplied to the water flow, stimulating the crystallization of calcium carbonate in the bulk of the water, which consequently reduces the precipitation on the equipment surfaces.

Another new method uses an ultrasonic field, which retards the crystallization of the calcite

[10]. Zelo podoben učinek j ebil ugotovljen z ultravijoličnim sevanjem [11].

1.3 Magnetna obdelava vode

Najbolj uporabljana fizikalna metoda za nadzor vodnega kamna je magnetna obdelava vode (MOV), pri kateri voda teče skozi magnetno polje. Naprave za MOV so doslej proizvajala in prodajala številna mednarodna podjetja več ko 50 let v izvedbah od majhnih gospodinjskih do ogromnih industrijskih naprav [12]. Kljub nekaj desetletni praktični rabi ostaja učinkovitost teh naprav negotova zaradi nepopolnega razumevanja, kako magnetno polje vpliva na vodni disperzni sistem. Poleg tega se poročani učinki na tem področju včasih ne ujemajo ali niso ponovljivi. To je verjetno zato, ker imajo celo majhne spremembe v sestavi vode in odstopanja v obdelovalnem postopku močan vpliv na jedrenje in kristalizacijo komponent, ki tvorijo vodni kamen.

Številne raziskave, izvedene na laboratorijsko pripravljenih vodnih disperzijah, so potrdile učinek MOV ([13] do [15]). Nekaj zanimivih rezultatov je bilo ugotovljenih, ko je bila mirujoča voda izpostavljena različnim oblikam magnetnih polj [16], vendar so učinki močneje izraženi, ko se voda pretaka skozi magnetno polje, ki je pravokotno na smer toka vode [17].

Vendar mehanizem MOV še ni povsem razjasnjen, ker se opaženi magnetni učinki ne morejo preprosto pojasniti z neposrednimi elektromagnetnimi interakcijami med diamagnetnimi komponentami, ki delajo vodni kamen v vodni disperziji. Predvsem je interakcijska energija med magnetnim poljem in ionom bistveno manjša od termične energije kT in je zato učinek medmolekularnih trkov zanemarljiv. Tako se eksperimentalno opaženi učinek, ki se ohranja še po MOV, t.i. »magnetni spomin«, ne more pojasniti na ta način.

Obstaja nekaj hipotez o mehanizmu MOV ([18] in [19]). Ena možnost je, da magnetno polje povzroča deformacijo difuzijske plasti, ki obdaja dispergirane delce v vodni disperziji ([20] in [21]). Ta deformacija vodi v začasno znižanje odboja in posledično v pospešeno kristalizacijo. V magnetnem polju se bodo premaknjeni proti – ioni dlje časa zadržali v Sternovi plasti in na ta način se lahko pojasni magnetni spomin.

Učinek preprečevanja oblog vodnega kamna je verjetno rezultat spremenjene kristalizacije komponent, ki tvorijo vodni kamen v sredici vode, kar posledično zmanjša obseg oblaganja na površinah tehnološke opreme. Torej je z vidika dodajanja fino razpršenega prahu kalcijevega karbonata MOV podobna novi napravi Geno-K4.

crystal form [10]. A very similar effect has been demonstrated with ultraviolet radiation [11].

1.3 Magnetic water treatment

The most used physical anti-scale method is magnetic water treatment (MWT), where the water flows through a magnetic field. MWT devices have been produced and marketed by a number of international companies for over 50 years with applications ranging from small domestic to gigantic industrial devices [12]. Despite several decades of practical use the efficiency of these devices still remains unclear due to an incomplete understanding of how the magnetic field affects water-dispersion systems. Additionally, reported effects in this area are sometimes not consistent or not reproducible. This is probably because even small variations in the water composition and differences in the treatment process can have a great influence on the nucleation and crystallization of scale-forming components.

A number of investigations carried out on laboratory-prepared water dispersions have confirmed MWT effects ([13] to [15]). Some interesting results were found when static water was exposed to various types of magnetic fields [16], but stronger effects are present when water flows through the magnetic field, which is perpendicular to the stream [17].

The MWT mechanism, however, is not clear yet, because the observed magnetic effects cannot be explained simply by direct electromagnetic interactions among the diamagnetic scale-forming components in water dispersions. First of all, the interaction energy between the magnetic field and the ion is much smaller than the thermal energy, kT, therefore, it is negligible in comparison to the effects due to molecular collisions. This means that the experimentally observed remaining magnetic effect, the so-called “memory effect”, cannot be explained in this way.

