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Načrtovanje in optimiranje avtomatiziranih regalnih skladiščnih sistemov

The Design and Optimization of Automated Storage and Retrieval Systems

Tone Lerher - Iztok Potrč
(Fakulteta za strojništvo, Maribor)

V predloženem prispevku je predstavljen model za načrtovanje in optimiranje avtomatiziranih regalnih skladiščnih sistemov za delo v enem in več hodnikih. Zaradi zahtevanega pogoja o tehnično zelo zmogljivem in stroškovno sprejemljivem skladiščnem sistemu, predstavljajo namensko funkcijo v računskem modelu načrtovanja najmanjši skupni stroški. Namenska funkcija združuje elemente statičnega in dinamičnega dela skladiščnega sistema ter investicijske in obratovalne stroške skladišča. Zaradi nelinearnosti, večparametričnosti in diskretne oblike namenske funkcije smo za optimizacijo projektnih spremenljivk uporabili metodo genetskih algoritmov. Prikazana je analiza izbranega regalnega skladiščnega sistema, pri dveh različnih sistemih regalnega dvigala za delo v enem in več hodnikih. Ugotovili smo, da so stroškovno optimalne rešitve skladišč nahajajo v področju visokih in dolgih skladiščnih regalih, kar vpliva na zmanjšanje števila regalnih hodnikov in števila regalnih dvigal ter skupno na celotne stroške skladišča. Rezultati analize so pokazali, da je izbira posameznega sistema regalnega dvigala, za delo v enem ali več hodnikih, izrazito odvisna od zahtevane pretočne zmogljivosti skladišča. Predloženi model predstavlja uporabno in prilagodljivo orodje za načrtovanje skladiščnih sistemov ter izbiro posameznega sistema regalnega dvigala za delo v enem ali več hodnikih v postopku načrtovanja regalnih skladiščnih sistemov.
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(Ključne besede: sistemi skladiščni, skladišča avtomatizirana, načrtovanje, optimiranje)

In this paper a model for the design and optimization of an automated storage-and-retrieval system for single- and multi-aisle systems is presented. Because of the required conditions, i.e., that the warehouse should be technically highly efficient and that it should be designed at reasonable expense, the objective function is represented by minimum total costs. The objective function combines elements of the static and dynamic parts of the warehouse, the investment, and the operational costs of the warehouse. Due to the non-linear, multi-variable and discrete shape of the objective function, the method of genetics algorithms was used for the optimization process of the decision variables. An analysis of the chosen automated warehouse with two types of the single- and multi-aisle automated storage and retrieval systems is presented. It was established that the optimum solutions regarding total costs of the warehouse can be found in the area of high and long storage racks. Consequently, this influences the reduction of the number of picking aisles and the number of storage and retrieval machines. The results of the analysis show that the choice of a type of single- or multi-aisle system depends crucially on the required throughput capacity of the warehouse. The presented model is a very useful and flexible tool for choosing a particular type of single- or multi-aisle system when designing automated warehousing systems.
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(Keywords: storage systems, automated warehousing systems, design, optimization)

0 UVOD

Skladišča s svojim osnovnim namenom so nujno potrebna za zvezno in optimalno delovanje tako proizvodnih kakor tudi oskrbnih postopkov. Žal

0 INTRODUCTION

The key feature of a warehouse is the absolute necessity for the continuous and optimum operation of the production and distribution processes.

so bili v preteklosti skladiščni, transportni in pretovorni postopki močno zapostavljeni, kar se še dandanes izkazuje v razmeroma nizki stopnji avtomatizacije v primerjavi s stanjem v proizvodnji. Skladišča so potrebna iz številnih razlogov, ki jih lahko razporedimo v naslednje skupine [1]: (*i*) neusklajen dotok in odtok blaga zaradi neustrezne dinamike v proizvodnji in porabi, (*ii*) prevzemanje blaga številnih izdelovalcev za izdelavo kombiniranih odprem, (*iii*) izvedba dnevne preskrbe blaga v proizvodnji in dostavi, (*iv*) izvedba dodatnih dejavnosti, kakor so pakiranje, končna montaža itn. Skladišča predstavljajo blagovno-tehnični del gospodarjenja z blagom ter glede na zapostavljenost v preteklosti predstavljajo priložnost pri zmanjšanju skupnih stroškov pri načrtovanju in obratovanju skladišča.

V prispevku so predstavljena avtomatizirana skladišča, ki jih imenujejo tudi avtomatizirani regalni skladiščni sistemi (ARSS). V zadnjih desetletjih se izdatno povečuje delež ARSS, ki omogočajo doseganje večjih zmogljivosti v primerjavi z običajnimi skladišči. Razmišljanja o uporabi ARSS segajo že desetletja nazaj, ko je leta 1962 podjetje Demag izdelalo prvi ARSS [2]. Omenjeni ARSS je bilo prvo visoko regalno skladišče višine 20 metrov in je zaznamoval novo obdobje v razvoju transportno-skladiščne tehnike. ARSS so v osnovi sestavljeni iz skladiščnih regalov (SR), regalnega dvigala (RD), zveznih transporterjev, vhodne in izhodne (V/I) lokacije skladišča in računalniškega sistema za vodenje in organizacijo skladiščne dejavnosti. Glavne prednosti v primerjavi z običajnimi sistemi skladišč se izkazujejo z: (*i*) veliko pretočno zmogljivostjo skladišča *Pf*, (*ii*) velikim izkoristkom zalogovnega skladišča *Q*, (*iii*) veliko zanesljivostjo in večjim nadzorom skladiščnega postopka, (*iv*) izboljšanimi varnostnimi razmerami in (*v*) zmanjšanjem poškodb ter izgube blaga. Zaradi njihove tehnološke popolnosti in popolne avtomatizacije sistema, zahtevajo velike investicijske stroške. Prav tako so ARSS, pri katerih RD oskrbuje samo pripadajoč regalni hodnik, neprilagodljivi glede na morebitno spremembo pretočne zmogljivosti skladišča.

Uspešnost izvedbe ARSS je odvisna predvsem od preudarnega in učinkovitega postopka načrtovanja, da bo izpolnjen glavni pogoj o tehnično zelo zmogljivem sistemu, ob predpostavki o optimalnih investicijskih in obratovalnih stroških skladišča. Zmogljivost ARSS je v največji meri odvisna od zmogljivosti transportno-skladiščnega

Unfortunately, in the past, warehousing, transport systems and transferring processes were neglected, and this nowadays shows itself in a relatively low degree of automation in comparison with the production process. Warehouses are needed for the following reasons [1]: (*i*) an imbalance in the flow and outflow of goods due to the inappropriate dynamics of production and consumption, (*ii*) taking goods from numerous producers for the production of combined shipments, (*iii*) the realization of the daily supply of goods in the production and distribution, (*iv*) the realization of additional activities, such as packaging, final assembly, etc. Warehouses represent a technical part of dealing with goods. Since they were neglected in the past, they represent an opportunity to reduce total costs relating to the design and operation processes.

In this study, automated warehouses, also named automated storage and retrieval systems (ASRS), are presented. In the past few decades, the share of ASRS, which in comparison with conventional warehouses provides a higher level of technological efficiency, has increased. The use of the ASRS already received consideration decades ago, when in 1962 the company Demag created the first ASAR [2]. The aforementioned ASRS was the first high-bay warehouse measuring 20 meters in height, which marked the beginning of a new era in the development of material handling equipment in Europe. The ASRS consists of storage racks (SRs), a storage and retrieval machine (SR machine), accumulating conveyors, an input and output location (I/O location) and a computer system for managing and organizing the activities in the warehouse. In comparison with conventional warehousing systems, the key advantages of the ASRS are: (*i*) high throughput capacity *Pf*, (*ii*) high warehouse volume *Q* (rack capacity), (*iii*) high reliability and better control of the warehousing process, (*iv*) improved safety conditions and (*v*) a decrease in the amount of damage and the loss of goods. Due to advanced technology and the complete automation of the system, the ASRS demands extensive investment. Additionally, those ASRSs where the SR machine operates only in the single picking aisle are rather inflexible as far as a possible change of the throughput capacity of the warehouse is concerned.

The success of the ASRS largely depends on a careful and efficient design process, whereby the basic condition that the system is technically highly efficient must be fulfilled, along with the condition of optimum investment and the operational costs of the warehouse. The efficiency of the ASRS mainly depends on the efficiency of the material sredstva in vrste transportno-skladiščne enote TSE. V tipičnem ARSS samostojno RD oskrbuje samo pripadajoči regalni hodnik, kar imenujemo *sistem* RD *za delo v enem hodniku*. V primeru zahteve po manjši pretočni zmogljivosti in večji prilagodljivosti skladišča, uporabimo *sistem* RD *za delo v več hodnikih* ([4] do [6]). V omenjenem sistemu RD z uporabo pomičnega vozička, ki zagotavlja vožnjo v prečnem hodniku, oskrbuje več regalnih hodnikov. Ker zahteva RD tudi do 40 % [3] vrednosti celotne investicije ARSS, je izbira *sistema* RD *za delo v enem in več hodnikih* eno izmed ključnih vprašanj pri načrtovanju skladišč. Zmogljivost ARSS je odvisna tudi od geometrijske oblike SR in ustrezne skladiščne strategije.

Načrtovanje in optimiranje skladiščnih sistemov (ne nujno ARSS) so v preteklosti obravnavali številni avtorji. Ena izmed prvih objav s področja optimizacije skladišča je delo *Basana in sodelavcev* [7], ki so analizirali optimalne izmere skladišča pri izbrani zalogovni velikosti skladišča v odvisnosti od različnih skladiščnih strategij. *Karasawa in sodelavci* [8] so predstavili model za načrtovanje ARSS. V njihovem delu je namenska funkcija definirana kot nelinearna in večparametrična ter se sestoji iz treh glavnih spremenljivk: (*i*) števila RD, (*ii*) dolžine SR in (*iii*) višine SR; ter nespremenljivih vrednosti: stroškov za nakup zemljišča, stroškov za izdelavo skladiščne zgradbe, stroškov za nakup regalne konstrukcije in stroškov za nakup regalnih dvigal. Pomanjkljivost modela [8] je, da se navezuje samo na *sistem* RD *za delo v enem hodniku* in skladiščno opravilo enojnega delovnega kroga. *Ashayeri in sodelavci* [9] so predstavili model načrtovanja ARSS, ki omogoča določitev glavnih vplivnih parametrov pri načrtovanju skladišč. V nasprotju s *Karasawo in sodelavci* [8], so avtorji upoštevali skladiščno opravilo dvojnega delovnega kroga. *Bafna in sodelavci* [10] ter *Perry in sodelavci* [11] so pri načrtovanju skladišč uporabili kombinacijo analitičnega modela in sistema diskretnih numeričnih simulacij. Pri tem so *Perry in sodelavci* [11] uporabili posebno iskalno metodo za določitev optimalnih rešitev ARSS, ki so jo vključili v simulacijski model ARSS. Za merilo zmogljivosti sistema so uporabili pretočno zmogljivost skladišča, v odvisnosti od števila RD ter števila delovnih mest. Načrtovanje skladišč z upoštevanjem vpliva skladiščno-upravljalne strategije sta predstavila *Rosenblatt in Roll* [12]. Pri opisu skupnih stroškov sta upoštevala, da so le-ti odvisni od: (*i*) stroškov za izgradnjo

handling equipment and the type of transport unit load (TUL). In a typical ASAR, the SR machine independently operates only in the single picking aisle, which is called a *single-aisle* ASRS. In the case of smaller throughput capacities and higher flexibility of the warehouse, the *multi-aisle* ASRS is used ([4] to [6]). In the above-mentioned system, the SR machine serves several picking aisles with the help of the aisle transferring vehicle, which ensures driving in the cross aisle. Since the SR machine takes up to 40% [3] of the entire investment of the ASRS, the choice between a *single*- and *multi-aisle* ASRS is of key importance for the design of the automated warehouse. The efficiency of the ASRS is also dependent on the layout of the SR and the appropriate storage strategy.

The design of warehouses (not necessarily ASRS) has been studied in the past by several authors. One of the first publications on the subject of optimizing warehouses is the work of *Basan et al.* [7], who analyzed the optimum dimensions of the warehouse, considering the chosen volume of the warehouse and the dependence on various storage strategies. *Karasawa et al.* [8] presented a design model of the ASRS. In their work, the objective function is defined as non-linear and multi-variable, consisting of three main variables: (*i*) the number of SR machines, (*ii*) the length of the SR and (*iii*) the height of the SR; and also of constant values: the cost of buying the land, the cost of building the warehouse, the cost of buying the SR construction and the cost of buying the SR machines. The main disadvantage of this model [8] is that it refers only to the *single-aisle* ASRS and the warehousing operation of the single command cycle (SC). *Ashayeri et al.* [9] presented a design model of the ASRS that enables the determination of the main influential parameters when designing warehouses. Unlike *Karasawa et al.* [8], they considered the warehousing operation of the dual command cycle (DC). *Bafna et al.* [10] and *Perry et al.* [11] used a combination of an analytical model and a system of discrete event simulations when designing the warehouse. *Perry et al.* [11] used a special search method to determine the optimum solutions for the ASRS, which they have included in the simulation model of the ASRS. As a measure of the efficiency of the system, they used the throughput capacity of the warehouse, with its dependence on the number of SR machines and the number of workplaces. The design of warehouses with regard to the influence of the storage policy was presented by *Rosenblatt* skladiščne zgradbe, (*ii*) stroškov za nakup skladiščne opreme, (*iii*) stroškov, ki nastanejo zaradi preobremenitve skladiščnega sistema (trenutno pomanjkanje skladiščnega prostora) ter (*iv*) stroškov, ki so odvisni od posamezne skladiščno-upravljalne strategije. Poglobljen pregled s področja načrtovanja in upravljanja regalnih skladiščnih sistemov je predstavil *Rouwenhorst s sodelavci* [13], in sicer v obliki metodologije za načrtovanje skladiščnih sistemov. Postopek načrtovanja je predstavljen s strukturiranim postopkom, ki pri sprejemanju odločitev upošteva strateško, taktično in opravilno raven odločanja.

