

# Skedulering van gade-vermydende gemengde-dubbels rondomtalie-tennistoernooie

*Scheduling spouse-avoiding mixed doubles round-robin tennis tournaments*

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## ABSTRACT

### *Scheduling spouse-avoiding mixed doubles round-robin tennis tournaments*

The problem of scheduling a spouse-avoiding mixed doubles round-robin tennis tournament (SMDRTT) of order  $n$  involves finding a playing schedule for  $n$  married couples in such a way that no player teams up with his/her spouse, no player opposes his/her spouse, each player opposes every other player of the same sex exactly once, each player teams up with every player of the opposite sex (except his/her spouse) exactly once, and each player opposes every player of the opposite sex (except his/her spouse) exactly once. These mixed doubles tennis matches have to be partitioned into the smallest number of rounds so that no player plays more than once per round and so that each round comprises the maximum number of matches. If  $n$  is even, then each player may be scheduled to compete in every round and hence an SMDRTT of even order  $n$  comprises  $n - 1$  rounds, each containing  $n/2$  matches. However, if  $n$  is odd, then one man and one woman must necessarily receive a bye during each round and hence an SMDRTT of odd order  $n$  comprises  $n$  rounds, each containing  $(n - 1)/2$  matches.

The notion of an SMDRTT may be attributed to the director of the Briarcliff Racquet Club in New York, who sought such a schedule for his club in 1972. His motivation was that spouses know each other too well and hence may have an unfair advantage with respect to anticipating elements in each other's play. Although it is known that results from the mathematical subdiscipline of design theory may be used to construct SMDRTTs of virtually any order, neither these techniques nor the application thereof is easily accessible to administrators of tennis clubs, who are typically not mathematicians. The aim in this paper is therefore two-fold:

- (I) to investigate which techniques from design theory are applicable in the construction of playing schedules for SMDRTTs, and
- (II) to apply these techniques in the construction of playing schedules for SMDRTTs of order  $n \leq 20$ , and to document the resulting schedules in a way that is easily accessible to non-mathematicians.

It transpires that the notion of a Latin square is central in the construction of SMDRTT playing schedules. A Latin square of order  $n$  is an  $n \times n$  array of  $n$  symbols arranged so that each row and each column of the array contains every symbol (exactly once). Two Latin squares of order  $n$  are said to be orthogonal if, when super-imposed on one another, all  $n^2$  ordered pairs of symbols appear (exactly once). A Latin square is called self-orthogonal if it is orthogonal to its transpose. It is well known that self-orthogonal Latin squares of all orders  $n > 3$  exist, except for  $n = 6$ . In fact, if  $p$  is a prime number,  $q$  is a natural number and  $\lambda$  is an element of the Galois field of order  $p^q$  (with  $\lambda \neq 0, 1, 2^{-1}$ ), then a well-known 1971-result states that the array whose entry in row  $y$  and column  $z$  is the linear combination  $\lambda y + (1 - \lambda)z$ , is a self-orthogonal Latin square of order  $p^q$ , where arithmetic is performed over the field. This result may be combined with the well-known result that the Kronecker product of two self-orthogonal Latin squares of orders  $n_1$  and  $n_2$  is a self-orthogonal Latin square of order  $n_1 n_2$ , in order to construct a self-orthogonal Latin square of virtually any order. The following characterisation has been known since 1973: The matches of an SMDRTT of order  $n$  can be listed if and only if there exists a self-orthogonal Latin square  $\mathbf{L} = [L_{ij}]$  of order  $n$  satisfying

$$L_{ii} = i \quad \text{for all } i \in \{0, \dots, n - 1\}. \quad (1)$$

If such a Latin square exists, then the matches of the SMDRTT may be read off from the upper-triangular part of the square. More specifically, in the match in which man  $i$  opposes man  $j$ , woman  $L_{ij}$  should be the team mate of man  $i$ , while woman  $L_{ji}$  should be the team mate of man  $j$ . It is therefore easy to list the matches of an SMDRTT of order  $n$  for all  $n \neq 6$ . However, this leaves the far more difficult problem of scheduling these matches into rounds satisfying the requirements set out above.

A pair of Latin squares  $\mathbf{L}, \mathbf{S}$  of order  $n$  for which it holds that (i)  $\mathbf{L}$  is self-orthogonal, (ii)  $\mathbf{S}$  is symmetric, and (iii)  $\mathbf{L}$  and  $\mathbf{S}$  (and hence  $\mathbf{L}^T$  and  $\mathbf{S}$ ) are orthogonal is known as a self-orthogonal Latin square with symmetric orthogonal mate (SOLSSOM) of order  $n$ . A SOLSSOM  $\mathbf{L}, \mathbf{S}$  of order  $n$  is said to be regular if the square  $\mathbf{L} = [L_{ij}]$  satisfies (1) and the square  $\mathbf{S} = [S_{ij}]$  satisfies

$$S_{ii} = \begin{cases} n-1 & \text{if } n \text{ is even} \\ i & \text{if } n \text{ is odd.} \end{cases} \quad (2)$$

If a regular SOLSSOM  $\mathbf{L}, \mathbf{S}$  of order  $n$  is known, then the matches of an SMDRRT of order  $n$  may be listed by means of the self-orthogonal square  $\mathbf{L}$  as described above. It has additionally been known since 1978 that these matches may be scheduled into rounds satisfying the requirements set out above by means of the symmetric orthogonal mate  $\mathbf{S}$ . In particular, the match in which men  $i$  and  $j$  oppose each other may be scheduled in round  $S_{ij}$  for all  $i, j \in \{0, \dots, n-1\}$  in order to form an SMDRRT of order  $n$ . SOLSSOMs of all orders  $n > 3$  exist, except for  $n = 6$  and possibly  $n = 10, 14$ . We therefore use the last result mentioned above to construct SMDRRTs of orders  $n = 4, 5, 7, 8, 9, 11, 12, 13, 15, 16, 17, 18, 19$  and 20 — playing schedules for these SMDRRT may be found in the appendix to the paper. For the outstanding cases ( $n = 6, 10, 14$ ) we additionally provide good playing schedules that are not necessarily optimal (in the sense that these schedules do not adhere exactly to the tournament rules, but contain a certain level of redundancy in terms of teams and opponents).