A number of hypotheses about the MWT mechanism exist ([18] and [19]). One possibility is that the magnetic field induces a deformation of the diffuse layer surrounding the dispersed particles in the water ([20] and [21]). This deformation leads to a temporary decrease in the repulsion barrier and, consequently, to an increased crystallization. In the magnetic field, the shifted counter-ions will remain absorbed in the Stern layer for a longer time; therefore, the magnetic memory can be explained.

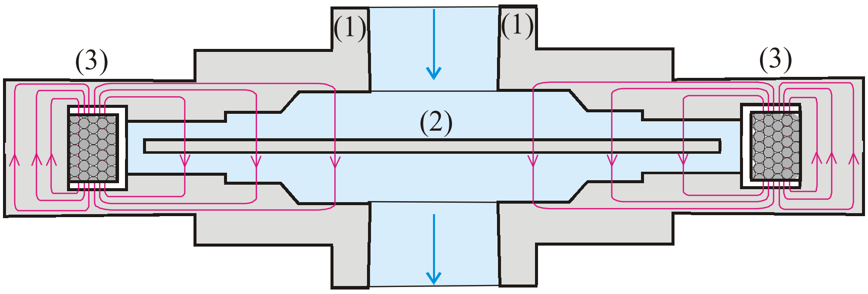
The anti-scale effect is possibly caused by accelerated or modified crystallization of scale-forming components in the bulk of the water, which consequently reduces the precipitation on the equipment surfaces. Therefore, from the point of view of adding fine dispersed powder of calcium carbonate, MWT is similar to the new Geno-K4 device.

2 PREIZKUSI

V polnilnici mineralne vode Radenska v Sloveniji se MOV uporablja za nadzor vodnega kamna v toplotnih menjalnikih in stroju za pomivanje steklenic. Karbonatne obloge na testnih ploščicah iz različnih materialov so bile proučevane s tržno magnetno napravo EM IV, prikazano na sliki 1.

2 EXPERIMENTS

At the mineral-water company Radenska, in Slovenia, MWT is extensively used for scale control in heat exchangers and bottle-cleaning machines. The carbonate incrustations on test plates of various materials were investigated for the commercial magnetic device EM IV, presented in Fig. 1.



Sl. 1. *Naprava EM IV za magnetno obdelavo vode*
Fig. 1. *EM IV device for magnetic water treatment*

Okrov naprave (1) je iz litega železa in notranja plošča (2) je jeklena. Magnetno polje povzroča solenoid (3), nameščen znotraj okrova. Voda vstopa na vrhu naprave in prečno obliva notranjo ploščo ter se nato spodaj vrača k izhodu na dnu. Solenoid ustvarja 100 Hz utripajoče magnetno polje povprečne gostote 0,05 T.

Postopek pomivanja steklenic obsega neprekinjeno nameščanje steklenic v tekoči trak in obdelavo le teh z več zaporednimi fazami:

- vodna kopel s temperaturo do 34 °C,
- obdelava z natrijevim hidroksidom - vroča kopel do 65 °C, obrizgavanje do 90 °C in vroča kopel do 70 °C,
- vmesno spiranje s toplo vodo do 50 °C,
- obrizgavanje s toplo fosforno kislino do 50 °C,
- spiranje z vodo – najprej s toplo vodo do 45 °C in nato s postopnim ohlajanjem steklenic do končnega spiranja s svežo hladno vodo.

Napajalna voda je lokalna podtalnica z naslednjimi podatki: temperatura 12 °C, *pH* = 7,4, električna prevodnost 0,047 S/m, stopnja nasičenja s kisikom 32% in celotna trdota 13,5 nemških trdotnih stopinj. Ionska sestava je podana v preglednici 1.

V prehodnem območju med lužno in kislinsko obdelavo postane voda prenasičena, ker je

The housing of the device (1) is an iron casting and the inner plate (2) is made from steel. The magnetic field is induced by a solenoid (3), placed inside the housing. Water enters through the top of the device, flows radially over the inner plate and then returns to the bottom output. The solenoid produces a 100-Hz pulsating magnetic field with an average field density of about 0.05 T.