Večina opisanih modelov načrtovanja se navezuje na *sistem* RD *za delo v enem hodniku* ([8] do [11]). Razlika med omenjenimi postopki in modeli se zrcali v stroških, ki so vključeni v namensko funkcijo, v izbiri projektnih spremenljivk ter v uporabi optimizacijskih tehnik. Veliko manj je bilo storjeno za druge tipe skladišč, predvsem za sisteme, pri katerih je število RD (S) manjše ali enako od števila regalnih hodnikov (R) (pogoj $S \leq R$) ([3] in [14]). Zaradi tega smo v model načrtovanja vključili izpopolnjene analitične modele za določitev zmogljivosti *sistema* RD *za delo v več hodnikih* ([2] in [15]).

Zahteva po zelo zmogljivih skladiščih in najmanjših investicijskih in obratovalnih stroških skladišča je bila vodilo pri razvoju in izdelavi namenske funkcije *najmanjši skupni stroški* (*NSS - Min. TC*). Zaradi nelinearnosti, diskretne oblike in večparametričnosti namenske funkcije *NSS* [3] smo za optimizacijo projektnih spremenljivk uporabili *postopek genetskih algoritmov* ([16] in [17]). Rezultat modela načrtovanja regalnih skladiščnih sistemov je določitev tehnično zelo zmogljivega ARSS, ob pogoju o najmanjših investicijskih in obratovalnih stroških skladišča.

1 NAČRTOVANJE AVTOMATIZIRANIH REGALNIH SKLADIŠČNIH SISTEMOV

Model načrtovanja ARSS temelji na strukturiranem postopku [13], pri čemer moramo upoštevati vse parametre, ki vplivajo na zalogovno velikost skladišča Q, pretočno zmogljivost skladišča Pf ter investicijske in obratovalne stroške skladišča. Pri razvoju in izdelavi modela načrtovanja smo upoštevali predloge in priporočila preostalih avtorjev ([3], [8], [12] in [18] do [22]). Na sliki 1 je predstavljen algoritem poteka modela načrtovanja ARSS z

and Roll [12]. When describing total costs, the authors took into account: (*i*) the cost of building the warehouse, (*ii*) the cost of buying the storage equipment, (*iii*) the costs arising from overloading the warehousing system (a temporary shortage of storage space) and (*iv*) the costs that depend on a particular storage policy. An in-depth overview of the area of designing and controlling warehouses was presented by *Rouwenhorst et al.* [13] in the form of the methodology of designing warehousing systems. The design process is presented with a structured approach, which takes into account the strategic, tactical and operational level of decision making.

The majority of described models refer only to the *single-aisle* ASAR ([8] to [11]). The difference between the discussed approaches and models lies in the costs included in the objective function, the decision on considered project variables and the use of optimization techniques. Less has been done for other types of warehouses, especially for systems where the number of SR machines (S) is less than or equal to the number of picking aisles (R) (the condition $S \leq R$) ([3] and [14]). Therefore, our newly proposed analytical travel-time models for the efficiency determination of *multi-aisle* ASRS have been included in our design model ([2] and [15]).

The requirement for a highly efficient warehouse and minimum investment and operational costs of the warehouse was the guidance for how to develop and create the objective function *minimum total costs* (*Min. TC*). Due to the non-linear, discrete and multi-variable objective function *Min. TC* [3], *the method of genetics algorithms* ([16] and [17]) to optimize the project variables have been applied. The result of the model for designing warehouses is the determination of the technologically highly efficient ASRS under the condition that investment and operational costs of the warehouse are minimized.

1 DESIGNING AUTOMATED STORAGE AND RETRIEVAL SYSTEMS

The model for designing the ASRS is based on the structured approach [13], where all the parameters influencing the warehouse volume Q (rack capacity), the throughput capacity Pf, the investment, and the maintenance costs have to be taken into account. When developing and creating the design model, propositions and references from other authors were considered ([3], [8], [12] and [18] to [22]). Figure 1 shows the algorithm of the design model of the naslednjimi glavnimi moduli:

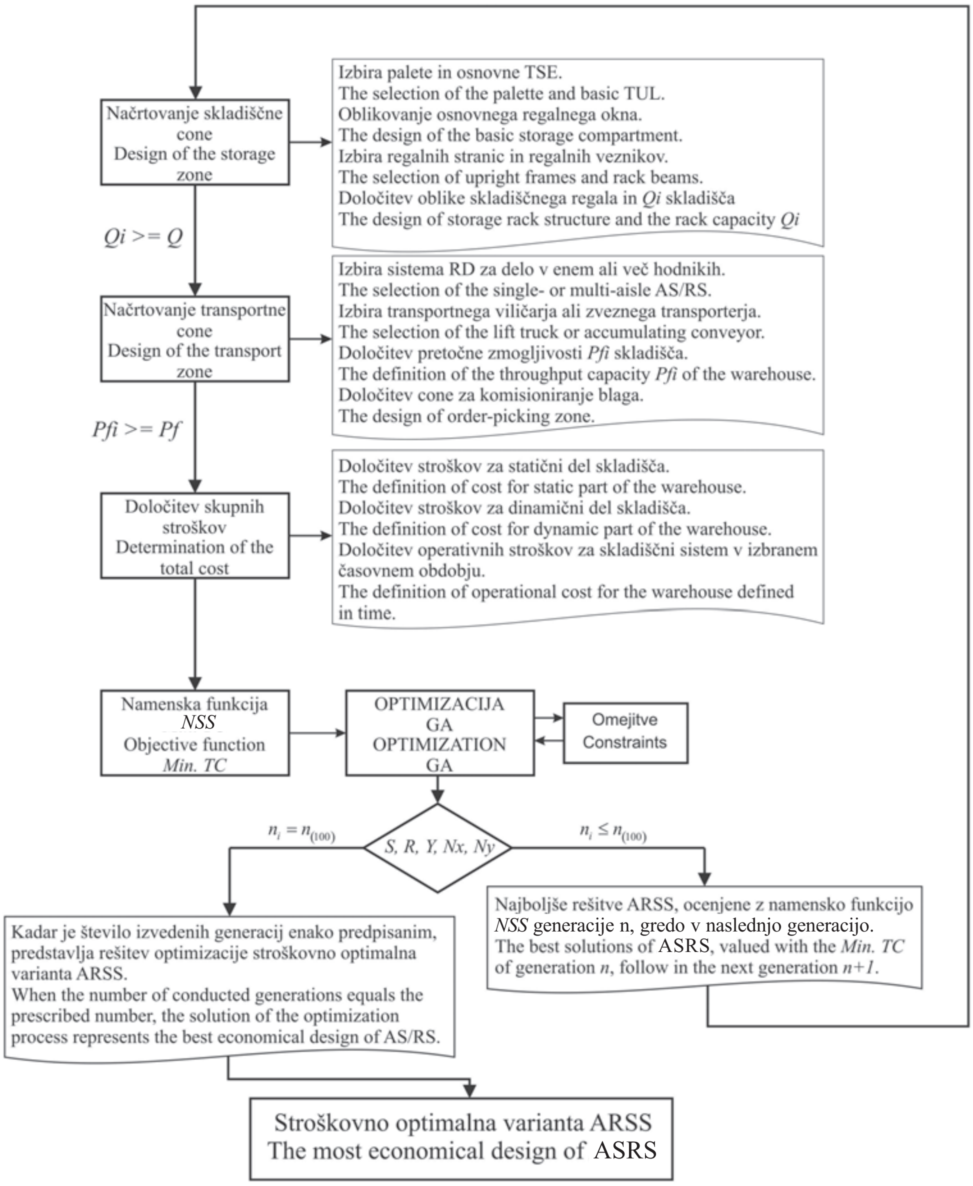
- ***Načrtovanje skladiščne cone***, ki obsega izbiro palete in določitev osnovne transportno-skladiščne enote (TSE). Na podlagi izbrane TSE lahko določimo regalno okno (RO), ki je temelj za postavitev SR. V okviru določitve SR izberemo regalne stranice in regalne veznike, ki skupno sestavljajo regalno konstrukcijo. Vrsto regalne konstrukcije izberemo v odvisnosti od teže TSE ter njihove razporeditve v vodoravni smeri x in v navpični smeri y. Na podlagi zahtevane Q skladišča, geometrijske oblike skladiščnega objekta ter oblike SR, določimo obliko skladiščne cone.
- ***Načrtovanje transportne cone in določitev zmogljivosti skladišča***, ki obsega izbiro osnovnega transportno-skladiščnega sredstva. Izbira se izvede glede na geometrijsko obliko SR in zahtevano *Pf* skladišča. V odvisnosti od zahtevane *Pf* skladišča izbiramo med sistemom: (*i*) RD *za delo v enem hodniku* ter (*ii*) RD *za delo v več hodnikih*. Za premik TSE do skladiščne cone imamo na voljo transportne viličarje ali zvezne transporterje. V odvisnosti od kombinacije transportno-skladiščnih sredstev določimo zmogljivost skladišča in izmere transportne cone.
- ***Določitev skupnih stroškov***, ki se deli na: (*i*) stroške za statični del skladišča, (*ii*) stroške za dinamični del skladišča in (*iii*) stroške za obratovanje skladiščnega sistema v izbranem časovnem obdobju.
- ***Oblikovanje namenske funkcije in optimizacija parametrov namenske funkcije Min. TC***, ki predstavlja kombinacijo projektnih spremenljivk, opravilnih parametrov in skupnih stroškov ARSS ter temelji na optimizacijski *metodi z genetskimi algoritmi* [16] in [17]. Cilj optimizacije *NSS (Min. TC)* je določiti takšno različico ARSS, da bo izpolnjen pogoj o tehnično zelo zmogljivem in stroškovno optimalnem ARSS.

Novost v modelu načrtovanja je uporaba pogoja, da je število RD lahko manjše od števila regalnih hodnikov ($S \leq R$). *Karasawa in sodelavci* [8], *Ashayeri in sodelavci* [9], *Azadivar* [23] so v svojih modelih uporabili pogoj ($S = R$). Glede na dejstvo, da je RD najdražji element v ARSS (približno 40 % celotne investicije [3]), smo v model načrtovanja vključili uporabo RD *s pomičnim vozičkom* [2], ki se navezuje na pogoj, $S \leq R$. Bistvo omenjenega sistema se kaže v veliki prilagodljivosti glede na morebitno povečanje Q in *Pf* skladišča ter v izrazito manjših

ASRS, including the following main modules:

- ***Design of the storage zone***, which includes the choice of the palette and the determination of the basic transport unit load (TUL). On the basis of the chosen TUL, the storage compartment, which forms the basis for setting up the SR, can be determined. When determining the SR, upright frames and rack beams, which together form a storage rack structure, have been chosen. The type of storage-rack structure is selected in accordance with the weight of the TUL and their arrangement in the horizontal x and vertical y directions. On the basis of the required Q of the warehouse, the geometry of the warehouse and the form of SR, and the form of the storage zone, have been determined.
- ***Design of the transport zone and the determination of the efficiency of the warehouse***, which covers the choice of basic material handling equipment. The choice is made according to the geometrical form of the SR and the required *Pf* of the warehouse. Due to the throughput capacity *Pf*, two systems of handling equipment are possible: (*i*) the *single-aisle* system; (*ii*) the *multi-aisle* system. Lift trucks and conveyors are used for manipulating the TUL to the storage-rack zone. Depending on the combination of the material handling equipment and the warehouse volume Q, the dimensions of the transport zone can be determined.
- ***Determination of the total costs***, which is divided into: *(i)* costs of the static part of the warehouse, *(ii)* costs of the dynamic part of the warehouse and *(iii)* costs of operating the warehousing system in a selected time period.
- ***Design of the objective function and optimization of the parameters of the objective function min TC.***, which presents a combination of project variables, operational variables and overall costs of the ASRS, and are based on the optimization *method of genetics algorithms* [16], [17]. The aim of the optimization of the decision variables in *Min. TC* is to define the cost-optimal solution for the ASRS, considering the conditions of technically high and economically optimal solution for the ASRS.