**KEY CONCEPTS:** Spouse-avoiding mixed-doubles round-robin tennis tournament, Latin square.

## OPSOMMING

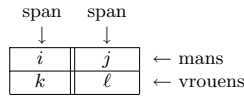
By die opstel van 'n gade-vermydende gemengde-dubbels rondomtalie-tennistoernooi van orde  $n$  word daar gesoek na 'n spelskedule waarvolgens  $n$  getroude pare op só 'n manier in gemengde-dubbels tennispotte kragte meet dat geen speler saam met sy/haar eggenoot in 'n span afgepaar word nie, geen speler teen sy/haar eggenoot te staan kom nie, elke speler presies een keer teen elke ander speler van dieselfde geslag te staan kom, elke speler presies een keer saam met elke speler van die teenoorgestelde geslag (behalwe sy/haar gade) in 'n span afgepaar word, en elke speler presies een keer teen elke speler van die teenoorgestelde geslag (behalwe sy/haar gade) te staan kom. Hierdie potte moet boonop in die kleinste moontlike aantal rondtes ingedeel word sodat geen speler in meer as een pot per rondte meeding nie, en sodat die aantal potte per rondte dieselfde en 'n maksimum is. Spelskedules vir sulke toernooie word vir  $n \leq 20$  opgestel en ter wille van naslaandoeleindes op 'n gebruikersvriendelike manier gedokumenteer.

**TREFWOORDE:** Gade-vermydende gemengde-dubbels rondomtalie-tennistoernooi, Latynse vierkant.

## 1 INLEIDING

In 'n *gemengde-dubbels* tennispot bestaan die twee opponerende spanne elk uit een manlike en een vroulike speler. Elke gemengde-dubbels tennisspan moet een keer in 'n *rondomtalie-tennistoernooi* teen elke ander span kragte meet. Die skedulering van 'n *gade-vermydende gemengde-dubbels rondomtalie-tennistoernooi* van orde  $n$ , wat ons as 'n *GGRTT* van orde  $n$  sal afkort, behels die soeke na 'n spelskedule waarvolgens  $n$  getroude pare (man 0, vrou 0), (man 1, vrou 1), ..., (man  $n-1$ , vrou  $n-1$ ) op só 'n manier in  $\binom{n}{2} = n(n-1)/2$  tennispotte kragte meet, dat:

- (V1) geen speler saam met sy/haar eggenoot in 'n span afgepaar word nie,
- (V2) geen speler teen sy/haar eggenoot te staan kom nie,
- (V3) elke speler presies een keer teen elke ander speler van dieselfde geslag te staan kom,
- (V4) elke speler presies een keer saam met elke speler van die teenoorgestelde geslag in 'n span speel,
- (V5) elke speler presies een keer teen elke speler van die teenoorgestelde geslag te staan kom.



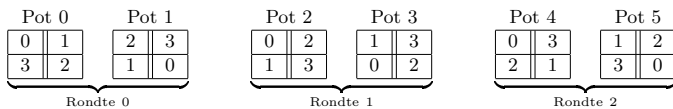
**Figuur 1:** Roosternotasie vir die spelers in 'n GGRTT-pot.

Ons gebruik die roosternotasie in Figuur 1 om 'n tennispot voor te stel waarin die paar (man  $i$ , vrou  $k$ ) teen die paar (man  $j$ , vrou  $\ell$ ) te staan kom. Die potte van 'n GGRTT van orde  $n$  kan **gelys** word deur  $2(n - 1)$  kopieë van die getalle  $0, 1, \dots, n - 1$  in  $\binom{n}{2}$  roosters van die formaat in Figuur 1 te rangskik sodat:

- (A) elke *ongeordende* paar van *verskillende* getalle uit die versameling  $\{0, 1, \dots, n - 1\}$  een keer in beide die boonste en onderste rye van 'n rooster voorkom,
- (B) elke *geordende* paar van *verskillende* getalle uit die versameling  $\{0, 1, \dots, n - 1\}$  een keer as 'n kolom van 'n rooster voorkom, en
- (C) elke *geordende* paar van *verskillende* getalle uit die versameling  $\{0, 1, \dots, n - 1\}$  een keer in 'n [NW-SO of NO-SW] diagonaal van 'n rooster voorkom.

Vereiste (A) verseker dat daar aan voorwaarde (V3) voldoen word, terwyl vereistes (B) en (C) verseker dat daar aan onderskeidelik voorwaardes (V4) en (V5) voldoen word. Die feit dat die geordende pare in vereistes (B) en (C) verskillend moet wees, verseker dat daar aan onderskeidelik voorwaardes (V1) en (V2) voldoen word.

Hierdie potte moet dan in 'n aantal **ronktes gegroepeer of ingedeel** word met dien verstande dat geen speler in meer as een pot per rondte mag meeding nie, sodat al die potte van 'n rondte gelyktydig gespeel kan word (indien daar genoeg tennisbane vir hierdie doel is). Indien die potte van 'n GGRTT in die minimum aantal rondtes ingedeel is (en die aantal potte per rondte dus 'n maksimum is), sê ons die potte van die GGRTT is optimaal in rondtes beslis, en verwys ons na die spelskedule vir  $n$  getroude pare as 'n *optimaal besliste GGRTT van orde  $n$* , afgekort as 'n *OBGGRTT van orde  $n$* . Indien  $n$  ewe is, kan elke speler potensieel geskeduleer word om in elke rondte mee te ding, en bestaan 'n OBGGRTT van orde  $n$  uit  $n - 1$  rondtes van  $n/2$  potte elk. Indien  $n$  eger onewe is, moet minstens een man en een vrou noodgedwonge 'n loslootjie per rondte ontvang, en bestaan 'n OBGGRTT van orde  $n$  uit  $n$  rondtes van  $(n - 1)/2$  potte elk. 'n Voorbeeld van 'n OBGGRTT van orde  $n = 4$  word in Figuur 2 getoon. Die aantal tennisbane wat vir die toernooi benodig word (sodat die potte van 'n rondte gelyktydig gespeel kan word) is dus twee.



**Figuur 2:** 'n Voorbeeld van 'n OBGGRTT van orde 4 in die roosternotasie van Figuur 1.

Die direkteur van die Briarcliff Racquet Club in New York het in 1972 met die begrip van 'n GGRTT vorendag gekom [12]. As motivering hiervoor het hy aangevoer dat 'n getroude paar se spel deur hulle verhouding beïnvloed word, en dat dit gevolglik onwenslik is dat hulle in 'n gemengde-dubbels rondomtalie-tennistoernooi 'n span vorm of teen mekaar te staan kom. Die outeurs van hierdie artikel het tydens 'n persoonlike kommunikasie met Laurie [15] van die begrip van 'n GGRTT bewys geword, nadat Laurie deur Lisa de Swardt van *Rekreasie Tennisklub* op Somerset-Wes genader is om so 'n toernooi vir die klub te skeduleer. Dit het tydens daaropvolgende gesprekke met lede van ander tennisklubs en navorsing oor verwysings na GGRTT'e in die literatuur vir die outeurs duidelik geword dat hoewel tegnieke uit ontwerpteorie gebruik kan word om OBGGRTT'e van bykans alle ordes te vind, nòg die toepassing van sulke tegnieke, nòg die resultate van sulke toepassings toeganklik is vir

administrateurs van tennisklubs (wat tipies nie wiskundiges is nie). Die doel van hierdie artikel is dus tweeledig:

- (I) om ondersoek in te stel na die tegnieke uit ontwerpteorie wat gebruik kan word om op 'n wiskundig verantwoordbare wyse met OBGGRIT'e vorendag te kom, en
- (II) om hierdie tegnieke vir OBGGRIT'e van ordes  $n \leq 20$  toe te pas en die resultate daarvan op 'n gebruikersvriendelike manier te dokumenteer, sodat die resulterende skedules op 'n naslaanbasis toeganklik is vir nie-wiskundiges.