The bottle-cleaning process consists of continuously inserting bottles into a conveyor and treating them in several successive steps:

- water bath with temperature up to 35 °C,
- treatment with natrium hydroxide – hot bath up to 65 °C, high-pressure splashing up to 90 °C and then hot bath up to 70 °C,
- intermediate washing with warm water up to 50 °C,
- splashing with warm phosphoric acid up to 50 °C,
- splashing with water – first with warm water up to 45 °C, then with successive cooling of the bottles until the final splashing with cold fresh water.

The supplied water is local ground water with following data: temperature 12 °C, *pH* = 7.4, electric conductivity 0.047 S/m, oxygen saturation degree 32% and total hardness 13.5 German hardness degrees. The ion composition is given in Table 1.

In the intermediate zone between the alkaline and acidic treatments the water gets oversaturated

Preglednica 1. *Sestava napajalne vode*
Table 1. *The supplied water composition*

Kationi Cations	(g/m^3)
Ca^{+2}	62
Mg^{+2}	21
Na^{+}	8
K^{+}	4,5

Anioni Anions	(g/m^3)
Cl^{-}	26
SO_4^{-2}	24
NO_3^{-}	22

Mikroelementi Microelements	(mg/m^3)
Fe^{+2}	50
Zn^{+2}	20
Mn^{+2}	8
Cu^{+2}	1,6

med postopkom spiranja njena temperatura 60 °C in $pH = 9$. To vodi v obilno izločanje vodnega kamna.

Magnetna naprava je bila vgrajena na dovodno cev, da bi se preverila alternativna rešitev za nadzor vodnega kamna. Preizkusi so bili izvedeni v dvomesečnih zagonih z magnetno napravo in brez nje v stalnih obratovalnih razmerah. Testne ploščice so bile nameščene v pomivalni stroj, da bi se obloge analizirale utežno in kvalitativno. Vzorci so bili morfološko in kemično razpoznani z elektronskim vrstičnim mikroskopom JEOL JSM-840A, ki je dodatno opremljen z mikrostrukturnim programom Digiscan FDC.

Za testne ploščice so bili izbrani trije materiali:

- nerjavno jeklo (11X5CRNI189) za simulacijo pogojev izločanja na stenah pomivalnega stroja ter na tekočem traku,
- steklo za simulacijo pogojev izločanja na steklenicah in
- jeklo (FE 360B) za razširitev opazovanj še na korozijske ostanke.

because its temperature is 60 °C and $pH = 9$ during the washing process. This leads to abundant scale precipitation.

The magnetic device was inserted into the water input pipeline to test it as an alternative solution for scale control. Experiments were performed in two-month runs with and without MWT under constant operational conditions. Test plates were inserted into the washing machine to analyze the precipitate gravimetrically and qualitatively. Samples were morphologically and chemically identified by JEOL JSM-840A scanning electron microscope (SEM) including the micro-structural program Digiscan FDC.

Three different test plate materials were chosen:

- stainless steel (11X5CRNI189) to simulate the precipitation conditions on the heat exchanger, washing machine walls and conveyor,
- glass to simulate the precipitation conditions on the bottles,
- steel (FE 360B) to extend the research on corrosion products.

3 REZULTATI IN RAZPRAVA

Značilno enomesečno izločanje vodnega kamna je pri hitrosti toka vode 160 l/min znašalo 0,25g/cm^2. Relativne količine, pri katerih so kot referenca vzete steklene ploščice v neobdelani vodi, so podane v preglednici 2. Povprečna relativna količina oblog na vseh testnih ploščicah je bila v primeru MOV približno za 20% manjša kakor v primeru neobdelane vode.

Kakovostna analiza je pokazala, da MOV ni bistveno spremenila sestave vodnega kamna, ampak je vplivala na njegovo morfologijo. Izjema so bili vzorci na navadnem jeklu, pri katerih je MOV povečala delež železovih hidroksidov. Slika 1 prikazuje primerjavo posnetkov z vrstičnim elektronskim mikroskopom med vzorci iz obdelane in neobdelane vode.

Prstom podobne ploščice, ki so razvidne na posnetku vzorca na jeklu z MOV, so kristali lepidokrokita (γ – FeOOH).

V primerih brez MOV so nastajale bolj trde in adhezivne obloge. Takšen vodni kamen lahko zadržuje natrijev hidroksid, ki delno nevtralizira kislino v naslednji fazi obdelave. To povečuje porabo kemikalij in zahteva pogosto čiščenje stroja. MOV je

3 RESULTS AND DISCUSSION

The typical scale deposition for one month at a water flow rate of 160 l/min was 0.25 g/cm^2. The relative amounts, where glass plates in untreated water are taken as a reference, are presented in Table 2. The average relative amount of deposit on all the test plates was about 20% lower in the case of MWT than in the case of untreated water.