An innovation in the design model is the application of the condition that the number of SR machines is lower than or equal to the number of picking aisles ($S \leq R$). *Karasawa et al.* [8], *Ashayeri et al.* [9], *Azadivar* [23] have applied the condition ($S = R$) to their models. Given that the SR machine is the most expensive element in the ASRS (taking up approximately 40% of the entire investment [3]), the utilization of aisle transferring storage and retrieval machine, which refers to the condition $S \leq R$, has been included in the design model [2]. The essential element of the above-mentioned



Sl. 1. *Algoritem poteka modela načrtovanja ARSS*
Fig. 1. *The algorithm of the design model of the ASRS*

investicijskih stroških v primerjavi s *sistemom* RD *za delo v enem hodniku*. Enak pogoj, $S \leq R$, sta v svojem modelu načrtovanja predstavila *Rosenblatt in Roll* [3] v okviru kombiniranega analitičnega in simulacijskega postopka za načrtovanje ARSS. V njunem modelu je *Pf* skladišča za pogoj, $S \leq R$, določena s simulacijo modela ARSS, ki nato zagotavlja vnos glavnih podatkov v analitično-optimizacijski model načrtovanja. Model načrtovanja [3] tako temelji na interakciji med simulacijami ARSS (diskretni sistem) in analitičnim

system reflects in a high degree of flexibility regarding a possible increase of *Q* and *Pf* of the warehouse and in smaller investment costs in comparison with the *single-aisle* ASRS. The same $S \leq R$ condition was set out by *Rosenblatt and Roll* [3] in their combined analytical and simulation approach to designing the ASRS. In their model, the *Pf* of the warehouse is determined under the $S \leq R$ condition with a simulation of the ASRS, which then ensures the input of the basic relevant information into the analytical optimization design model. The design model [3] is based on the interaction between simulations modelom (uporaba zvezne optimizacije). Bistvena razlika med modelom načrtovanja [3] in v prispevku predstavljenim modelom načrtovanja, je v vpeljavi izpopolnjenih analitičnih modelov pri pogoju, $S \leq R$. V primerjavi z modelom [3] omogoča predstavljen model načrtovanja izdelavo hitrejšega, v celoti dokumentiranega, tehnično zelo zmogljivega in stroškovno optimalnega predloga ARSS. Poleg naštetih prednosti je bistveni del v modelu načrtovanja vpeljava namenske funkcije *NSS* in optimizacija projektnih spremenljivk znotraj namenske funkcije *NSS*. V nadaljevanju bo zato podrobneje predstavljeno oblikovanje namenske funkcije *NSS*.

1.1 Oblikovanje namenske funkcije najmanjši skupni stroški

Namenska funkcija *NSS* je sestavljena iz *projektnih spremenljivk*, opravilnih parametrov in stroškov pri gradnji in obratovanju skladišča. V modelu načrtovanja ARSS smo pri oblikovanju namenske funkcije uporabili naslednje predpostavke in omejitve:

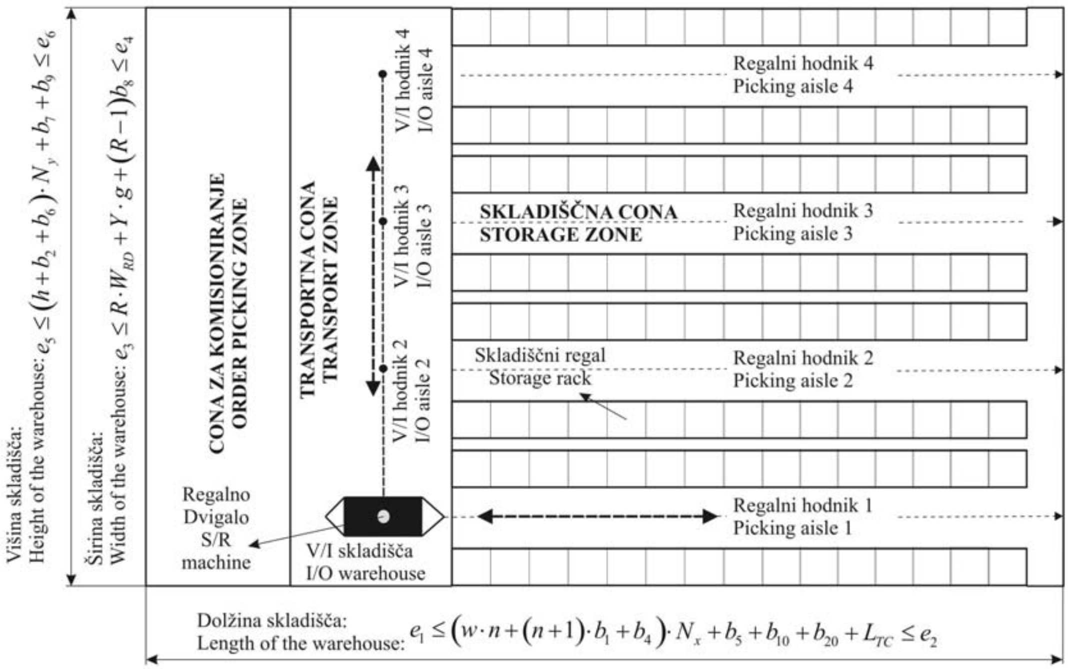
- Regalno skladišče je ponazorjeno s SR, ki so ločeni z regalnimi hodniki, v katerih obratuje RD. Vsakemu regalnemu hodniku pripadata po dva SR, in sicer

of the ASRS (discrete system) and the analytical model (the utilization of the continuous optimization). The essential difference between the design model [3] and the design model presented in this paper is the introduction of newly improved analytical travel-time models under the condition that $S \leq R$. In comparison with the design model [3], the presented model enables the creation of a faster, entirely documented, technical highly efficient and also the most economical design of the ASRS. Along with the enumerated advantages, the essential element in the design model is represented by the introduction of the objective function *Min. TC* and the optimization of decision variables within the *Min. TC*. Consequently, in the following section the design of the objective function *Min. TC* will be discussed in detail.

1.1 Design of the objective function minimum total costs

The objective function *Min. TC* consists of *decision variables*, operational parameters and the costs of building and operating the warehouse. When designing the objective function, the following assumptions, notations and constraints have been applied to the design model of the ASRS:

- The warehouse is divided into SRs, which are separated by picking aisles, in which the SR



Sl. 2. *Tloris avtomatiziranega regalnega skladiščnega sistema*
Fig. 2. *The layout of the automated warehouse*

na vsaki strani regalnega hodnika po eden SR. V/I lokacija skladišča je nameščena na spodnjem, skrajno levem robu regalnega skladišča (sl. 2).

- Število RD S je lahko manjše ali enako R ($S \leq R$). RD *za delo v več hodnikih* potuje v prečnem hodniku na pomičnem vozičku, ki mu omogoča dostop do poljubnega regalnega hodnika i (sl. 2).
- SR je ponazorjen s pravokotno obliko, pri čemer je V/I lokacija skladiščnega regala i definirana v spodnjem levem robu regala (sl. 2).
- RD omogoča opravilo enojnega in dvojnega delovnega kroga, kateremu moramo prišteti še spremenljivi delež časa za vožnjo v prečnem hodniku ($S \leq R$).
- Pri izvedbi skladiščnega opravila dvojnega delovnega kroga ($S \leq R$) smo obravnavali: (*i*) sistem uskladiščenja in odpreme v istem regalnem hodniku i in (*ii*) sistem uskladiščenja in odpreme v dveh naključno izbranih regalnih hodnikih i in j.
- Znane so tehnične značilnosti RD in pomičnega vozička (hitrost v, pospešek in pojemek a) ter dolžina L in višina H skladiščnega regala.
- RD potuje v regalnem hodniku sočasno v vodoravni smeri x in v navpični smeri y.
- Dolžina L in višina H SR sta dovolj veliki, da RD doseže svojo največjo hitrost $v_{max.}$ v vodoravni smeri x in v navpični smeri y.
- Dolžina prečnega hodnika W je dovolj velika, da sklop RD s pomičnim vozičkom doseže največjo hitrost v prečni smeri.
- Uporabili smo strategijo naključnega skladiščenja, kar pomeni, da ima vsaka skladiščna lokacija enako verjetnost, da bo izbrana za opravilo uskladiščenja ali odpreme transportno-skladiščne enote.

S spreminjanjem projektnih spremenljivk: število transportno-skladiščnih sredstev S, število regalnih hodnikov R, število skladiščnih regalov Y, število RO v vodoravni smeri N_x, in število RO v navpični smeri N_y se spreminja vrednost namenske funkcije *NSS* za vsako posamezno različico ARSS. Opravilni parametri se v modelu načrtovanja ARSS navezujejo na oblikovanje skladišča, oblikovanje in določitev zmogljivost ARSS, medtem ko se stroški delijo na stroške za postavitev skladiščne zgradbe, nakupa transportno-skladiščnih sredstev in stroške, ki nastanejo zaradi obratovanja ARSS v izbranem časovnem obdobju. Namenska funkcija *NSS* je

machine operates. To each picking aisle belong two SRs: on each side of the picking aisle there is one SR. The I/O location of the warehouse is set on the low, extreme left-hand side of the warehouse (Fig. 2).

- The number of SR machines S can be lower than or equal to R ($S \leq R$). *The multi-aisle* ASRS travels in the transverse aisle on the aisle transferring vehicle, which enables access to any picking aisle i (Fig. 2).
- The SR is marked by a rectangular shape, whereby the I/O location of the SR i is defined on the low left-hand side of the rack (Fig. 2).
- The SR machine enables the operation of single and dual command cycles, to which a variable time period for traveling in the transverse aisle ($S \leq R$) must be added.
- When performing the warehousing operation of the dual command cycle ($S \leq R$), we have discussed: (*i*) the storage and retrieval in the same picking aisle i and (*ii*) the storage and retrieval in two randomly chosen picking aisles i and j.
- The technical characteristics of the SR machine and the traverse vehicle (velocity v, acceleration and deceleration a) as well as the length L and height H of the SR are known.
- The SR machine travels in the picking aisle simultaneously in the horizontal direction x and the vertical direction y.
- The length L and height H of the SR are long enough so that the SR machine can reach its maximum velocity v_{max} in the horizontal direction x and vertical direction y.
- The length of the transverse aisle W is long enough so that the SR machine with the traverse vehicle reaches its maximum velocity v_{max} in the transverse direction.
- A random strategy was applied, so each warehousing location has an equal chance to be chosen for the storage or retrieval of the TUL.

Changing the project variables (the number of SR machines S, the number of picking aisles R, the number of storage racks Y, the number of storage compartments in the horizontal direction N_x and the number of storage compartments in the vertical direction N_y) causes a change in the value of the objective function *Min. TC* for each model of the ASRS. The operational parameters in the design model of the ASRS refer to the design of the warehouse, the design, and the determination of the efficiency of the ASRS. Moreover, the costs comprise the costs of building the warehouse, the costs of buying storage and material handling equipment and the costs arising from operating the ASRS in a selected time period. The objective function tako kombinacija projektnih spremenljivk, opravilnih parametrov (sl. 2, 3) in skupnih stroškov ter sestoji iz naslednjih modulov:

Min. TC is therefore a combination of project variables, operational parameters (Figs. 2 and 3) and overall costs. It composes the following modules:

1) Skladiščni objekt

• *Investicija za nakup zemljišča I_1:*

1) The warehouse building

• *The investment in buying the land I_1:*

$$I_1 = \left(P_z \cdot \frac{100}{D_z}\right) \cdot C_1 \tag{1}$$

P_z [m²] pomeni površino zemljišča za skladišče; D_z je delež zazidanosti skladišča in C_1 [€/m²] se navezuje na strošek za nakup zemljišča.

• *Investicija za izdelavo temeljne plošče I_2:*

P_z [m²] indicates the surface of the land for the warehouse; D_z stands for the share of the built warehouse, and C_1 [€/m²] refers to the cost of buying the land.