Die begrip van 'n *Latynse vierkant* speel 'n sentrale rol by die opstel van OBGGRIT'e. Ons wy dus §2 van hierdie artikel aan 'n aantal basiese resultate oor Latynse vierkante en wys in §3 hoe hierdie resultate gebruik kan word om OBGGRIT'e op te stel. Dit sal in hierdie twee afdelings duidelik word dat OBGGRIT'e van alle ordes  $n > 3$  bestaan (en met behulp van Latynse vierkante gevind kan word), afgesien van  $n = 6$  en moontlik  $n = 10, 14$ . In §4 maak ons voorstelle ten opsigte van die bevredigende (maar nie noodwendig optimale) hantering van die gevalle  $n = 6, 10$  en  $14$ , waarna 'n aantal slotopmerkings en oop probleme in §5 volg. 'n Gebruikersvriendelike lys van OBGGRIT'e van ordes  $4 \leq n \leq 20$  ( $n \neq 6, 10, 14$ ) asook 'n lys van goeie rondte-beslissings vir toernooie van ordes  $n = 6, 10, 14$  verskyn ter wille van naslaandoelendes in 'n aanhangsel aan die einde van die artikel. Hierdie aanhangsel bevat geen wiskundige inhoud nie, en nie-wiskundige lesers wat bloot in die uiteindelijke spelskedules belangstel, kan die inhoud van die artikel gevolglik met vrug oorslaan, en direk na die aanhangsel blaai.

## 2 LATYNSE VIERKANTE

'n *Latynse vierkant* van orde  $n$  is 'n  $n \times n$  skikking van  $n$  simbole waarin elke simbool een keer in elke ry en elke kolom verskyn [7, §II.1.1]. Twee voorbeelde van Latynse vierkante van orde 3 is

$$\mathbf{\Lambda}^{(1)} = \begin{bmatrix} 0 & 1 & 2 \\ 1 & 2 & 0 \\ 2 & 0 & 1 \end{bmatrix} \text{ en } \mathbf{\Lambda}^{(2)} = \begin{bmatrix} 0 & 1 & 2 \\ 2 & 0 & 1 \\ 1 & 2 & 0 \end{bmatrix}. \quad (3)$$

Die groot wiskundige Leonhard Euler (1707–1783) het belangstelling in Latynse vierkante getoon, en was die eerste persoon om Latynse simbole in sy skikkings te gebruik, vanwaar die benaming *Latynse vierkante*.

Ons dui die versameling  $\{0, 1, 2, \dots, n-1\}$  deur middel van die gebruikelike simbool  $\mathbb{Z}_n$  aan, en gebruik hierdie simbole deurgaans in 'n Latynse vierkant van orde  $n$ . Die rye en kolomme van die vierkante word ook deurgaans  $0, 1, 2, \dots, n-1$  genommer. Tesame met die binêre operasies *optelling* (+) en *vermenigvuldiging* ( $\times$ ) modulo  $n$  vorm die versameling  $\mathbb{Z}_n$  'n *ring* in die terminologie van abstrakte algebra [1, §3.2, Definisie 3.2.2]. Die sogenaamde  $\lambda$ -lineêre kombinasietabel van die ring  $(\mathbb{Z}_n, +, \times)$  is 'n  $n \times n$  skikking waarvan die element in ry  $i$  en kolom  $j$  gegee word deur  $(\lambda \times i) + j \pmod{n}$ , vir alle  $i, j = 0, \dots, n-1$ . Dit is maklik om aan te toon dat indien  $\lambda$  en  $n$  relatief priem is (m.a.w. geen gemene faktore groter as 1 besit nie), hierdie  $\lambda$ -lineêre kombinasietabel 'n Latynse vierkant is. Trouens, die Latynse vierkante  $\mathbf{\Lambda}^{(1)}$  en  $\mathbf{\Lambda}^{(2)}$  in (3) is onderskeidelik die 1- en 2-lineêre kombinasietabelle van die ring  $(\mathbb{Z}_3, +, \times)$ . Gevolglik is daar Latynse vierkante van alle ordes  $n \in \mathbb{N}$ , en is dit maklik om sulke vierkante te konstrueer.

Twee Latynse vierkante word *verskillend* genoem indien hulle inskrywings in minstens een posisie van mekaar verskil. Die vierkante  $\mathbf{\Lambda}^{(1)}$  en  $\mathbf{\Lambda}^{(2)}$  in (3) is dus verskillend, omdat hulle in hul laaste twee rye verskillende inskrywings het. Die aantal verskillende Latynse vierkante van orde  $n$  groei baie vinnig as 'n funksie van  $n$  soos wat  $n$  toeneem; sien byvoorbeeld die laaste kolom van Tabel 1.

Daar word gesê dat 'n Latynse vierkant *gereduseer* is indien die eerste ry en kolom daarvan die elemente  $0, 1, \dots, n-1$  in volgorde bevat. 'n Gereduseerde Latynse vierkant kan deur middel van 'n