A qualitative analysis showed that MWT did not affect much the chemical composition of the scale, but it did have an influence on the morphology. The exceptions were the samples on steel, where MWT raised the portion of iron hydroxides. Figure 1 shows the comparison between the SEM micrographs of samples from treated and untreated water.

The finger-like plates, which can be seen in the micrgrph of the sample on steel with MWT, are crystals of lepidocrocite (γ – FeOOH).

In the cases without MWT, more compact and adhesive linings were formed. Such scale is able to retain natrium hydroxide, partially neutralizing the acid in the following phase. This raises the consumption of chemicals and demands frequent cleaning of the ma-

Preglednica 2. *Relativne količine oblog na testnih ploščah*
Table 2. *Relative amounts of deposits on test plates*

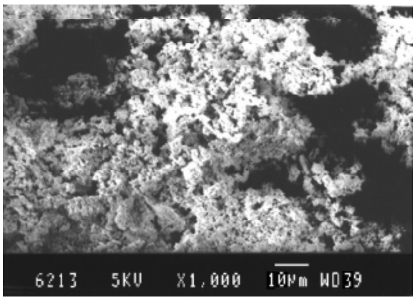
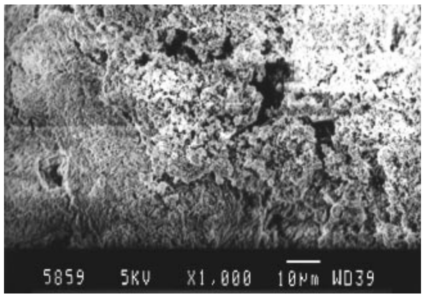
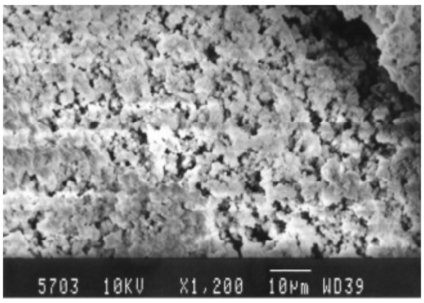
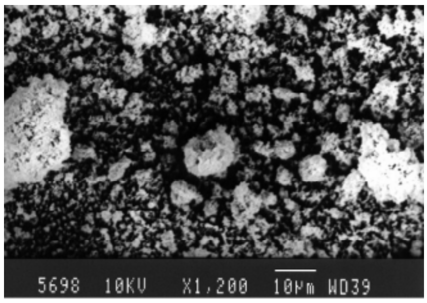
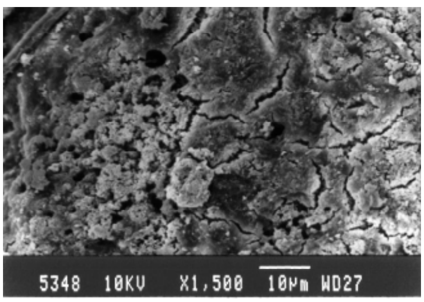
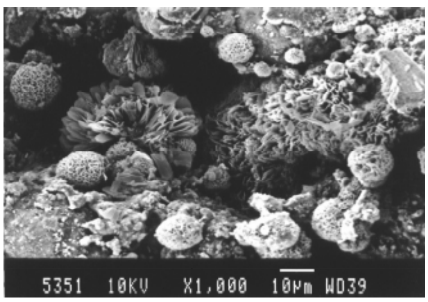
Material testne ploščice Material of test plate	Steklo Glass	Nerjavno jeklo Stainless steel	Jeklo Steel
neobdelana voda untreated water	1,00	1,13	2,15
MOV MWT	0,83	0,92	1,81

povzročala neadhezivne, praškaste obloge, ki se zlahka odstranijo, in se lahko pomivalni stroj vzdržuje v bolj čistem stanju.