• *The investment in laying the foundations I_2:*

$$I_2 = \left[\left(\left(w \cdot n + (n+1) \cdot b_1 + b_4\right) \cdot N_x + b_5 + b_{10} + b_{20}\right) + L_{TZ} \cdot \left(R \cdot W_{RD} + Y \cdot g + (R-1) b_8\right)\right] \cdot C_2 \tag{2}$$

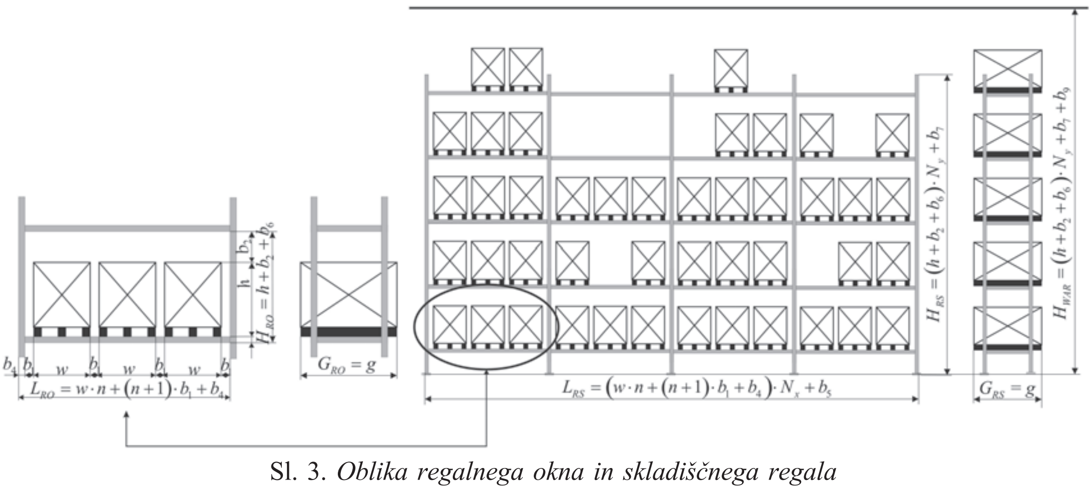
R, Y in N_x so projektne spremenljivke; *n* se navezuje na število TSE v RO; *w*, *g* in *h* [mm] predstavljajo širino, dolžino in višino palete/TSE; W_{RD} [mm] je širina RD; L_{TZ} [mm] je dolžina transportne cone; b_1, b_4, b_5, b_8, b_{10}, b_{20} [mm] predstavljajo varnostni dodatek za širino RO, širino stebra, debelino stebra, varnostni razmik med soležnimi regali, dodatek za širino palete na prevzemnem mestu, dodatek na koncu skladišča; C_2 [€/m²] je strošek za postavitev temeljne plošče (sl. 2 in 3).

R, Y and N_x are decision variables; *n* refers to the number of TUL in the storage compartment; *w, g* and *h* [mm] indicate the width, length and height of the palette/TUL; W_{RD} [mm] indicates the width of the SR machine; L_{TZ} [mm] indicates the length of the transport zone; b_1, b_4, b_5, b_8, b_{10}, b_{20} [mm] stand for a safety addition to the width of the storage compartment, the width of the upright frame, the thickness of the upright frame, the safety spacing between racks that are placed close to each other, the addition to the width of the palette at the input buffer, the addition to the end of the warehouse; C_2 [€/m²] stands for the cost of laying the foundations (Figs. 2 and 3).

• **Investicija za postavitev sten skladiščnega objekta I_3:**

• **The investment in building the walls of the warehouse I_3:**

$$I_3 = \left[\left(\begin{array}{l}\left(\left(w \cdot n + (n+1) \cdot b_1 + b_4\right) \cdot N_x + b_5 + b_{10} + b_{20}\right) + L_{TZ} + \\ \left(R \cdot W_{RD} + Y \cdot g + (R-1) b_8\right)\end{array}\right) \cdot \left(\left(h + b_2 + b_6\right) \cdot N_y + b_7 + b_9\right)\right] \cdot 2C_3 \tag{3}$$



Sl. 3. *Oblika regalnega okna in skladiščnega regala*

Fig. 3. The layout of the storage compartment and storage rack

N_y je projektna spremenljivka; b_2, b_6, b_7, b_9 [mm] predstavljajo varnostni dodatek za višino RO, višino regalnega nosilca, odmik regalnega okna od tal in varnostni dodatek za višino skladišča; C_3 [€/m²] je strošek postavitve sten skladiščnega objekta (sl. 2 in 3).

- *Investicija za postavitev strehe skladiščne zgradbe I_4:*

N_y is the decision variable; b_2, b_6, b_7, b_9 [mm] indicate the safety addition to the height of the storage compartment, the height of rack beams, the deviation of the storage compartment from the floor and a safety addition to the height of the warehouse; C_3 [€/m²] is the cost of building the walls of the warehouse (Figs. 2 and 3).

- *The investment in building the roof of the warehouse I_4:*

$$I_4 = \left[\left(\left(w\cdot n+(n+1)\cdot b_1+b_4\right)\cdot N_x+b_5+b_{10}+b_{20}\right)+L_{TZ}\cdot\left(R\cdot W_{RD}+Y\cdot g+(R-1)b_8\right)\right]\cdot C_4 \qquad (4),$$

C_4 [€/m²] pomeni strošek za postavitev strehe skladiščne zgradbe (sl. 2 in 3).

C_4 [€/m²] indicates the cost of building the roof of the warehouse (Figures 2 and 3).

2) Transportna in skladiščna sredstva

- *Investicija za nakup regalnih stranic I_5:*

2) Storage and material-handling equipment

- *The investment in buying upright frames I_5:*

$$I_5 = \left((N_x+1)\cdot 2Y\right)\cdot C_5 \qquad (5),$$

C_5 [€/m] pomeni strošek za nakup regalnih stranic.

- *Investicija za nakup regalnih veznikov in dodatek za ojačitev regalne konstrukcije I_6:*

C_5 [€/m] indicates the cost of buying upright frames.

- *The investment in buying rack beams and an addition to the reinforcement of the storage-rack structure I_6:*

$$I_6 = \left(\left(\left((N_x+1)\cdot 2Y\right)\cdot C_5\right)+\left(N_x\cdot N_y\cdot 2Y\cdot L_v\right)\cdot C_6\right)\cdot\left(1+\frac{PD}{100}\right) \qquad (6),$$

L_v [mm] je dolžina regalnega veznika (nosila); PD pomeni dodatek za ojačitev skladiščnih regalov; C_6 [€/m] pomeni strošek za nakup regalnih veznikov.

- *Investicija za nakup prevzemnih miz I_7 in montažo regalne konstrukcije I_8:*

L_v [mm] is the length of the rack beam; PD indicates an addition to the reinforcement of storage racks, C_6 [€/m] indicates the cost of buying rack beams.

- *The investment in buying buffers I_7 and the assembly of the storage-rack structure I_8:*

$$I_7 = 2R\cdot C_7$$
$$I_8 = Q\cdot C_8 \qquad (7),$$

C_7 [€] pomeni strošek za nakup prevzemnih miz, C_8 [€] pomeni strošek montaže.

- *Investicija za požarno varnost I_9 in klimatske zahteve I_{10}:*

C_7 [€] indicates the cost of buying buffers and C_8 [€] the cost of assembly.

- *The investment in fire-safety I_8 and air conditioning I_9 equipment:*

$$I_9 = \left((N_x\cdot N_y)\cdot 3\cdot 2\right)\cdot C_9$$
$$I_{10} = \left(L_{WAR}\cdot H_{WAR}\cdot W_{WAR}\right)\cdot C_{10} \qquad (8),$$

C_9 [€/PM] pomeni strošek požarne varnosti, C_{10} [€/m³] pa strošek prezračevanja.

- *Investicija za transportni I_{11} in regalni viličar I_{12}:*

C_9 [€/PM] indicates the cost of fire safety and C_{10} [€/m³] the cost of air ventilation.

- *The investment in lift truck I_{11} and reach trucks I_{12}:*

$$I_{11} = S_{TV}\cdot C_{11}$$
$$I_{12} = S_{RV}\cdot C_{12} \qquad (9),$$

S_{TV} pomeni število transportnih viličarjev (spremenljivka); S_{RV} pomeni število regalnih viličarjev (spremenljivka); C_{11} [€] pomeni strošek za nakup transportnega viličarja; C_{12} [€] strošek za nakup regalnega viličarja.

S_{TV} indicates the number of lift trucks (variable), S_{RV} indicates the number of reach trucks (variable); C_{11} [€] indicates the cost of buying a lift truck; C_{12} [€] indicates the cost of buying a reach truck.

• *Investicija za RD za delo v enem hodniku I_{13}:*

• *The investment in the single-aisle ASRS I_{13}:*

$$I_{13} = S_{RD} \cdot C_{13} + L_{TZ} \cdot C_{14} \quad (10),$$

• *Investicija za RD za delo v več hodnikih I_{14}:*

• *The investment in the multi-aisle ASRS I_{14}:*

$$I_{14} = C_{13} \cdot S_{RD} + \left(L_{TZ} \cdot C_{14}\right) \cdot R - \left(W_{WAR} - \left(\frac{2g + S_{RD}}{2}\right)\right) \cdot C_{15} \quad (11),$$

S_{RD} pomeni število RD (spremenljivka); L_{TZ} [mm] je dolžina skladiščne cone; W_{WAR} [mm] je širina skladišča; C_{13} [€] pomeni strošek za nakup RD; C_{14} [€] pa strošek regalnega hodnika; C_{15} [€] pomeni strošek prečnega hodnika.

Za uskladiščenje in odpremo TSE v regalnem skladišču (vožnja v regalnih hodnikih) so namenjena samo regalna dvigala in regalni viličarji. Transportni viličarji se uporabljajo v izbirnemu in distribucijskemu delu skladišča.

S_{RD} indicates the number of SR machines (decision variable); L_{TZ} [mm] is the length of the transport zone; W_{WAR} [mm] is the width of the warehouse; C_{13} [€] indicates the cost of buying the SR machine; C_{14} [€] indicates the cost of the picking aisle; C_{15} [€] indicates the cost of the cross aisle.

For the storage and retrieval operation of the TUL in the high-bay warehouse (routing in the picking aisles), only the SR machines and reach trucks are used. Lift trucks are used in the order picking and distribution area.

• *Investicija za zvezni transporter I_{15}:*

• *The investment in the accumulating conveyor I_{15}:*

$$I_{15} = C_{16} + 2 \cdot R \cdot C_{17} \quad (12),$$

C_{16} [€] pomeni strošek zveznega transporterja (krmilni sistemi, krmilni program); C_{17} [€] pa strošek preusmeritvenega elementa.

C_{16} [€] indicates the cost of the accumulating conveyor (the controls, the control system); C_{17} [€] indicates the cost of the diverted element.

3) Obratovanje ARSS

• *Stroški vzdrževanja regalnega skladiščnega sistema C_{VZD}:*

3) Operating the ASRS

• *Costs of maintaining the automated storage and retrieval system C_{VZD}:*

$$C_{VZD} = P(\%) \cdot C_{13} \cdot S \quad (13),$$

• *Metoda neto sedanje vrednosti NPV* – diskontni stroški obratovanja, ki predvidevajo določeno dobo trajanja ARSS i in diskontno stopnjo r:

• *The method of net present value NPV* – discount operational costs that assume a certain life expectancy of the ASRS i and the discount rate r

$$NPV = \sum_{i=1}^{T} \frac{\left(\left(P(\%) \cdot C_{13} \cdot S\right) + C_{OD}\right)}{\left(1+r\right)^{i}} \quad (14),$$

P(%) pomeni delež vrednosti RD za vzdrževanje; S pomeni število transportno-skladiščnih sredstev; C_{OD} je strošek osebnega dohodka za viličariste, ki delajo s transportnimi in regalnimi viličarji; r je diskontna stopnja; T_i je predvidena doba trajanja obratovanja ARSS.

Namenska funkcija *NSS* je vsota stroškov za postavitev skladiščnega objekta, nabavo vseh transportnih in skladiščnih sredstev ter stroškov obratovanja za načrtovano dobo trajanja skladišča. V namenski funkciji pomenijo stroški nespremenljivo vrednost in se v odvisnosti od geometrijske oblike skladišča ne spreminjajo. Namenska funkcija *NSS* ima naslednjo obliko:

P (%) indicates the share of the value of the SR machine for maintenance; S indicates the number of pieces of material-handling equipment; C_{OD} is the cost of personal income for operators working with lift trucks and reach trucks; r is the discount rate; T_i is the anticipated life expectancy of the operation of the ASRS.

The objective function *Min. TC* refers to all the costs of building the warehouse, purchasing the material-handling equipment and the costs of operating the warehouse within the expected operational time period. In the objective function, the costs indicate the constant value and do not change depending on the geometry of the warehouse. The objective function *Min. TC* has the following form:

- *Namenska funkcija NSS*

$$Min.\ TC = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7 + I_8 + I_9 + I_{10}$$
$$I_{11} + I_{12} + I_{13} + I_{14} + I_{15} + NPV \quad (15).$$

Pri optimizaciji projektnih spremenljivk *S, R, Y,* N_x, N_y v namenski funkciji *NSS* moramo upoštevati določene omejitve, ki se nanašajo na (1) geometrijske omejitve skladišča, (2) najmanjšo zahtevano *Q* skladišča in (3) število RD je lahko manjše ali enako številu regalnih hodnikov ($S \leq R$).

1) Izračunana prostornina skladišča V_i ne sme presegati dovoljene prostornine skladiščne zgradbe *V* (sl. 2).