**TABEL 1:** Aantal isotoopklasse, reduksieklasse en verskillende Latynse vierkante van orde  $2 \leq n \leq 9$  [21].

$n$	Aantal isotoopklasse	Aantal reduksieklasse	Aantal verskillende Latynse vierkante
2	1	1	2
3	1	1	12
4	2	4	576
5	2	56	161 280
6	22	9 408	812 851 200
7	564	16 942 080	61 479 419 904 000
8	1 676 267	535 281 401 856	108 776 032 459 082 956 800
9	115 618 721 533	377 597 570 964 258 816	5 524 751 496 156 892 842 531 225 600

permutasie van die rye en kolomme daarvan tot enigeen in 'n versameling van  $n!(n-1)!$  verskillende Latynse vierkante (bekend as 'n *reduksieklas*) omvorm word [14, §1.2, Stelling 1.2], en die oorspronklike gereduseerde Latynse vierkant kan weer deur middel van die omgekeerde permutasieproses (bekend as *reduksie*) uit enige Latynse vierkant in die reduksieklas herwin word. Die vierkant  $\mathbf{\Lambda}^{(1)}$  in (3) is 'n voorbeeld van 'n gereduseerde Latynse vierkant van orde 3, terwyl die vierkant  $\mathbf{\Lambda}^{(2)}$  nie gereduseer is nie.  $\mathbf{\Lambda}^{(2)}$  kan egter tot  $\mathbf{\Lambda}^{(1)}$  gereduseer word deur die laaste twee rye daarvan om te ruil; gevolglik is hierdie twee vierkante lede van dieselfde reduksieklas. Daar is trouens volgens Tabel 1 net een reduksieklas van orde 3, terwyl die vier gereduseerde Latynse vierkante

$$\mathbf{\Gamma}^{(1)} = \begin{bmatrix} 0 & 1 & 2 & 3 \\ 1 & 0 & 3 & 2 \\ 2 & 3 & 0 & 1 \\ 3 & 2 & 1 & 0 \end{bmatrix}, \quad \mathbf{\Gamma}^{(2)} = \begin{bmatrix} 0 & 1 & 2 & 3 \\ 1 & 0 & 3 & 2 \\ 2 & 3 & 1 & 0 \\ 3 & 2 & 0 & 1 \end{bmatrix}, \quad \mathbf{\Gamma}^{(3)} = \begin{bmatrix} 0 & 1 & 2 & 3 \\ 1 & 2 & 3 & 0 \\ 2 & 3 & 0 & 1 \\ 3 & 0 & 1 & 2 \end{bmatrix} \quad \text{en} \quad \mathbf{\Gamma}^{(4)} = \begin{bmatrix} 0 & 1 & 2 & 3 \\ 1 & 3 & 0 & 2 \\ 2 & 0 & 3 & 1 \\ 3 & 2 & 1 & 0 \end{bmatrix} \quad (4)$$

van orde 4 almal lede van verskillende reduksieklasse is, en hierdie klasse is volgens Tabel 1 die enigste reduksieklasse van orde 4. Om die  $576 = 4 \times 4!$  verskillende Latynse vierkante van orde 4 te verkry, kan die kolomme van elkeen van die bogenoemde vierkante op  $4!$  maniere gepermuteer word en kan die laaste drie rye vir elkeen van hierdie permutasies op 'n verdere  $3!$  maniere gepermuteer word.

Twee Latynse vierkante word *isotopies* genoem indien een vierkant uit die ander verkry kan word deur 'n permutasie van die rye en kolomme daarvan, en/of van die simboolname daarin. 'n Maksimale versameling van paarsgewys isotopiese Latynse vierkante word 'n *isotoopklas* genoem. Die Latynse vierkante  $\mathbf{\Gamma}^{(2)}$ ,  $\mathbf{\Gamma}^{(3)}$  en  $\mathbf{\Gamma}^{(4)}$  is paarsgewys isotopies en dus lede van dieselfde isotoopklas, terwyl  $\mathbf{\Gamma}^{(1)}$  nie 'n lid van dieselfde isotoopklas is nie. Ry-, kolom- en simboolnaam-permutasies

$$R_i : \text{Rye}(\mathbf{\Gamma}^{(i)}) \mapsto \text{Rye}(\mathbf{\Gamma}^{(4)}), \quad K_i : \text{Kol}(\mathbf{\Gamma}^{(i)}) \mapsto \text{Kol}(\mathbf{\Gamma}^{(4)}) \quad \text{en} \quad N_i : \text{Sim}(\mathbf{\Gamma}^{(i)}) \mapsto \text{Sim}(\mathbf{\Gamma}^{(4)})$$

wat op die vierkante  $\mathbf{\Gamma}^{(i)}$  vir  $i = 2, 3$  toegepas kan word om die vierkant  $\mathbf{\Gamma}^{(4)}$  te lewer, word gegee deur

$$R_2 = \begin{pmatrix} 0123 \\ 1230 \end{pmatrix}, \quad K_2 = \begin{pmatrix} 0123 \\ 1230 \end{pmatrix}, \quad N_2 = \begin{pmatrix} 0123 \\ 0321 \end{pmatrix}$$

en

$$R_3 = \begin{pmatrix} 0123 \\ 1023 \end{pmatrix}, \quad K_3 = \begin{pmatrix} 1023 \\ 1023 \end{pmatrix}, \quad N_3 = \begin{pmatrix} 0123 \\ 3102 \end{pmatrix}.$$

## 2.1 Ortogonale Latynse vierkante

Twee Latynse vierkante  $\mathbf{L} = [L_{ij}]$  en  $\mathbf{M} = [M_{ij}]$  van orde  $n$  word *ortogonaal* genoem indien elke geordende paar van simbole een keer onder die  $n^2$  paar-inskrywings  $(L_{ij}, M_{ij})$  voorkom, soos wat  $i, j \in \mathbb{Z}_n$  varieer [7, §II.2.1, Opmerking 2.1]. Een van die vroegste geskrewe verwysings na Latynse vierkante verskyn trouens in 'n probleem wat dateer uit 1624, waarin sestien speelkaarte op só 'n wyse

in 'n  $4 \times 4$  skikking gerangskik moet word dat geen ry, kolom of (hoof)diagonaal meer as een kaart van dieselfde huis of waarde bevat nie [8, Probleem 304]. Die 1723-oplossing van hierdie probleem is 'n spesiale paar ortogonale Latynse vierkante [13]. Die twee Latynse vierkante  $\mathbf{\Lambda}^{(1)}$  en  $\mathbf{\Lambda}^{(2)}$  in (3) is ortogonaal, aangesien al nege geordende pare in die skikking

$$(\mathbf{\Lambda}^{(1)}, \mathbf{\Lambda}^{(2)}) = \begin{bmatrix} (0,0) & (1,1) & (2,2) \\ (1,2) & (2,0) & (0,1) \\ (2,1) & (0,2) & (1,0) \end{bmatrix}$$

voorkom. Dit is nie toevallig dat die Latynse vierkante  $\mathbf{\Lambda}^{(1)}$  en  $\mathbf{\Lambda}^{(2)}$  in (3) ortogonaal is nie, soos wat in die volgende resultaat verwoord word.