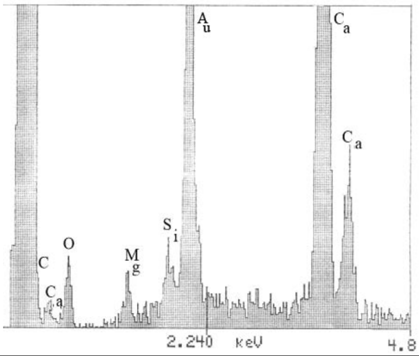
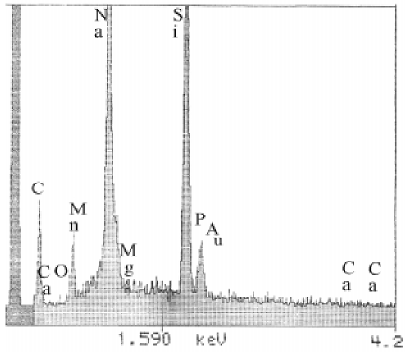
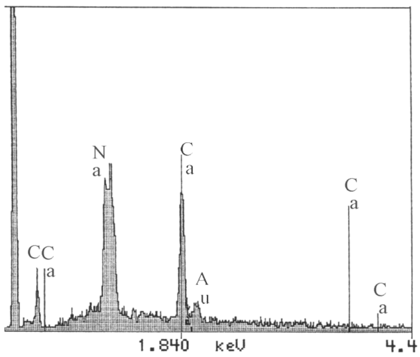
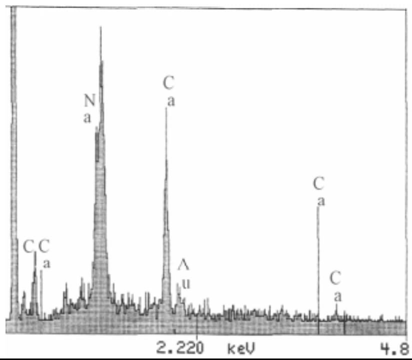
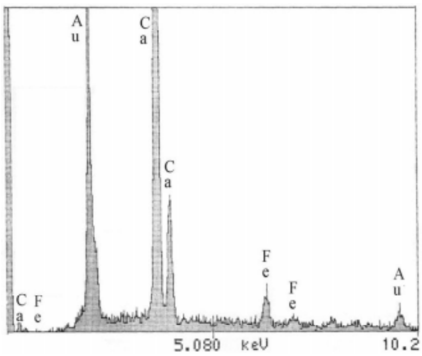
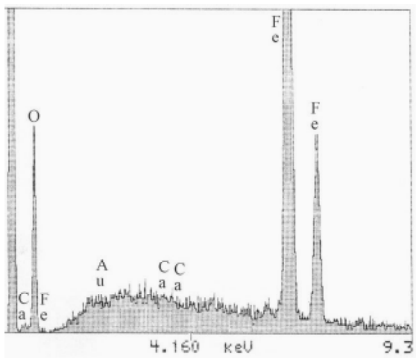
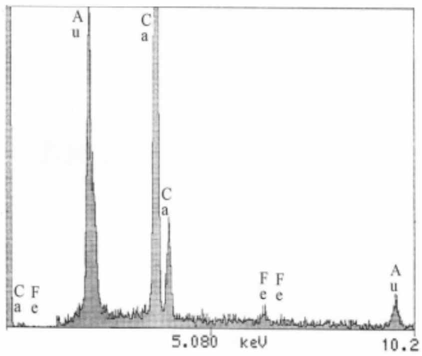
Rentgenski spektri vzorcev so prikazani na sliki 2. Spektri podajajo sestavo vzorcev le kvalitativno. Na podlagah iz stekla in nerjavnega jekla prevladuje kalcijev karbonat, na korozivnem jeklu pa je v velikem deležu tudi železov hidroksid. Natrij je prisoten v spektrih zaradi natrijevega hidroksida in zlato, zato ker so bili vzorci prevlečeni z njim za potrebe elektronskega mikroskopiranja.

chine. The MWT caused non-adhesive and powder-like linings, which are easier to remove and therefore the washing machine can be maintained in a cleaner condition.

X–ray spectra of the samples are presented in Fig. 2. The spectra identify the compositions of the samples only qualitatively. The main component on the glass and stainless-steel surfaces is calcium carbonate; while on the corrosive steel a high proportion of iron hydroxide is also present. Natrium is present in the spectra because of the natrium hydroxide, and gold is present because the samples were coated with it for the electron microscopy requirements.