- Dolžina skladišča L_{WAR}:

$$e_1 \leq \left(w \cdot n + (n+1) \cdot b_1 + b_4\right) \cdot N_x + b_5 + b_{10} + b_{20} + L_{TZ} \leq e_2 \quad (16).$$

- Širina skladišča W_{WAR}:

$$e_3 \leq R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \leq e_4 \quad (17).$$

- Višina skladišča H_{WAR}:

$$e_5 \leq \left(h + b_2 + b_6\right) \cdot N_y + b_7 + b_9 \leq e_6 \quad (18).$$

2) Izračunana Q_i skladišča mora biti enaka ali večja zahtevani *Q* skladišča:

$$2 \cdot 3 \cdot N_x \cdot N_y \cdot R \geq Q \quad (19).$$

3) Število RD je lahko manjše ali enako številu regalnih hodnikov ($S \leq R$)

Osnovo za določitev števila RD pomeni povprečni čas enojnega in dvojnega delovnega kroga. Le-tega določimo na podlagi analitičnih modelov, ki so vključeni v model načrtovanja. V primeru *sistema* RD *za delo v enem hodniku* ($S = R$) smo za določitev števila RD uporabili analitične modele *Vössnerja* [24], *Hwanga in Leeja* [25]. Za določitev števila RD v primeru *sistema* RD *za delo v več hodnikih* ($S \leq R$) smo uporabili izpopolnjene analitične modele *Lerher in sodelavci* ([2] in [15]). Na temelju geometrijske oblike SR, števila zahtevanih enojnih in dvojnih delovnih krogov, povprečnega časa enojnega in dvojnega delovnega kroga, določimo potrebno število transportno-skladiščnih sredstev S_{pot}:

- *The objective function Min. TC*

When optimizing the decision variables *S, R, Y,* N_x, N_y in the objective function *Min. TC,* one must take into account certain constraints referring to (1) the geometrical constraints of the warehouse, (2) the minimum required *Q* of the warehouse, and (3) the fact that the number of SR machines has to be lower than or equal to the number of picking aisles ($S \leq R$).

1) The calculated volume of the warehouse V_i cannot exceed the allowed volume of the warehouse *V* (Fig. 2).

- The length of the warehouse L_{WAR}:
- The width of the warehouse W_{WAR}:
- The height of the warehouse H_{WAR}:

2) The calculated Q_i of the warehouse must be equal to or higher than the required *Q* of the warehouse:

3) The number of SR machines can be lower than or equal to the number of picking aisles ($S \leq R$).

The determination of the number of SR machines is based on the average time of the single and dual command cycles. It is determined on the basis of analytical models, which are included in the design model. In the case of the *single-aisle* ASRS ($S = R$), the analytical travel- time models from *Vössner* [24] and *Hwang and Lee* [25] have been applied to the design model. To determine the number of SR machines in the case of the *multi-aisle* ASRS ($S \leq R$), the newly improved analytical travel-time models by *Lerher et al.* ([2] and [15]) have been applied. With regard to the layout of the SR, the number of the required SC and DC and the average travel time of SC and DC, the necessary number of pieces of material handling equipment S_{pot} can be determined:

$$S_{pot} = \frac{n_{SC} \cdot T(SC) + n_{DC} \cdot T(DC)}{T \cdot \eta} \quad (20),$$

T [h] pomeni čas delovne izmene.

V primeru uporabe *sistema* RD *za delo v enem hodniku* algoritem v modelu načrtovanja pri pogoju, $S = R$, vsakemu regalnemu hodniku predpiše samostojno RD. Algoritem tudi hkrati preveri, ali je predpisano RD, ki ustreza pogoju, $S = R$, zmožno dosegati zahtevano Pf skladišča. Če je izračunana Pf_i manjša od predpisane Pf, algoritem izvede izbiro novega tipa RD. Kadar je izbran *sistem* RD *za delo v več hodnikih*, ki omogoča vožnjo v prečnem hodniku, ne potrebujemo samostojnega transportno-skladiščnega sredstva v vsakem regalnem hodniku. V tem primeru je izpolnjen pogoj ($S \leq R$), pri čemer algoritem določi potrebno število RD, vendar ne več kot je število regalnih hodnikov R. Če izračunana Pf_i skladišča ne doseže predpisane Pf, se izvede izbira novega tipa RD.

Na podlagi diskretne oblike namenske funkcije *NSS*, nelinearnosti in upoštevanja večjega števila projektnih spremenljivk smo za optimizacijo projektnih spremenljivk v namenski funkciji *NSS* uporabili *postopek genetskih algoritmov*. Genetski algoritmi (GA) so hevristični iskalni algoritmi, ki jih uporabljamo za reševanje zahtevnih analiz in optimizacijskih problemov. Metoda z GA simulira razvojne postopke oz. "preživetje najprilagojenejšega organizma" [17].

V modelu načrtovanja GA naključno ustvari zahtevano število *osebkov v generaciji – organizmu*. Osebek predstavlja ARSS, medtem ko so *geni* v *organizmu* ponazorjeni s spremenljivkami N_x, N_y in S. Spremenljivki Y in R v organizmu nista upoštevani neposredno, saj sta neposredno odvisni od spremenljivk N_x, N_y in S. Na podlagi predpisane namenske funkcije *NSS* in projektnih omejitev GA ovrednoti vsak posamezen *osebek* v *generaciji* in jih razvrsti glede na njihovo oceno – najmanjše celotne stroške. Preostali del *generacij* v GA (npr. 95 %) nastaja s *križanjem*, *reprodukcijo* in *mutacijo*. Postopek optimizacije z GA in pomen posameznih genetskih in razvojnih operatorjev so podrobneje predstavljeni v delih [2] in [17].

2 ANALIZA: PRIMER NAČRTOVANJA ARSS

Z optimizacijo projektnih spremenljivk S, R, Y, N_x in N_y v namenski funkciji *Min. TC* smo iskali optimalne različice. Optimalni model ARSS mora ustrezati naslednjim projektnim omejitvam: dolžina skladišča L_{WAR} ($e_1 = 0 - e_2 = 100$) m, širina skladišča

T [h] indicates the time for a working shift.

In the case of the application of the *single-aisle* ASRS, the algorithm in the design model assigns the SR machine to each picking aisle, under the condition $S = R$. At the same time the algorithm examines whether the assigned SR machine, which meets the condition $S = R$, is able to reach the required Pf of the warehouse. If the calculated Pf_i is lower than the required Pf, the algorithm chooses a new type of SR machine. When the *multi-aisle* ASRS, which enables transferring in the cross aisle, is chosen, then a single SR machine serves multiple picking aisles. In this case the condition ($S \leq R$) is fulfilled, whereby the algorithm determines the necessary number of SR machines, which is not higher than the number of picking aisles R. If the calculated Pf_i does not reach the required Pf, a new type of SR machine is chosen.

Considering the discrete form of the objective function *Min. TC*, non-linearity and the proposed decision variables, *the method of genetics algorithms* to optimize the decision variables in the *Min TC* has been applied. Genetics algorithms (GA) are heuristic search algorithms that are used to perform demanding analyses and to solve problems of optimization. The method of GA simulates evolutionary processes "the survival of the most flexible organism" [17].

In the design model, the GA randomly creates the required number of *subjects in a generation – organism.* The subject refers to the ASRS, whereas *genes in the organism* are demonstrated by the decision variables N_x, N_y and S. The variables Y and R are not directly considered in the organism, since they are directly dependent on the variables N_x, N_y and S. Based on the *Min. TC* and project constraints, the GA evaluates each *subject in the generation* and arranges them with regard to their evaluation – the minimum total costs. The rest of the *generations* in the GA (e.g. 95%) are created by *crossover, reproduction* and *mutation*. The optimization process of GA and the meaning of individual genetic and evolutionary operators are presented in detail in [2] and [17].

2 ANALYSIS: AN EXAMPLE OF DESIGNING ASRS

With the optimization of the decision variables S, R, Y, N_x and N_y in the *Min. TC*, the optimum design of the ASRS was searched for. The optimum design of the ASRS should suit the following project constraints: the length of the warehouse L_{WAR} ($e_1 = 0 - e_2 = 100$) m,

W_{WAR} ($e_3 = 0 –\ e_4 = 200$) m in višina skladišča H_{WAR} ($e_5 = 0 – e_6 = 20$) m. Vhodni podatki za analizirani primer temeljijo na podatkih iz prakse. Rezultati analize se nanašajo na izbran ARSS [2], ki je določen z naslednjimi parametri; ***(i) vhodni parametri:*** zalogovna velikost skladišča Q = 15000 TSE, pretočna zmogljivost skladišča Pf = 140 TSE/h, ***(ii) opravilni parametri skladišča:*** w = 800 mm, g = 1200 mm, h = 800 mm, m = 1000 kg, b_1 = 100 mm, b_2 = 200 mm, n = 3, b_3 = 1100 mm, b_4 = 120 mm, b_5 = 65 mm, b_6 = 162 mm, b_7 = 300 mm, b_8 = 200 mm, b_9 = 1000 mm, b_{10} = 0 mm, T_{01} = 3 s, T_{02} = 3 s, $n_{(SC)}$ = 40, $n_{(DC)}$ = 70, W_{TV} = 800 mm, L_{TV} = 2000 mm, b_{11} = 300 mm, b_{14} = 500 mm, b_{16} = 1800 mm, W_{RD} = 1400 mm, L_{RD} = 2000 mm, b_{22} = 70 %, ***(iii) transportno-skladiščna sredstva:*** RD *za delo v več hodnikih* – Stöklin AT RBG 0-Q: G_{RD} = 1250 kg, H_{RD} = 22000 mm, W_{RD} = 1400 mm, v_x = 3 m/s, v_y = 0,8 m/s, v_i = 0,6 m/s, a_x = 0,5 m/s^2, a_y = 0,8 m/s^2, a_i = 0,4 m/s^2, RD *za delo v enem hodniku* – Single MAN: G_{RD} = 1200 kg, H_{RD} = 21900 mm, W_{RD} = 1400 mm, v_x = 3 m/s, v_y = 1 m/s, a_x = 0,5 m/s^2, a_y = 0,5 m/s^2, *Transportni viličar* – Jungheinrich ERC 214: G_{TV} = 1400 kg, W_{RD} = 800 mm, v_x = 3 m/s, a_x = 0,5 m/s^2, ***(iv) stroški:*** C_1 = 50 €/m^2, C_2 = 168 €/m^2, C_3 = 23 €/m^2, C_4 = 25 €/m^2, C_5 = 30 €/m^2, C_6 = 23 €/m^2, C_7 = 200 €/kos, C_8 = 10 €/RO, C_9 = 5 €/PM, C_{10} = 10 €/m^3, C_{11} = 17000 €/kos, C_{13} = 240000 €/kos, C_{14} = 50 €/m, C_{15} = 40 €/m, C_{16} = 150000 €/m, C_{17} = 50 €/m, b_{23} = 5 %, C_{18} = 12000 €/leto, T = 10, i = 8 (%).

Na temelju opravljene analize optimizacije projektnih spremenljivk v namenski funkciji *NSS* s postopkom *genetskih algoritmov* [17] lahko podamo bistvene sklepe, ki so predstavljeni v diagramih na sliki 4*i*, 4*ii*, 4*iii*, 4*iv*. V nadaljevanju so prikazani diagrami optimizacije projektnih spremenljivk *S, R, Y,* N_x in N_y v namenski funkciji *NSS* pri številu generacij n = 1 in n = 100 v GA.

- **Optimizacija projektnih spremenljivk v namenski funkciji NSS**

V diagramih na sliki 4*i*, 4*ii*, 4*iii*, 4*iv* so predstavljeni rezultati optimizacije projektnih spremenljivk pri številu generacij v GA – n = 1 in n = 100. Odziv optimizacije projektnih spremenljivk *S, R, Y,* N_x in N_y v namenski funkciji *NSS* predstavlja celotne stroške (€) v odvisnosti od števila RO v vodoravni smeri x in v navpični smeri y, pri izbranem *sistemu* RD *za delo v enem ali več hodnikih*. Optimizacija projektnih spremenljivk je bila izvedena glede na naslednje predpisane razvojne in genetske operatorje: *stopnja križanja* – 0,8; *stopnja mutacije*

the width of the warehouse W_{WAR} ($e_3 = 0 – e_4 = 200$) m and the height of the warehouse H_{WAR} ($e_5 = 0 – e_6 = 20$) m. The input data for this example is based on information from practice. The analysis refers to the chosen model of the ASRS [2], which is determined by the following parameters: ***(i) entry-level parameters:*** the storage volume of the warehouse Q = 15000 TUL, throughput capacity of the warehouse Pf = 140 TUL/h, ***(ii) operational parameters of the warehouse:*** w = 800 mm, g = 1200 mm, h = 800 mm, m = 1000 kg, b_1 = 100 mm, b_2 = 200 mm, n = 3, b_3 = 1100 mm, b_4 = 120 mm, b_5 = 65 mm, b_6 = 162 mm, b_7 = 300 mm, b_8 = 200 mm, b_9 = 1000 mm, b_{10} = 0 mm, T_{01} = 3 sec., T_{02} = 3 sec., $n_{(SC)}$ = 40, $n_{(DC)}$ = 70, W_{TV} = 800 mm, L_{TV} = 2000 mm, b_{11} = 300 mm, b_{14} = 500 mm, b_{16} = 1800 mm, W_{RD} = 1400 mm, L_{RD} = 2000 mm, b_{22} = 70 %, ***(iii) material handling equipment:*** the multi-aisle ASRS – Stöklin AT RBG 0-Q: G_{RD} = 1250 kg, H_{RD} = 22000 mm, W_{RD} = 1400 mm, v_x = 3 m/s, v_y = 0,8 m/s, v_i = 0,6 m/s, a_x = 0,5 m/s^2, a_y = 0,8 m/s^2, a_i = 0,4 m/s^2, *the single-aisle ASRS* – Single MAN: G_{RD} = 1200 kg, H_{RD} = 21900 mm, W_{RD} = 1400 mm, v_x = 3 m/s, v_y = 1 m/s, a_x = 0,5 m/s^2, a_y = 0,5 m/s^2, *lift truck* – Jungheinrich ERC 214: G_{TV} = 1400 kg, W_{RD} = 800 mm, v_x = 3 m/s, a_x = 0,5 m/s^2, ***(iv) costs:*** C_1 = 50 €/m^2, C_2 = 168 €/m^2, C_3 = 23 €/m^2, C_4 = 25 €/m^2, C_5 = 30 €/m^2, C_6 = 23 €/m^2, C_7 = 200 €/piece, C_8 = 10 €/RO, C_9 = 5 €/PM, C_{10} = 10 €/m^3, C_{11} = 17000 €/piece, C_{13} = 240000 €/piece, C_{14} = 50 €/m, C_{15} = 40 €/m, C_{16} = 150000 €/m, C_{17} = 50 €/m, b_{23} = 5 %, C_{18} = 12000 €/year, T = 10, i = 8 (%).