**Stelling 1 ([7, §II.2.3, Stelling 2.20])** *Gestel  $n$  is priem. Dan is die  $\lambda$ -lineêre kombinasietabelle van  $\mathbb{Z}_n$  vir alle  $\lambda \in \mathbb{Z}_n \setminus \{0\}$  'n versameling van  $n - 1$  paarsgewys ortogonale Latynse vierkante. ■*

Hierdie resultaat kan egter veralgemeen word deur van die algebraïese begrip van 'n *eindige liggaam* [1, §3.2, Definisie 3.2.2] gebruik te maak.

## 2.2 Ortogonale Latynse vierkante van orde 'n priem mag

Laat  $p$  'n priemgetal wees, en dui die versameling van alle polinome met koëffisiënte in  $\mathbb{Z}_p$  aan deur  $\mathbb{Z}_p[x]$ . Volgens die delingsalgoritme [9, §17.1, Stelling 17.3] bestaan daar vir elke paar polinome  $f(x), g(x) \in \mathbb{Z}_p[x]$  'n unieke paar polinome  $q(x), r(x) \in \mathbb{Z}_p[x]$ , met die graad van  $r(x)$  streng kleiner is as dié van  $f(x)$ , sodat  $g(x) = q(x)f(x) + r(x)$ . Die polinoom  $r(x)$  word die *res* ná deling van  $g(x)$  deur  $f(x)$ , of die *res* van  $g(x)$  modulo  $f(x)$  genoem. Indien  $r(x) = 0$ , word  $q(x)$  en  $f(x)$  *faktore* van  $g(x)$  genoem. 'n Polinoom word *onverdeelbaar* oor  $\mathbb{Z}_p[x]$  genoem indien dit geen faktore van graad minstens 1 oor  $\mathbb{Z}_p[x]$  besit nie. Ons dui die versameling van alle reste van polinome in  $\mathbb{Z}_p[x]$  modulo  $f(x)$  deur middel van die simbole  $\mathbb{Z}_p[x]/f(x)$  aan. Die volgende resultaat is goed bekend.

**Stelling 2 ([9])** *Die versameling  $\mathbb{Z}_p[x]/f(x)$  tesame met die binêre operasies polinoomoptelling en polinoomvermenigvuldiging modulo  $f(x)$  vorm 'n eindige liggaam van orde  $p^q$  as en slegs as  $f(x)$  'n onverdeelbare polinoom van graad  $q$  oor  $\mathbb{Z}_p[x]$  is. ■*

Die eindige liggaam waarvan daar in die bogenoemde stelling melding gemaak word, staan as die *Galois liggaam van orde  $p^q$*  bekend en word aangedui deur  $GF(p^q)$ , omdat Evariste Galois (1811–1832) bewys het dat *alle* eindige liggame die vorm het wat in Stelling 2 beskryf word [9, §17.2, Stelling 17.13]. Die volgende resultaat is 'n veralgemening van Stelling 1.

**Stelling 3 ([9, §17.3, Stelling 17.16])** *Laat  $n = p^q$ , waar  $p$  priem is, en  $q \in \mathbb{N}$ . Dan bring die polinome  $\lambda y + z$  vir enige nie-nul element  $\lambda \in GF(n)$  'n Latynse vierkant voort soos wat  $y$  en  $z$  oor die elemente van  $GF(n)$  varieer. Verder is die versameling van  $n - 1$  Latynse vierkante wat só verkry word deur  $\lambda \in GF(n)$  te laat varieer ( $\lambda \neq 0$ ), paarsgewys ortogonaal. ■*

Beskou byvoorbeeld die polinoom  $f^*(x) = 1 + x + x^2$  wat onverdeelbaar oor  $\mathbb{Z}_2[x]$  is. In hierdie geval is die versameling reste  $\mathbb{Z}_2[x]/f^*(x)$  alle polinome in  $\mathbb{Z}_2[x]$  van graad hoogstens 1, met ander woorde  $\{0, 1, x, 1 + x\}$ . Die optel- en vermenigvuldigingstabelle van hierdie eindige liggaam,  $GF(4)$ , word deur onderskeidelik

$$\begin{array}{c|cccc} + & 0 & 1 & x & 1+x \\ \hline 0 & 0 & 1 & x & 1+x \\ 1 & 1 & 0 & 1+x & x \\ x & x & 1+x & 0 & 1 \\ 1+x & 1+x & x & 1 & 0 \end{array} \quad \text{en} \quad \begin{array}{c|cccc} \times & 0 & 1 & x & 1+x \\ \hline 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & x & 1+x \\ x & 0 & x & 1+x & 1 \\ 1+x & 0 & 1+x & 1 & x \end{array} \quad (5)$$

gegee. Die opteltabel in (5) is natuurlik ook die 1-liniêre kombinasietabel van  $GF(4)$ . Die 2- en 3-liniêre kombinasietabelle van  $GF(4)$  word gegee deur onderskeidelik

$$\begin{bmatrix} 0 & 1 & x & 1+x \\ x & 1+x & 0 & 1 \\ 1+x & x & 1 & 0 \\ 1 & 0 & 1+x & x \end{bmatrix} \quad \text{en} \quad \begin{bmatrix} 0 & 1 & x & 1+x \\ 1+x & x & 1 & 0 \\ 1 & 0 & 1+x & x \\ x & 1+x & 0 & 1 \end{bmatrix}.$$

Hierdie drie tabelle is paarsgewys ortogonale Latynse vierkante volgens Stelling 3. Die konstruksie in Stelling 3 werk nie vir  $n = 2$  nie, want dan is  $n - 1 = 1$  en lewer die konstruksie slegs een Latynse vierkant; die Galois liggaam  $GF(2)$  is te klein om die konstruksie in Stelling 3 toe te laat. Vir *alle* ander eindige liggame is die konstruksie egter geldig.

### 2.3 Ortogonale Latynse vierkante van saamgestelde orde

Die vraag ontstaan hoe ortogonale Latynse vierkante van 'n saamgestelde orde (wat nie 'n priem mag is nie) gevind kan word. Die begrip van die Kronecker-produk vir matrikse kan hiervoor ingespan word. Gestel  $\mathbf{M} = [M_{ij}]$  is 'n Latynse vierkant van orde  $m$  en  $\mathbf{N} = [N_{ij}]$  is 'n Latynse vierkant van orde  $n$ . Dan is die *Kronecker produk* van  $\mathbf{M}$  en  $\mathbf{N}$  die  $n \times n$  matriks

$$\mathbf{L} = \mathbf{M} \otimes \mathbf{N} = \begin{bmatrix} (N_{11}, \mathbf{M}) & (N_{12}, \mathbf{M}) & \cdots & (N_{1n}, \mathbf{M}) \\ (N_{21}, \mathbf{M}) & (N_{22}, \mathbf{M}) & \cdots & (N_{2n}, \mathbf{M}) \\ \vdots & \vdots & \ddots & \vdots \\ (N_{n1}, \mathbf{M}) & (N_{n2}, \mathbf{M}) & \cdots & (N_{nn}, \mathbf{M}) \end{bmatrix}$$