Testna ploščica Test plate	brez MOV without MWT	z MOV with MWT
steklo glass	 *kalcijev karbonat* *calcium carbonate*	 *kalcijev karbonat in silikati* *calcium carbonate and silicates*
nerjavno jeklo stainless steel	 *kalcijev karbonat* *calcium carbonate*	 *kalcijev karbonat* *calcium carbonate*
jeklo steel	 *kalcijev karbonat* *z nekaj železa* *calcium carbonate* *with some iron*	 *železov hidroksid* *z nekaj kalcijevega karbonata* *iron hydroxide* *with some calcium carbonate*

Sl. 2 *Fotografije vzorcev z vrstičnim elektronskim mikroskopom*
Fig. 2 *SEM photographs of samples*

Testna ploščica Test plate	brez MOV without MWT	z MOV with MWT
steklo glass		
nerjavno jeklo stainless steel		
jeklo steel		*radialno rastoče plošče lipidokrokita* *radial growing plates of lepidocrocite* *manjši okrogli delci* *smaller spherical particles*

Sl. 3 *Rentgenski spektri vzorcev (vodoravna os – energija sevanih žarkov X, navpična os – intenziteta žarkov X)*
Fig. 3 *X – ray spectra of samples (horizontal-axis – X-ray emission energy, vertical-axis – X-ray intensity)*

4 SKLEP

Sklepamo, da je bila magnetna obdelava vode učinkovita s pozitivnim vplivom za nadzor vodnega kamna pri vseh uporabljenih testnih materialih (steklo, navadno in nerjavno jeklo) z zmanjšanimi količinami oblog in mehkejšo strukturo. Z uporabo magnetne naprave za pripravo izpiralne vode v pomivalnih strojih za steklenice se lahko vodni kamen bolje nadzira.

Tudi v primeru korozivnega testnega materiala je bila obloga manj kompaktna, vendar se je povečala količina železovih hidroksidov, kar je v skladu z magnetno pospešenim oksidacijskim postopkom komponent, ki vsebujejo železo [22].

V primeru steklenih ploščic lahko iz primerjave rentgenskih spektrov vidimo, da je delež silikatov v oblogah iz magnetno obdelane vode razmeroma večji, kar se ujema z merilnimi rezultati drugih avtorjev [23].

4 CONCLUSION

We have established that magnetic water treatment is effective, with a positive influence on scale control for all the used test materials (glass, steel and stainless steel), with smaller amounts of scale and a softer deposit. Using the magnetic device for conditioning the washing water in machines for bottle cleaning, the scale precipitation can be better controlled.

In the case of the corrosive test material the deposit was still less compact, but the amount of iron hydroxides increased as regards the magnetically enhanced oxidation process of iron-containing components [22].

In the case of glass plates, from a comparison of X-ray spectra it is clear that the proportion of silicates was relatively higher in deposits from magnetically treated water, which is in agreement with the experimental results of other authors [23].

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Osebne vesti
Personal Events

Ob 80-letnici zaslužnega profesorja dr. Milana Kaca

V teh dneh praznuje visok življenjski jubilej upokojeni redni profesor matematike in računalništva na Fakulteti za strojništvo v Mariboru, zaslužni profesor dr. Milan Kac. Z velikim spoštovanjem in naklonjenostjo se priljubljenega profesorja spominjajo številne generacije študentov, ki so se na študiju strojništva in elektrotehnike v Mariboru zvrstile od samih začetkov mariborskega višjega in visokega šolstva v začetku šestdesetih pa vse do sredine devetdesetih let minulega stoletja. Profesor Kac je med študenti slovel po svojih odličnih (in zato dobro obiskanih) predavanjih, na katerih je zahtevno matematično ali računalniško snov znal podati natančno, pa vendar tudi zanimivo in zelo nazorno. Poslušalcev na njegovih predavanjih ni nikoli manjkalo. Profesor Kac je bil v mariborskem visokem šolstvu tudi prvi pri uvajanju uporabe računalnikov v pedagoško-raziskovalno delo. Leta 1969 je postal tudi prvi predstojnik računalniškega centra takratne Višje tehniške šole. Svoje pedagoško in raziskovalno delo je nadgradil še kot avtor številnih učbenikov s področja matematike in računalništva, po katerih so enako radi segali študentje, raziskovalci in inženirji. Zaradi organizacijskih sposobnosti in širokega obzorja je pogosto kot član ali predsednik sodeloval v različnih strokovnih organih in odborih od lokalne pa do republiške in zvezne ravni. Med drugim se ga sodelavci fakultete spomnimo tudi kot uspešnega in priljubljenega predstojnika Oddelka za strojništvo v drugi polovici osemdesetih let. Za vse doseženo mu je Univerza v Mariboru leta 1992 podelila naziv zaslužnega profesorja.