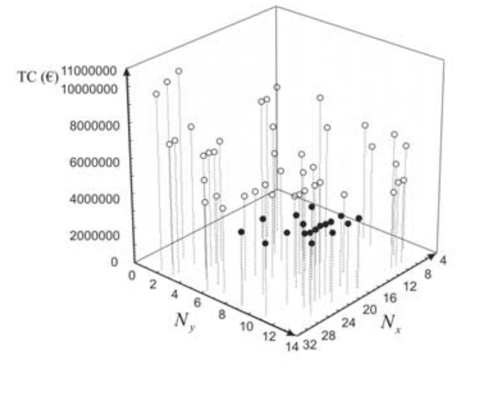
Based on the performed analysis of the optimization of the decision variables in the *Min. TC* with the method of GA [17], the main conclusions, which are shown in the diagrams in Figures 4*i*, 4*ii*, 4*iii*, 4*iv*, can be presented. The following section shows the diagrams of the optimization of the decision variables *S, R, Y,* N_x, N_y in the *Min. TC* with the number of generations n =1 and n =100 in the GA.

- **The optimization of decision variables in the objective function minimum total costs**

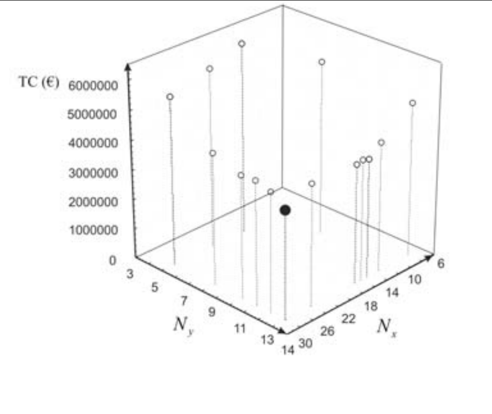
The diagrams in Figures 4*i*, 4*ii*, 4*iii*, 4*iv* show the results of the optimization of decision variables with the number of generations in the GA n = 1 and n = 100. The response to the optimization of the decision variables *S, R, Y,* N_x, N_y in the *Min. TC* indicates the total costs (€), depending on the number of storage compartments in the horizontal direction x and the vertical direction y for the chosen *single-* or *multi-aisle* ASRS. The optimization of the project variables was carried out according to the following evolutionary and genetics operators: *the degree of crossover* – 0.8; *the*

– 0,05; *stopnja elitizma* – 0,05; *velikost populacije* – 100; *število generacij* – 100. Vrednosti stopnje *križanja*, *mutacije* in *elitizma* so izbrane glede na izkušnje raziskovalcev [17], ki so se ukvarjali z razvojem in uporabo metode GA. Vrednosti so izbrane tako, da rešitev ne zaide v lokalni optimum, temveč je rešitev v globalnem optimumu. Velikost populacije je odvisna predvsem od števila spremenljivk v namenski funkciji *NSS*, kar posredno vpliva tudi na potrebno število generacij. Zaradi sorazmerno majhnega števila projektnih spremenljivk *S, R, Y,* N_x in N_y v namenski funkciji *NSS,* se je pri obsežnem analiziranju izkazalo, da GA v večini primerov najde stroškovno optimalno rešitev že pri stotih generacijah. V primeru večjega števila predpisanih generacij bi

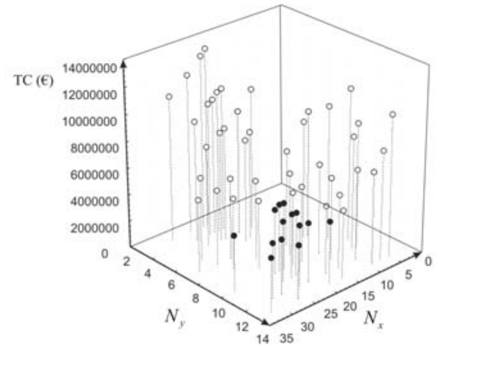
degree of mutation – 0.05; *the degree of elitism* – 0.05; *the size of the population* – 100; *the number of generations* – 100. The values of the *crossover, mutation* and *elitism degrees* are chosen based on the experiences of researchers [17] who have been engaged in the development and application of the GA method. The values are chosen so that the solution does not get into a local optimum, but it lies in the global optimum. The size of the population depends a great deal on the number of decision variables in the *Min. TC*, which indirectly influences the necessary number of generations. Due to the relatively small number of project variables *S, R, Y,* N_x, N_y in the *Min. TC*, the comprehensive analyses has indicated that in most cases the GA finds the most economical solution with just 100 generations. In the case of a larger number of generations, the GA would



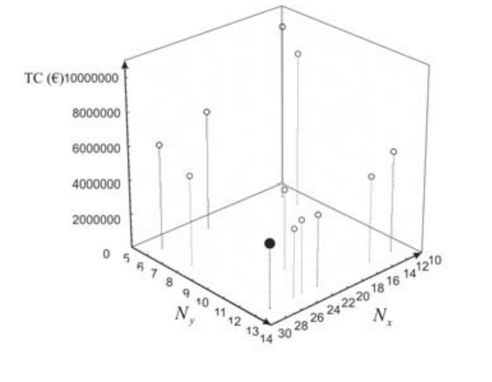
(*i*) ARSS za delo v več hodnikih
(GA – generacija 1)
(*i*) The multi-aisle ASRS
(GA – generation 1)



(*ii*) ARSS za delo v več hodnikih
(GA – generacija 100)
(*ii*) The multi-aisle ASRS
(GA – generation 100)



(*iii*) ARSS za delo v enem hodniku
(GA – generacija 1)
(*iii*) The single-aisle ASRS
(GA – generation 1)



(*vi*) ARSS za delo v enem hodniku
(GA – generacija 100)
(*vi*) The single-aisle ASRS
(GA – generation 100)

Sl. 4. *Diagrami celotnih stroškov sistemov RD za delo v enem in več hodnikih*
Fig. 4. *The total costs of the single- and multi-aisle ASRS*

GA prav tako prišel do rešitve, vendar bi za rešitev porabil več časa.

V diagramih na slikah 4*i* in 4*iii* lahko vidimo, da tvori GA za obe različici transportno-skladiščnega sredstva (RD *za delo v enem hodniku* in RD *za delo v več hodnikih*) izbrano število naključnih različic ARSS. Skladiščne različice, ki ne ustrezajo predpisanim omejitvam, definiranim pri optimizaciji projektnih spremenljivk *S, R, Y*, N_x in N_y v namenski funkciji *NSS*, so izbrisane in na diagramih niso prikazane. Število naključno izbranih različic ARSS je tako enako velikosti populacije *n* ali v večini primerov manjše od *n*. Zaradi naključnega izbire množice ARSS, ki pomenijo nadaljnjo osnovo za optimizacijo, so vrednosti skupnih stroškov v namenski funkciji *NSS* največje prav v generaciji n = 1, kar velja za obe različici transportno-skladiščnega sredstva. V diagramih (slika 4*i* in 4*iii*) lahko vidimo, da skladiščne različice, označene s potemnjenimi simboli, pomenijo stroškovno najugodnejše rešitve ARSS. Večina najugodnejših rešitev je v področju večjega števila RO v vodoravni smeri *x* in v navpični smeri *y*, kar pomeni, da imajo omenjene rešitve ARSS na podlagi metode *izbire z razvrščanjem* veliko verjetnost, da bodo vključene v naslednjo generacijo.

Na podlagi predpisanih *razvojnih* in *genetskih* operatorjev se izvedejo naslednje *generacije* $n = (1 – 100)$, pri čemer je vsaka *generacija* boljša ali pa vsaj njej enaka. V diagramih na sliki 4*ii* in 4*iv* so prikazani rezultati optimizacije projektnih spremenljivk pri generaciji $n = 100$. Opazimo lahko, da je število različic ARSS v generaciji $n = 100$ manjše kakor v primerjavi z generacijo $n = 1$, kar nakazuje na pravilno delovanje GA. Stroškovno optimalna rešitev ARSS se navezuje na ARSS z $N_x = 28$ RO v vodoravni *x* in $N_y = 13$ RO v navpični smeri *y*, za obe različici transportno-skladiščnega sredstva (v diagramu 4*ii* in 4*iv* označena s potemnjenim simbolom). Vidimo lahko, da so skupni stroški najmanjši (optimalni) pri sorazmerno visokem $N_y = 13$ in dolgem $N_x = 28$ SR (glede na podane geometrijske omejitve e_i skladišča) za obe izvedbi transportno-skladiščnih sredstev. Predstavljeno odvisnost lahko komentiramo z dejstvom, da imamo v primeru velikega SR (>> N_x in >> N_y), veliko zalogovno velikost *Q*, pri manjšem številu SR ter zato majhno širino skladišča < *W*. Slednje ima za posledico manjše potrebno število transportno-skladiščnih sredstev *S* (še posebej očitno pri *sistemu* RD *za delo v enem hodniku*), kar ima velik vpliv na celotno investicijo skladišča.

also arrive at a solution, but it would take more time to do so.

The diagrams in Figures 4*i* and 4*iii* show that the GA forms a chosen number of random designs of the ASRS for both types of the *single*- and *multi-aisle* ASRS. Warehouses that do not follow the required constraints, defined at the optimization of the decision variables *S, R, Y*, N_x, N_y in the *Min. TC*, are deleted and not considered in the next generations. The number of randomly chosen designs of the ASRS is the same as the size of the population *n* or in most cases smaller than *n*. Because of the random selection of the number of ASRS, which present a further basis for the optimization, the values of the total costs in the *Min. TC* are the highest in the generation $n = 1$, which holds true for both types of the *single*- and *multi-aisle* ASRS. The diagrams ion Figures 4*i* and 4*iii* illustrate that warehouse designs, marked with darkened symbols, present the most economical designs of the ASRS. The majority of the most economical designs lies in the area of a large number of storage compartments in the horizontal direction *x* and the vertical direction *y*. Accordingly, the above-mentioned designs of the ASRS have a strong likelihood of being included in the next generation on the basis of *the selection method with ranging*.

Based on the specified *evolutionary* and *genetics* operators, the next generations $n = (1 – 100)$ are carried out, whereby each generation is better or at least equally good. The diagrams in Figures 4*ii* and 4*iv* show the results of the optimization of the decision variables with the generation $n = 100$. It can be seen that the number of designs of the ASRS in the generation $n = 100$ is smaller than in the generation $n = 1$, which indicates the correct operation of the GA. The most economical design of the ASRS refers to the ASRS with $N_x = 28$ storage compartments in the horizontal *x* and $N_y = 13$ storage compartments in the vertical direction *y*, for both types of storage systems (in diagrams 4*ii* and 4*iv*, marked with a darkened symbol). It can be seen that the total costs are minimum (optimum) at a relatively high $N_y = 13$ and long $N_x = 28$ storage racks (with regard to the given geometrical constraints e_i of the warehouse) for both variants of the *single*- and *multi-aisle* ASRS. One can comment on the presented dependence that in the case of a large SR (>> N_x and >> N_y) we have a large storage volume *Q*, a small number of SR and consequently a small width of the warehouse < *W*. The latter takes the consequence of a lower number of necessary numbers of SR machines *S* (apparently obvious with the *single-aisle* ASRS), which has a significant influence on the entire investment in the warehouse.

V odvisnosti od S lahko vidimo, da pri uporabi *sistema* RD *za delo v enem hodniku* potrebujemo 7 RD, medtem ko pri uporabi *sistema* RD *za delo v več hodnikih* potrebujemo le 4 RD. Čeprav omogoča ARSS s *sistemom* RD *za delo v več hodnikih* samo uporabo 4 RD, je znesek investicije za določen primer ARSS [2] (Q = 15 000 TSE in Pf = 140 TSE/h), približno enak za oba ARSS (3,626 • 10^3 € – slika 4*ii* in 3,800 • 10^3 € – slika 4*iv*). Vrednost RD *za delo v več hodnikih* je za približno 60 % večja od vrednosti RD *za delo v enem hodniku* prav zaradi dodatnih elementov (pomični voziček za vožnjo v prečnem hodniku, dodatna vodila, stikala, obsežnejše krmiljenje itn), ki omogočajo izvedbo skladiščnega opravila. Odločitev o uporabi posameznega *sistema* RD je v največji meri odvisna od zahtevane Pf skladišča. V nadaljevanju bo zato prikazana primerjava učinkovitosti (v odvisnosti od *NSS*) *sistema* RD *za delo v enem in več hodnikih* pri različnih Pf skladišča.