waarin die element  $(N_{ij}, \mathbf{M})$  die  $m \times m$  matriks

$$(N_{ij}, \mathbf{M}) = \begin{bmatrix} N_{ij, M_{11}} & N_{ij, M_{12}} & \cdots & N_{ij, M_{1m}} \\ N_{ij, M_{21}} & N_{ij, M_{22}} & \cdots & N_{ij, M_{2m}} \\ \vdots & \vdots & \ddots & \vdots \\ N_{ij, M_{m1}} & N_{ij, M_{m2}} & \cdots & N_{ij, M_{mm}} \end{bmatrix}$$

is. Dit is maklik om aan te toon dat  $\mathbf{L}$  'n Latynse vierkant van orde  $mn$  is. Ortogonaliteit van kleiner Latynse vierkante bly trouens ook onder die Kronecker-produk tydens die konstruksie van groter Latynse vierkante behoue, soos in die volgende resultaat beskryf.

**Stelling 4 ([14, §2.3, Stelling 2.6])** *Gestel  $\mathbf{M}^{(1)}$  en  $\mathbf{M}^{(2)}$  is twee ortogonale Latynse vierkante van orde  $m$  en dat  $\mathbf{N}^{(1)}$  en  $\mathbf{N}^{(2)}$  twee ortogonale Latynse vierkante van orde  $n$  is. Dan is  $\mathbf{L}^{(1)} = \mathbf{M}^{(1)} \otimes \mathbf{N}^{(1)}$  en  $\mathbf{L}^{(2)} = \mathbf{M}^{(2)} \otimes \mathbf{N}^{(2)}$  twee ortogonale Latynse vierkante van orde  $mn$ . ■*

Die enigste Latynse vierkant van orde 2 (tot op isotoop na) is

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

Gevolglik is daar geen ortogonale paar Latynse vierkante van orde 2 nie. As die priemfaktoriserings van  $n$  gegee word deur

$$n = \prod_{i=1}^k p_i^{e_i}, \quad (6)$$

waar  $p_1, \dots, p_k$  almal verskillend is,  $e_i \in \mathbb{N}$  vir alle  $i = 1, \dots, k$ , en 2 nie tot die mag 1 in (6) voorkom nie (m.a.w. as  $n \equiv 0, 1, 3 \pmod{4}$ ), kan 'n paar ortogonale Latynse vierkante  $\mathbf{L}^{(i)}$  en  $\mathbf{M}^{(i)}$  van orde  $p_i^{e_i}$  opgebou word deur van Stelling 3 gebruik te maak, en lewer die Kronecker-produkte

$$\mathbf{L} = \bigotimes_{i=1}^k \mathbf{L}^{(i)} \quad \text{en} \quad \mathbf{M} = \bigotimes_{i=1}^k \mathbf{M}^{(i)} \quad (7)$$



dan volgens Stelling 4 'n paar ortogonale Latynse vierkante van orde  $n$ . Die uitsluiting van  $2^1$  in (6) by die bogenoemde konstruksie volg uit die slotopmerking in §2.2 en het by Leonhard Euler 'n vraagstuk oor die bestaan van pare ortogonale Latynse vierkante van orde  $n \equiv 2 \pmod{4}$  laat ontstaan. Onsuksesvolle pogings tot 'n oplossing van die beroemde *36 offisiere-probleem* [7, §II.2.3, Opmerking 2.15], waarin daar gevra word dat 36 offisiere (ses offisiere van verskillende range uit elkeen van ses regimente) in 'n  $6 \times 6$  skikking gerangskik word sodat elke ry en elke kolom een offisier van elke rang en elke regiment bevat, het Euler op die vermoede gebring dat geen paar ortogonale Latynse vierkante van orde  $n \equiv 2 \pmod{4}$  bestaan nie. Tarry [18] het Euler se vermoede in 1900 vir die geval  $n = 6$  korrek bewys deur die 812 851 200 verskillende Latynse vierkante van orde 6 in 9 408 onderling uitsluitende reduksieklasse te verdeel (sien Tabel 1) en op 'n brute-kragwyse aan te toon dat daar nie 'n enkele ortogonale paar vierkante oor enige twee van hierdie klasse bestaan nie. Euler se vermoede is egter vals vir  $n = 10$ , soos die paar ortogonale Latynse vierkante

$$(\Psi^{(1)}, \Psi^{(2)}) = \begin{bmatrix} (1, 2) & (2, 3) & (3, 1) & (4, 6) & (5, 9) & (6, 4) & (7, 8) & (8, 7) & (9, 5) & (0, 0) \\ (7, 4) & (4, 2) & (2, 7) & (0, 9) & (6, 1) & (5, 8) & (8, 5) & (9, 0) & (3, 3) & (1, 6) \\ (5, 1) & (1, 4) & (4, 5) & (6, 7) & (0, 8) & (8, 0) & (9, 3) & (2, 2) & (7, 6) & (3, 9) \\ (0, 7) & (7, 1) & (1, 0) & (3, 8) & (8, 3) & (9, 2) & (4, 4) & (5, 6) & (2, 9) & (6, 5) \\ (3, 5) & (5, 7) & (7, 3) & (8, 2) & (9, 4) & (1, 1) & (0, 6) & (4, 9) & (6, 0) & (2, 8) \\ (2, 0) & (0, 5) & (5, 2) & (9, 1) & (7, 7) & (3, 6) & (1, 9) & (6, 3) & (4, 8) & (8, 4) \\ (4, 3) & (3, 0) & (0, 4) & (5, 5) & (2, 6) & (7, 9) & (6, 2) & (1, 8) & (8, 1) & (9, 7) \\ (8, 9) & (9, 8) & (6, 6) & (2, 4) & (3, 2) & (0, 3) & (5, 0) & (7, 5) & (1, 7) & (4, 1) \\ (6, 8) & (8, 6) & (9, 9) & (7, 0) & (1, 5) & (4, 7) & (2, 1) & (3, 4) & (0, 2) & (5, 3) \\ (9, 6) & (6, 9) & (8, 8) & (1, 3) & (4, 0) & (2, 5) & (3, 7) & (0, 1) & (5, 4) & (7, 2) \end{bmatrix}$$

toon [17, Voorblad]. Bose *et al.* [2] het trouens in 1960 bewys dat Euler se vermoede vals is vir *alle*  $n > 6$ . Ons het dus die volgende bestaansresultaat.