Tako so talent, marljivost in vztrajnost od otroških let v predvojni Slovenski Bistrici, težkih medvojnih let mladeniča iz zavedne Kacove družine, izseljene že leta 1941, zanesenjaštva do odrekanja polnih povojnih let izoblikovala človeka, ki se lahko s ponosom ozre na bogato bero svojih dosežkov. Vsi ti uspehi pa profesorja Kaca niso prevzeli. V medsebojnih stikih je profesor Kac tako do študentov kakor tudi do svojih kolegov ostal skromen, izjemno prijazen in korekten. Vse ljudi okrog sebe je navduševal s svojo uglajenostjo, intelektualno širino in iskrivim humorjem. In prav takšen je priljubljeni profesor in kolega tudi sedaj. Zato mu ob 80-letnici njegovi študentje, sodelavci in prijatelji kličemo: Hvala za vse in še na mnoga leta!

prof.dr. Andrej Polajnar

Zaslužni profesor dr. Želimir Dobovišek - 80-letnik

Profesorja dr. Želimira Dobovišeka sem spoznal najprej kot predstojnika Inštituta za energetsko strojništvo. To so bila moja prva leta zaposlitve na fakulteti, ko sem kot mlad asistent pedagoško in raziskovalno deloval na oddelku za strojništvo. Iz tega zgolj službenega odnosa sem si ustvaril le zelo površno in skopo podobo, zoženo v glavnem na predstavi, da je prof. Dobovišek velik strokovnjak za energetske stroje, zlasti za motorje z notranjim zgorevanjem, da je izredno marljiv, natančen in strog do sebe in svojih bližnjih sodelavcev. Šele mnogo let kasneje, ko sem od njega prevzel vodenje Inštituta za energetsko, procesno in okoljsko inženirstvo, po njegovi upokojitvi, sem ga spoznal kot univerzitetnega profesorja v pravem pomenu besede, ki zna izredno uspešno povezovati človečnost in strokovnost z veliko mero pozitivne energije. Primerna razdalja do dnevnih operativnih problemov na fakulteti mu daje možnost biti strokovni starešina, kolega in prijatelj Inštituta za energetsko, procesno in okoljsko inženirstvo.

Profesor dr. Želimir Dobovišek se je rodil 18. avgusta 1924 v Celju, kjer je končal osnovno šolo in gimnazijo. V juniju 1941 je bila vsa družina izseljena v Srbijo v Paračin, gimnazijo je zato končal v Kruševcu. Leta 1947 je končal vojaško letalsko tehniško akademjo v Rigi. Od leta 1947 do 1953 je kot vojaški štipendist študiral strojništvo v Ljubljani, kjer je diplomiral in bil nato štiri mesece na praksi v Dortmundu. Od junija 1954 do septembra 1965 je bil zaposlen v letalskem tehničnem zavodu Orel v Rajlovcu pri Sarajevu, kjer je bila njegova dejavnost povezana z letalskimi batnimi motorji in reaktivnimi potisniki, uporabo kemičnih in galvanskih prevlek na strojnih delih in orodjih. Magistriral je leta 1968 na Univerzi države Wisconsin v Madisonu, doktoriral pa leta 1972 na Univerzi v Sarajevu. Od leta 1960 do septembra leta 1980 je bil zaposlen na Strojni fakulteti v Sarajevu, najprej kot asistent, nato docent, izredni in redni profesor. Od septembra 1976 je sodeloval na Visoki tehniški šoli v Mariboru, kjer je bil leta 1980 zaposlen kot redni učitelj. Na tej, tedaj Tehniški fakulteti, je deloval na Oddelku za strojništvo do upokojitve v letu 1994.

Med svojim 34-letnim fakultetnim delom je vzgojil vrsto diplomiranih inženirjev in magistrov ter bil mentor in komentor doktorjem znanosti s področja motoristike in energetike v Sarajevu in Mariboru. V obdobju 1984 do 1988 je bil tudi gostujoči profesor na Oregonski državni univerzi v Portlandu.