2.1 Učinkovitost sistemov regalnega dvigala za delo v enem in več hodnikih

V primeru zahteve naročnikov skladišč po izdelavi ARSS se lahko odločamo med *sistemoma* RD *za delo v enem ali več hodnikih*. Kateri od *sistemov* RD se v določenem položaju najbolje obnese, je odvisno predvsem od zahtevane Pf skladišča. V analizi smo uporabili ARSS z zalogovno velikostjo Q = 15000 TSE, pri katerem smo spreminjali zahtevano pretočno zmogljivost skladišča v mejah od Pf = 60 do 160 TSE/h, glede na naslednje projektne omejitve: L_{WAR} ($e_1 = 0 - e_2 = 100$) m, širina skladišča W_{WAR} ($e_3 = 0 - e_4 = 200$) m in višina skladišča H_{WAR} ($e_5 = 0 - e_6 = 20$) m. Opravilni parametri, transportno-skladiščna sredstva in stroški se navezujejo na ARSS [2] in so podrobneje predstavljeni v poglavju 3. Rezultati analize v preglednici 1 in na sliki 5, predstavljajo stroškovno optimalne različic ARSS, dobljene z optimizacijo projektnih spremenljivk S, R, Y, N_x in N_y v namenski funkciji *NSS* pri generaciji n = 100.

- **Primerjava učinkovitosti sistemov RD za delo v enem in več hodnikih**

V preglednici 1 so prikazane različne izvedbe ARSS v odvisnosti od zahtevane Pf skladišča. Osnova za primerjavo *sistemov* RD predstavlja ARSS s *sistemom* RD *za delo v enem hodniku* z naslednjimi osnovnimi podatki: zalogovna velikost

In dependence on the S, when applying the *single-aisle* ASRS we need 7 SR machines, whereas when applying the *multi-aisle* ASRS we need only 4 SR machines. Even though the *multi-aisle* ASRS requires the application of only 4 SR machines, the investment in the analysed ASRS [2] (Q = 15000 TUL and Pf = 140 TUL/h) is approximately the same for both types of the *single-* and *multi-aisle* ASRS (3.626·10^3 € – diagram 4*ii* and 3.800·10^3 € – diagram 4*iv*). The cost of the SR machine for the *multi-aisle* system is approximately 60% higher than the cost of the SR machine for the *single-aisle* system due to additional elements (aisle transferring vehicle for traveling in the cross aisle, additional controls and switches, extensive control system, etc.) which make it possible to operate the warehouse. The decision on the application of a particular *single-* or *multi-aisle* system depends mainly on the required Pf of the warehouse. Consequently, in the following section a comparison between the *single-* and *multi-aisle* systems, with regard to various Pf of the warehouse, is presented.

2.1 The efficiency of the single- and multi-aisle ASRS

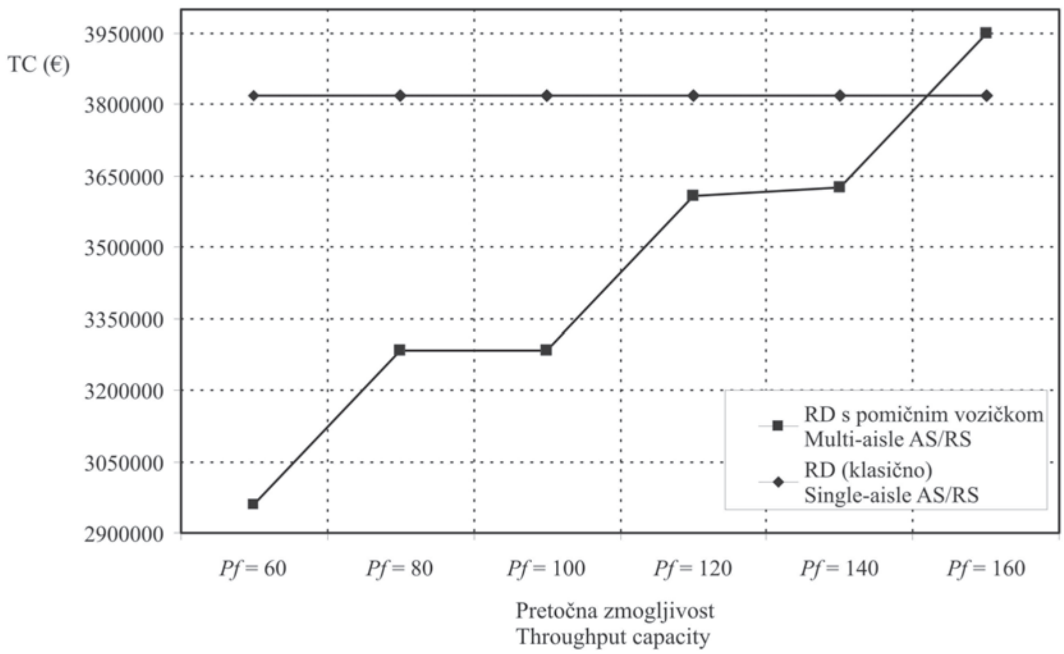
When an order for the creation of the ASRS is placed, we can decide between *the single-aisle* and *multi-aisle* ASRS. Which of both systems is most suitable for a particular case depends largely on the required Pf of the warehouse. In the analysis the ASRS with the storage volume Q = 15000 TUL has been used. The required throughput capacity has been changed from Pf = 60 to 160 TUL/h, with regard to the following project constraints: the length of the warehouse L_{WAR} ($e_1 = 0 - e_2 = 100$) m, the width of the warehouse W_{WAR} ($e_3 = 0 - e_4 = 200$) m and the height of the warehouse H_{WAR} ($e_5 = 0 - e_6 = 20$) m. Operational parameters, material handling equipment and costs refer to the ASRS [2] and are presented in detail in Section 3. The analysis results in Table 1 and Figure 5 present the most economical design of the ASRS, obtained from optimizing the decision variables $S, R, Y, N_{x,} N_y$ in the *Min. TC* within the generation n = 100.

- **Efficiency comparison between *the single-* and *multi-aisle* ASRS**

Table 1 shows different types of the ASRS depending on the required Pf of the warehouse. The basis for making the comparison between both systems is the *single-aisle* ASRS with the following data: storage volume of the warehouse Q = 15000 TUL, throughput

Preglednica 1: *Primerjava sistema RD za delo v več hodnikih v odvisnosti od sistema RD za delo v enem hodniku*
Table 1. *The comparison of the multi-aisle ASRS in dependence on the single-aisle ASRS*

	PRIMERJAVA ZMOGLJIVOSTI SKLADIŠČA COMPARISON OF THE WAREHOUSE EFFICIENCY					
	$Pf_2 = 60$ [TSE/h] [TUL/h]	$Pf_2 = 80$ [TSE/h] [TUL/h]	$Pf_3 = 100$ [TSE/h] [TUL/h]	$Pf_4 = 120$ [TSE/h] [TUL/h]	$Pf_5 = 140$ [TSE/h] [TUL/h]	$Pf_6 = 160$ [TSE/h] [TUL/h]
Q	15000	15000	15000	15000	15000	15000
R	7	7	7	7	7	7
S	2	3	3	4	4	5
N_x	28	28	28	28	28	28
N_y	13	13	13	13	13	13
η (%)	82	72,2	89	80	94	74
NSS [€] *Min. TC* [€]	$2{,}960 \cdot 10^3$	$3{,}284 \cdot 10^3$	$3{,}284 \cdot 10^3$	$3{,}609 \cdot 10^3$	$3{,}626 \cdot 10^3$	$3{,}951 \cdot 10^3$
Razlika v stroških [€] Differences in costs [€]	$-840 \cdot 10^3$	$-516 \cdot 10^3$	$-516 \cdot 10^3$	$-191 \cdot 10^3$	$-174 \cdot 10^3$	$+151 \cdot 10^3$



Sl. 5. P*orazdelitev najmanjših skupnih stroškov v odvisnosti od Pf skladišča*
Fig. 5. *Distribution of minimum total costs depending on the Pf of the warehouse*

skladišča Q = 15000 TSE, pretočna zmogljivost skladišča Pf = 160 TSE/h, število regalnih hodnikov R = 7, število RD S = 7, število SR Y = 14, število RO v vodoravni x smeri N_x = 28, število RO v navpični smeri y N_y = 13, najmanjši skupni stroški NSS = $3{,}800 \cdot 10^3$ €.

Na sliki 5 je prikazana odvisnost zahtevane *Pf* skladišča glede na stroškovno optimalno izvedbo ARSS za oba *sistema* RD. Vidimo lahko, da je *sistem*

capacity Pf = 160 TUL/h, the number of picking aisles R = 7, the number of SR machines S = 7, the number of SR Y = 14, the number of storage compartments in the horizontal direction N_x = 28, the number of storage compartments in the vertical direction N_y = 13, and the minimum overall costs *Min. CS* = $3.800 \cdot 10^3$ €.

The diagram in Figure 5 shows the dependence of the required *Pf* of the warehouse, with regard to the most economical design of the ASRS for

RD *za delo v več hodnikih* smiselno uporabiti pri nižjih zmogljivostih skladišča << *Pf*, saj je investicija skladišča neprimerno manjša kakor pri *sistemu* RD *za delo v enem hodniku*. V tem primeru je prispevek pri stroških v primerjavi s *sistemom* RD *za delo v enem hodniku* močno izrazit in znaša 840•10³ € (*Pf* = 60 TSE/h). Z naraščanjem *Pf* skladišča se zmanjšuje tudi prispevek pri stroških in primernost uporabe *sistema* RD *za delo v več hodnikih se zmanjšuje*. V primeru zahtevane pretočne zmogljivosti nad vrednostjo *Pf* = 140 TSE/h je upravičenost omenjenega *sistema* RD že vprašljiva, saj je RD že močno obremenjeno (η = 94 %), prispevek pri stroških pa neizrazit. Opazimo lahko, da je investicija pri vrednosti *Pf* = 160 TSE/h za vrednost 151•10³ € večja v primerjavi s *sistemom* RD *za delo v enem hodniku*, saj je v ARSS treba zagotoviti že 5 RD. Prav tako pa so pri omenjeni pretočni zmogljivosti vprašljivi primernost uporabe in problem vodenja ter nadzora 5 RD pri 7 regalnih hodnikih. Analiza je bila izvedena za primer skladiščne strategije (*i*) naključnega uskladiščenja in (*ii*) naključne odpreme TSE, brez vpeljave skladiščnih con. Z uporabo izpopolnjenih strategij bi bila zmogljivost *sistema* RD *za delo v več hodnikih* neprimerno večja. Sklenemo lahko, da na splošno za (zahtevane) >> *Pf*, pri uporabi klasične naključne skladiščne strategije, uporabimo *sistem* RD *za delo v enem hodniku*. Prav nasprotno velja v primeru sorazmerno << *Pf*, pri katerih pride v poštev predvsem *sistem* RD *za delo v več hodnikih*. Večjo zmogljivost *sistema* RD *za delo v več hodnikih* lahko v največji meri dosežemo prav z uporabo učinkovitejše skladiščne strategije in vpeljave skladiščnih con ABC.

3 SKLEPI

V tem prispevku je predstavljen izpopolnjen model načrtovanja ARSS. Zaradi vedno večje zahtevnosti skladišč in optimiranja skladiščnih virov, prehaja klasični postopek načrtovanja na višje in zahtevnejše stopnje, v obliki računalniško podprtega načrtovanja in optimiranja skladiščnih sistemov [13]. Model načrtovanja je tako zasnovan na sestavljenem postopku [13] in se navezuje na področje enoglobinskega regalnega skladiščnega sistema. Bistveni del v modelu načrtovanja je vpeljava in uporaba dveh različnih *sistemov* RD, in sicer (*i*) *sistem* RD *za delo v enem* ter (*ii*) *sistem* RD *za delo v več hodnikih*. V nasprotju s *sistemom* RD *za delo v enem hodniku* ([24] in [25]) so *sistemi* RD *za delo v*

both systems. It can be seen that at low throughput capacities of the warehouse (<< *Pf*) it is reasonable to apply the *multi-aisle* ASRS, since the investment in the warehouse is much smaller than in the case of the *single-aisle* ASRS. In this case the difference in costs (840·10³ € - *Pf* = 60 TUL/h) is more significant in comparison with the *single-aisle* ASRS. With the rising of the *Pf* of the warehouse, the costs increase and also the appropriateness of applying the *multi-aisle* ASRS decreases. If the required throughput capacity is above *Pf* = 140 TUL/h, the application of the *multi-aisle* ASRS becomes rather questionable, since the SR machines are already overloaded (η = 94%) and the differences in costs are quite small. It can be seen that the investment within *Pf* = 160 TUL/h is larger for the value of 151·10³ € in comparison with the single-aisle ASRS, since 5 SR machines must be used in the ASRS. Additionally, in the above-mentioned *Pf* the application and the problem of the management and control of 5 SR machines at 7 picking aisles is rather questionable. The analysis has been carried out for the case of (*i*) random storage strategy and (*ii*) random retrieval strategy, without the introduction of the class-based storage. With the application of improved strategies, the efficiency of the *multi-aisle* ASRS would be much higher. It can be concluded that for the required >> *Pf*, with the application of the classical random strategy, we should generally apply the *single-aisle* ASRS. The opposite holds true for relatively << *Pf*, where especially the *multi-aisle* ASRS should be applied. A higher efficiency of the *multi-aisle* ASRS can be achieved by applying the most effective storage strategies and introducing a class-based ABC storage system.