**Stelling 5 ([14, §2.3, Stelling 2.9])** *Daar bestaan 'n paar ortogonale Latynse vierkante van orde  $n$  vir enige  $n > 2$ , afgesien van  $n = 6$ . ■*

As  $n \equiv 2 \pmod{4}$  en  $n > 6$ , dan kan 'n paar ortogonale Latynse vierkante van orde  $n$  natuurlik nie deur middel van (7) bepaal word nie, maar so 'n paar vierkante kan wel deur middel van ander tegnieke uit ontwerpteorie bepaal word.

## 2.4 Self-ortogonale Latynse vierkante

'n Latynse vierkant  $L$  word *self-ortogonaal* genoem indien die vierkant self en die getransponeerde daarvan,  $L^T$ , 'n ortogonale paar Latynse vierkante vorm. Let op dat hierdie definisie impliseer dat

die diagonaalelemente van 'n self-ortogonale Latynse vierkant noodwendig almal verskillend is. (8)

Aangesien daar geen paar ortogonale Latynse vierkante van orde 2 bestaan nie, is daar ook geen self-ortogonale Latynse vierkant van orde 2 nie. Verder is die twee vierkante  $\Lambda^{(1)}$  en  $\Lambda^{(2)}$  in (3) tot op isotoop na die enigste paar ortogonale Latynse vierkante van orde 3. Geeneen van hierdie twee vierkante is egter self-ortogonaal nie. Die vraag ontstaan vir watter waardes van  $n$  daar self-ortogonale Latynse vierkante van orde  $n$  bestaan. Die antwoord op hierdie vraag word in die volgende resultaat gegee.

**Stelling 6 ([7, §III.5, Stelling 5.10])** *Daar bestaan 'n self-ortogonale Latynse vierkant van orde  $n$  vir enige  $n > 3$ , behalwe vir  $n = 6$ . ■*

Die volgende stelling dateer uit 1971 en gee uitsluiting oor die konstruksie van 'n self-ortogonale Latynse vierkant van orde 'n mag van 'n priemgetal.

**Stelling 7 ([16, Stelling 1])** Gestel  $p$  is 'n priemgetal en dat  $q \in \mathbb{N}$ . Laat  $\lambda \in GF(p^q)$ , met  $\lambda \neq 0, 1$  en  $2\lambda \neq 1$ . Dan is die skikking met inskrywing  $\lambda y + (1 - \lambda)z$  in ry  $y \in GF(p^q)$  en kolom  $z \in GF(p^q)$  'n self-ortogonale Latynse vierkant van orde  $p^q$ , waar rekenkunde oor  $GF(p^q)$  plaasvind. ■

Die bogenoemde konstruksie werk nie vir  $n = 2$  of  $n = 3$  nie, want dan is daar geen toelaatbare keuse vir  $\lambda$  nie; die Galois liggame  $GF(2)$  en  $GF(3)$  is te klein om die konstruksie in Stelling 7 toe te laat. Vir alle ander eindige liggame is die konstruksie egter geldig. Beskou as voorbeeld weer die Galois liggaam  $GF(4)$  waarvoor die optel- en vermenigvuldigingstabelle in (5) gegee word. Neem  $\lambda = x$ , sodat  $2\lambda = 0 \neq 1$ . Dan is  $\lambda y + (1 - \lambda)z = xy + (1 + x)z$  en lewer Stelling 7 die self-ortogonale Latynse vierkant

$$\begin{bmatrix} 0 & 1+x & 1 & x \\ x & 1 & 1+x & 0 \\ 1+x & 0 & x & 1 \\ 1 & x & 0 & 1+x \end{bmatrix}, \quad \text{oftewel} \quad \begin{bmatrix} 0 & 3 & 1 & 2 \\ 2 & 1 & 3 & 0 \\ 3 & 0 & 2 & 1 \\ 1 & 2 & 0 & 3 \end{bmatrix} \quad (9)$$

ná vervanging van  $0, 1, x$  en  $1 + x$  met onderskeidelik  $0, 1, 2$  en  $3$ . Self-ortonogale Latynse vierkante van saamgestelde ordes kan weereens deur middel van die Kronecker-produk vir matrikse opgebou word, soos gewaarborg deur die volgende stelling, wat 'n direkte gevolg van Stelling 4 is.

**Stelling 8** Gestel  $M$  en  $N$  is self-ortogonale Latynse vierkante van ordes  $m$  en  $n$  onderskeidelik. Dan is  $L = M \otimes N$  'n self-ortogonale Latynse vierkant van orde  $mn$ . ■

## 2.5 Self-ortogonale Latynse vierkante met simmetriese maats

'n Paar Latynse vierkante  $\mathbf{L}, \mathbf{S}$  van orde  $n$  waarvoor geld dat (i)  $\mathbf{L}$  self-ortogonaal is, (ii)  $\mathbf{S}$  simmetries is, en (iii)  $\mathbf{L}$  en  $\mathbf{S}$  (en dus  $\mathbf{L}^T$  en  $\mathbf{S}$ ) ortogonaal is, heet 'n self-ortogonale Latynse vierkant met simmetriese ortogonale maat (SLVSOM) van orde  $n$ . 'n SLVSOM  $\mathbf{L}, \mathbf{S}$  heet regulier indien die vierkant  $\mathbf{L} = [L_{ij}]$  aan die voorwaarde

$$L_{ii} = i, \quad i = 0, \dots, n-1 \quad (10)$$

voldoen, en die vierkant  $\mathbf{S} = [S_{ij}]$  aan die voorwaarde

$$S_{ii} = \begin{cases} n-1 & \text{as } n \text{ ewe is} \\ i & \text{as } n \text{ onewe is,} \end{cases} \quad (11)$$

voldoen. Ons motiveer die diagonaalvoorwaardes (10)–(11) in die volgende afdeling volledig. Let intussen daarop dat die voorwaarde in (10) natuurlik is in die lig van van opmerking (8). Op soortgelyke wyse is die tweede voorwaarde in (11), naamlik dat  $S_{ii} = i$  vir onewe waardes van  $n$ , 'n natuurlike vereiste, aangesien

die diagonaalelemente van 'n simmetriese Latynse vierkant van onewe orde almal verskillend is.

(12)

Die geldigheid van hierdie opmerking blyk uit die volgende: indien  $\mathbf{S}$  'n simmetriese Latynse vierkant van onewe orde is, moet elke simbool 'n onewe aantal keer in  $\mathbf{S}$  verskyn. Omdat elke simbool vanweë die simmetrie van  $\mathbf{S}$  'n ewe aantal keer af van die hoofdiagonaal af in  $\mathbf{S}$  voorkom, volg dit dus dat elke simbool 'n onewe aantal keer op die hoofdiagonaal van  $\mathbf{S}$  moet voorkom. Elke simbool kan egter hoogstens een keer op die hoofdiagonaal van  $\mathbf{S}$  verskyn, waaruit (12) geld.