Prof. dr. Želimir Dobovišek je prišel na univerzo iz industrije. Prav zaradi tega njegova razvojno-raziskovalna dejavnost (ki je potekala na Zavodu za motorje in vozila Strojne fakultete v Sarajevu, na Tehniški fakulteti v Mariboru pa v Laboratoriju za termoenergetske stroje, tehniške meritve in motorna vozila) obsega v veliki meri uporabno problematiko, ki je bila ves čas povezana predvsem s problemi motorne industrije.

Prof. dr. Želimir Dobovišek je vodil ali pa sodeloval pri mnogih projektih ali raziskavah razvojnega in raziskovalnega značaja, ki jih je financirala v Sarajevu republiška skupnost za raziskova1no dejavnost BiH, v Mariboru pa Raziskovalna skupnost Slovenije (sedaj MŠZŠ) in nekatera podjetja v obliki konkretnih pogodb.

Prof. dr. Želimir Dobovišek je vložil veliko truda skupaj s sodelavci, zlasti s prof. dr. Antonom Černejem, za ustanovitev in opremljanje laboratorijev. Pri nabavi potrebne laboratorijske opreme je vedno našel razumevanje v industriji, ki je zlasti na TF Maribor finančno omogočila opremljanje laboratorijev.

Na podlagi izjemnih in pomembnih dosežkov profesorja dr. Željka Doboviška na področju visokošolskega izobraževanja, znanstveno-raziskovalne dejavnosti na Univerzi v Mariboru ter prenosu znanja v gospodarstvo mu je Univerza v Mariboru na predlog Fakultete za strojništvo v letu 1995 podelila naziv zaslužni profesor.

Ob 80-1etnici želimo jubilantu, strokovni starešini in prijatelju Inštituta za energetsko, procesno in okoljsko inženirstvo, še veliko osebnega in strokovnega zadovoljstva.

prof. dr. Leopold Škerget

Doktorati, magisteriji, diplome

DOKTORATI

Na Fakulteti za strojništvo Univerze v Mariboru sta z uspehom zagovarjala svoji doktorski disertaciji:

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dne 19. oktobra 2004: **mag. Nataša Vujica Herzog**, z naslovom: "Razvoj sistema kazalnikov za vrednotenje prenove proizvodnih procesov".

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

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dne 12. oktobra 2004: **Simona Teodorović**, z naslovom: "Razbarvanje barvalnih kopeli z glivami in njihovimi ekstracelularnimi encimi";

dne 14. oktobra 2004: **Drago Hribernik**, z naslovom: "Primerjava prilagodljivih napajalnih hidravličnih sistemov";

dne 22. oktobra 2004: **Dejan Lorber**, z naslovom: "Razvoj sistema vzdrževanja anodnih nosil".

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Navodila avtorjem

Instructions for Authors

Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- 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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Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
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- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

Oblika članka

Besedilo naj bo pisano na listih formata A4, z dvojnim presledkom med vrstami in s 3 cm širokim robom, da je dovolj prostora za popravke lektorjev. Najbolje je, da pripravite besedilo v urejevalniku Microsoft Word. Hkrati dostavite odtis članka na papirju, vključno z vsemi slikami in preglednicami ter identično kopijo v elektronski obliki.

Prosimo, da ne uporabljate urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata. V urejevalniku LaTeX oblikujte grafe, preglednice in enačbe in jih stiskajte na kakovostnem laserskem tiskalniku, da jih bomo lahko presneli.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v slovenskem jeziku, npr. časovno spremenljiva geometrija (ČSG).

Papers submitted for publication should comprise:
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Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 typed pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

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The paper should be written in the following format:
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- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

The layout of the text

Texts should be written in A4 format, with double spacing and margins of 3 cm to provide editors with space to write in their corrections. Microsoft Word for Windows is the preferred format for submission. One hard copy, including all figures, tables and illustrations and an identical electronic version of the manuscript must be submitted simultaneously.

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Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Units and abbreviations

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.).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Za pripravo diagramov in risb priporočamo CDR format (CorelDraw), saj so slike v njem vektorske in jih lahko pri končni obdelavi preprosto povečujemo ali pomanjšujemo.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Za vse slike po fotografskih posnetkih je treba priložiti izvirne fotografije ali kakovostno narejen posnetek. V izjemnih primerih so lahko slike tudi barvne.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controler for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.

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Podatki o avtorjih

Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove, številke telefona in faksa ter naslove elektronske pošte.

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Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

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[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.

[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

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