3 CONCLUSIONS

In this paper an improved design model of the ASRS is presented. Due to the great complexity and the difficult optimization of the warehouse, the conventional design process rises to higher and more demanding levels, in the form of the computer-aided design and optimization of warehousing systems [13]. The presented design model is based on the structured approach [13] and refers to the single deep-storage system with several picking aisles. The essential part of the design model is the application of two different systems: (*i*) the *single-aisle* ASRS and (*ii*) the *multi-aisle* ASRS. Unlike the *single-aisle* ASRS ([24] and [25]) the *multi-aisle* ASRS has not been investigated much in the literature *več hodnikih* v literaturi veliko manj raziskani [22]. Zato smo v model načrtovanja vključili izpopolnjen analitični model za določitev zmogljivosti omenjenih sistemov [2]. Zaradi zahtev po stroškovno optimalni in hkrati tehnično zelo zmogljivi izvedbi skladišča, smo oblikovali namensko funkcijo *Min. TC*. Namenska funkcija je predstavljena z matematičnim modelom, ki vključuje projektne spremenljivke (S, R, Y, N_x, N_y), vse pomembne obratovalne in fizične parametre ter investicijske in obratovalne stroške [2]. Zaradi nelinearnosti namenske funkcije, njene diskretne oblike in predlaganih projektnih spremenljivk smo za optimizacijo projektnih spremenljivk v namenski funkciji *NSS* uporabili *postopek genetskih algoritmov* ([16] in [17]). Na temelju rezultatov optimizacije projektnih spremenljivk v namenski funkciji *Min. TC* in glede na določen *sistem* RD, lahko podamo naslednje glavne sklepe opravljene analize:

Glede na vrednost skupnih stroškov (diagrami na slikah 4*i*, 4*ii*, 4*iii* in 4*iv*) v odvisnosti od števila RO v vodoravni smeri x in v navpični smeri y, lahko povzamemo, da je stroškovno optimalna različica ARSS (za oba *sistema* RD) dosežena pri visokem N_y = 13 RO in dolgem N_x = 28 RO skladiščnem regalu. Omenjena odvisnost se navezuje na določen ARSS in predpisane projektne omejitve skladišča e_i [2]. Ugotovitev lahko pojasnimo z dejstvom, da veliki SR omogočajo doseganje visoke Q skladišča, kar vpliva na manjše število hodnikov R in zato na manjšo površino skladišča. To ima za posledico manjše število RD < S (še posebej očitno pri *sistemu* RD *za delo v enem hodniku)*, kar se izkazuje skozi celotne stroške investicije.

V odvisnosti primerjave *sistema* RD *za delo v enem in več hodnikih* (sl. 5) opazimo izrazit vpliv *Pf* skladišča na znesek celotne investicije. Analiza je bila izvedena za določen ARSS z zalogovno velikostjo Q = 15000 TSE in pretočno zmogljivostjo, ki smo jo spreminjali v mejah od Pf = (60 do 160) TSE/h [2]. Splošna ugotovitev glede naraščanja zahtevane *Pf* skladišča je, da je za obravnavani ARSS, pri << *Pf* skladišča, primerno uporabiti *sistem* RD *za delo v več hodnikih*. V primeru uporabe *sistema* RD *za delo v več hodnikih* pri zahtevani Pf = 60 TSE/h, znaša odstopanje med *sistemoma* RD 840•10^3 €, kar narekuje nujno potrebo po vrednotenju obeh izvedb RD v postopku načrtovanja skladišč. Na sliki 5 lahko vidimo, da se znesek investicije v odvisnosti od zahtevane *Pf* skladišča povečuje diskretno in ustreza izbiri vse do vrednosti Pf = 140 TSE/h. Nad omenjeno

[22]. Therefore, newly improved analytical travel-time models for the *single*- and *multi-aisle* systems have been included in the design model [2]. Due to requirements for the most economical design and at the same time technically highly efficient warehouse, the objective function *Min. TC*. has been formed. The objective function is represented by a mathematical model, which includes the decision variables (S, R, Y, N_x, N_y), all the relevant operational and physical parameters, the investment and the operating costs [2]. Due to the non-linearity of the *Min. TC*, its discrete shape and proposed decision variables, *the method of genetics algorithms* has been applied ([16] and [17]) in order to optimize the decision variables. On the basis of the results of the optimization of the decision variables in the *Min. TC* and with regard to the *single*- and *multi-aisle* system, the following conclusions can be drawn.

With regard to the total costs (the diagrams in Figures 4*i*, 4*ii*, 4*iii*, 4*iv*) in accordance with the number of storage compartments in the horizontal direction x and the vertical direction y, it can be concluded that the most economical design (for both types of the ASRS) is achieved with a high, (N_y = 13 storage compartments), and long (N_x = 28 storage compartments) storage rack. The above-mentioned dependence refers to the analysed ASRS and the prescribed project constraints e_i [2]. This finding can be explained with the fact that large SRs enable the achievement of a high warehouse volume of the warehouse, which influences a small number of picking aisles R and consequently a smaller width of the warehouse. Therefore, the number of SR machines is lower < S (particularly evident with the *single-aisle* ASRS), which shows in the overall costs of the investment.

Depending on the comparison of the *single*- and *multi-aisle* ASRS (Figure 5), a significant influence of the *Pf* of the warehouse on the total costs of the investment can be seen. The analysis was carried out for the ASRS with the storage volume Q = 15000 TUL and throughput capacity that was changed within the limits of Pf = (60 to 160) TUL/h [2]. The general ascertainment regarding the increase of the required *Pf* of the warehouse is that for the particular ASRS, at << *Pf* of the warehouse, it is reasonable to apply the *multi-aisle* ASRS. If the *multi-aisle* ASRS is applied at the required Pf = 60 TUL/h, there is a deviation (of 840·10^3 €) between the two systems, which calls for of the need to evaluate both *single*- and *multi-aisle* systems in the design process. Figure 5 indicates that the investment according to the required *Pf* of the warehouse increases vrednostjo je smiselno izbrati *sistem* RD *za delo v enem hodniku*, saj je *sistem* RD *za delo v več hodnikih* že močno obremenjen in obsega že štiri RD pri sedmih regalnih hodnikih (S = 4, R = 7). Predstavljena odvisnost na sliki 5 ima zelo velik pomen pri načrtovanju skladišč in omogoča ustrezno izbiro *sistema* RD v odvisnosti od zalogovne velikosti Q in zahtevane pretočne zmogljivosti Pf skladišča.

steadily and suits the choice up to the value Pf = 140 TUL/h. Above this value it is reasonable to choose the *single-aisle* ASRS, since the *multi-aisle* ASRS is already overloaded and encompasses four SR machines with seven picking aisles (S = 4, R = 7). The dependence shown in Figure 5 is extremely important when designing warehouses, since it enables the appropriate choice of the ASRS depending on the warehouse volume Q and the required throughput capacity Pf of the warehouse.

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4 OZNAKE
4 NOMENCLATURE

Projektne spremenljivke			**Decision variables**
število regalnih hodnikov	R		the number of picking aisles
število skladiščnih regalov	Y		the number of SR
število regalnih dvigal	S		the number of S/R machines
število regalnih oken v vodoravni smeri	N_x		the number of storage compartments in the horizontal direction
število regalnih oken v navpični smeri	N_y		the number of storage compartments in the vertical direction
Operacijski parametri			**Operational parameters**
zalogovna velikost skladišča	Q	TSE/TUL	warehouse volume (rack capacity)
pretočna zmogljivost	Pf	TSE/h / TUL/h	throughput capacity
število TSE v regalnem oknu	n		the number of TUL in storage compartment
širina palete	w	mm	the width of the pallet
dolžina palete	g	mm	the length of the pallet
višina TSE	h	mm	the height of the TUL
število enojnih delovnih krogov	n_{SC}		the number of single command cycles
število dvojnih delovnih krogov	n_{DC}		the number of dual command cycles
povprečni čas enojnega delovnega kroga	T(SC)	s	the average single command cycle time
povprečni čas dvojnega delovnega kroga	T(DC)	s	the average dual command cycle time

čas za delovno izmeno	T	h	time for one shift
zmogljivost regalnega dvigala	η		the efficiency of the S/R machine
dolžina regalnega veznika (nosila)	L_v	mm	the length of the rack beam
dodatek za ojačitev skladiščnih regalov	PD	%	the addition to the reinforcement of storage racks,
dolžina regalnega okna	L_{RO}	mm	the length of the storage compartment
višina regalnega okna	H_{RO}	mm	the height of the storage compartment
globina regalnega okna	G_{RO}	mm	the width of the storage compartment
dolžina skladiščnega regala	L_{RS}	mm	the length of the SR
višina skladiščnega regala	H_{RS}	mm	the height of the SR
dolžina transportne cone	L_{TZ}	mm	the length of the transport zone
dolžina skladišča	L_{WAR}	mm	the length of the warehouse
višina skladišča	H_{WAR}	mm	the height of the warehouse
širina skladišča	W_{WAR}	mm	the width of the warehouse
površina zemljišča za skladišče	P_Z		the surface of the land for the warehouse
delež zazidanosti skladišča	D_Z		the share of the built warehouse
varnostni dodatek za širino regalnega okna	b_1	mm	the safety addition to the width of the storage compartment
varnostni dodatek za višino regalnega okna	b_2	mm	the safety addition to the height of the storage compartment
širina stebra	b_4	mm	the width of the upright frame,
debelina stebra	b_5	mm	the thickness of the upright frame
višina regalnega nosila	b_6	mm	the height of rack beams
odmik regalnega okna od tal	b_7	mm	the deviation of the storage compartment from the floor
varnostni razmik med soležnimi regali	b_8	mm	the safety spacing between racks that are placed close to each other
varnostni dodatek za višino skladišča	b_9	mm	the safety addition to the height of the warehouse
dodatek za širino palete na prevzemnem mestu	b_{10}	mm	the addition to the width of the palette at input buffer
dodatek na koncu skladišča	b_{20}	mm	the addition to the end of the warehouse
Investicijski parametri			**Investment cost parameters**
strošek za nakup zemljišča	C_1	€/m^2	cost of buying the land
strošek za postavitev temeljne plošče	C_2	€/m^2	cost of laying the foundations
strošek za postavitev sten skladišča	C_3	€/m^2	warehouse cost of building the walls of the
strošek za postavitev strehe skladišča	C_4	€/m^2	cost of building the roof of the warehouse
strošek za nakup regalnih stranic	C_5	€/m^2	cost of buying upright frames
strošek za nakup regalnih veznikov	C_6	€/m^2	cost of buying rack beams
strošek za nakup prevzemnih miz	C_7	€	cost of buying buffers
strošek montaže	C_8	€	cost of the assembly
strošek požarne varnosti	C_9	€	cost of fire safety
strošek prezračevanja	C_{10}	€	cost of air ventilation
strošek za nakup transportnega viličarja	C_{11}	€	cost of buying a lift truck
strošek za nakup regalnega viličarja	C_{12}	€	cost of buying a reach truck
strošek za nakup regalnega dvigala	C_{13}	€	cost of buying S/R machine
strošek regalnega hodnika	C_{14}	€	cost of the picking aisle
strošek prečnega hodnika	C_{15}	€	cost of the cross aisle
strošek zveznega transporterja	C_{16}	€	cost of the accumulating conveyor
strošek preusmeritvenega elementa	C_{17}	€	cost of the diverted element

Parametri stroškov obratovanja			Operational cost parameters
delež vrednosti regalnega dvigala za vzdrževanje	P	%	the share of the value of the S/R machine for maintenance
strošek osebnega dohodka za viličariste, ki delajo z transportnimi in regalnimi viličarji	C_{OD}	€	the cost of personal income for operators working with lift trucks and reach trucks
neto sedanja vrednost	NPV	–	net present value
predvidena življenska doba obratovanja ARSS	T_i	let/years	the anticipated life expectancy of the operation of the AS/RS
diskontna stopnja	r	%	the discount rate

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Naslov avtorjev: dr. Tone Lerher
prof.dr. Iztok Potrč
Univerza v Mariboru
Fakulteta za strojništvo
Smetanova 17
2000 Maribor
tone.lerher@uni-mb.si
iztok.potrc@uni-mb.si

Authors‘ address: Dr. Tone Lerhet
Prof.Dr. Iztok Potrč
University of Maribor
Faculty of Mechanical Eng.
Smetanova 17
2000 Maribor, Slovenia
tone.lerher@uni-mb.si
iztok.potrc@uni-mb.si

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