Enige SLVSOM kan natuurlik tot 'n reguliere SLVSOM van dieselfde orde omvorm word deur die rye, kolomme en simboolname daarvan te permuteer [7, §III.5.7, Opmerking 5.41]. Die volgende stelling bied 'n gedeeltelike antwoord op die vraagstuk na die bestaan van SLVSOM'e.

**Stelling 9 ([7, §III.5, Stelling 5.40])** Daar bestaan geen SLVSOM van orde  $n = 2, 3$  of  $6$  nie. Vir alle ander natuurlike getalle  $n > 1$  bestaan daar wel 'n reguliere SLVSOM van orde  $n$ , behalwe moontlik vir  $n = 10$  en  $n = 14$ . ■

Die bogenoemde resultaat is nie konstruktief nie. Indien  $n$  egter 'n mag van 2 is ( $n \neq 2$ ), lewer die volgende pragtige konstruktiewe resultaat 'n metode waarvolgens 'n SLVSOM van orde  $n$  gevorm kan word.

**Stelling 10** ([7, §III.5, Konstruksie 5.45]) *Gestel  $q \in \mathbb{N} \setminus \{1\}$  en dui die self-ortogonale Latynse vierkant van orde  $2^q$  in Stelling 7 (met  $p = 2$ ) aan deur  $\mathbf{L}$ . Dan is die skikking  $\mathbf{S} = [S_{yz}]$  met inskrywing  $S_{yz} = y + z$  in ry  $y \in GF(2^q)$  en kolom  $z \in GF(2^q)$  'n simmetriese Latynse vierkant van orde  $2^q$  wat ortogonaal is met betrekking tot  $\mathbf{L}$  (en dus  $\mathbf{L}^T$ ), waar rekenkunde oor  $GF(2^q)$  plaasvind. Die paar  $\mathbf{L}, \mathbf{S}$  vorm dus 'n SLVSOM van orde  $2^q$ . ■*

Indien  $n$  'n mag van 'n onewe priem is ( $n \neq 3$ ), lewer die volgende konstruksie 'n SLVSOM van orde  $n$ .

**Stelling 11** ([7, §III.5, Konstruksie 5.44]) *Gestel  $p$  is 'n onewe priem, en dat  $q \in \mathbb{N}$  met  $p^q \neq 3^1$ . Dui die self-ortogonale Latynse vierkant van orde  $p^q$  in Stelling 7 aan deur  $\mathbf{L}$ . Dan is die skikking  $\mathbf{S} = [S_{yz}]$  met inskrywing  $S_{yz} = 2^{-1}(y + z)$  in ry  $y \in GF(p^q)$  en kolom  $z \in GF(p^q)$  'n simmetriese Latynse vierkant van orde  $p^q$  wat ortogonaal is met betrekking tot  $\mathbf{L}$  (en dus  $\mathbf{L}^T$ ), waar rekenkunde oor  $GF(p^q)$  plaasvind. Die paar  $\mathbf{L}, \mathbf{S}$  vorm dus 'n SLVSOM van orde  $p^q$ . ■*

Vir waardes van  $n$  wat relatief priem is ten opsigte van 6 (ongeg of sodanige ordes magte van priem is of nie) het Wallis [19, Stelling 1] verder in 1978 met die onderstaande konstruksie vir 'n SLVSOM van orde  $n$  vorendag gekom, wat op sy beurt weer gebaseer is op die 1971-konstruksie van self-ortogonale Latynse vierkante deur Mendelsohn [16, Stelling 2].

**Stelling 12** ([16, 19]) *Gestel  $\text{ggd}(n, 6) = 1$ . Dan is die skikking  $\mathbf{L} = [L_{yz}]$  met inskrywing  $L_{yz} \equiv 3^{-1}(y + 2z) \pmod{n}$  in ry  $y \in \mathbb{Z}_n$  en kolom  $z \in \mathbb{Z}_n$  'n self-ortogonale Latynse vierkant van orde  $n$ . Verder is die skikking  $\mathbf{S} = [S_{yz}]$  met inskrywing  $S_{yz} = 2^{-1}3^{-1}(y + z) \pmod{n}$  in ry  $y \in \mathbb{Z}_n$  en kolom  $z \in \mathbb{Z}_n$  'n simmetriese Latynse vierkant van orde  $n$  wat ortogonaal is tot  $\mathbf{L}$  (en dus  $\mathbf{L}^T$ ). Die matrikspaar  $\mathbf{L}, \mathbf{S}$  vorm gevolglik 'n SLVSOM van orde  $n$ . ■*

Let op dat die Kronecker-produk vir matrikse nie gebruik kan word om 'n reguliere SVLSOM  $\mathbf{L} = \mathbf{L}^{(1)} \otimes \mathbf{L}^{(2)}$ ,  $\mathbf{S} = \mathbf{S}^{(1)} \otimes \mathbf{S}^{(2)}$  van onewe orde uit twee kleiner reguliere SVLSOM'e  $\mathbf{L}^{(1)}, \mathbf{S}^{(1)}$  en  $\mathbf{L}^{(2)}, \mathbf{S}^{(2)}$  van onewe ordes op te bou nie, aangesien die produk  $\mathbf{S}^{(1)} \otimes \mathbf{S}^{(2)}$  noodwendig herhalende elemente op die hoofdiagonaal sal hê, wat strydig is met die opmerking in (12).

### 3 VAN LATYNSE VIERKANTE NA TENNISTOERNOOIE

Die volgende merkwaardige karakterisering vir die bestaan van 'n lys van GGRTT-potte dateer uit 1973.

**Stelling 13** ([3, §2]) *Die potte van 'n GGRTT van orde  $n$  kan gelys word as en slegs as daar 'n self-ortogonale Latynse vierkant  $\mathbf{L} = [L_{ij}]$  van orde  $n$  bestaan wat aan voorwaarde (10) voldoen. Indien daar wel so 'n vierkant bestaan, kan al die GGRTT potte uit  $\mathbf{L}$  afgelees word deur  $i$  en  $j$  oor die bo-driehoeksgedeelte van die vierkant te laat varieer. Meer spesifiek, in die pot waarin man  $i$  en man  $j$  teen mekaar te staan kom, moet vrou  $L_{ij}$  as die spanmaat van man  $i$  geskeduleer word, en moet vrou  $L_{ji}$  as die spanmaat van man  $j$  geskeduleer word. ■*

Die algemene pot waarvan daar in Stelling 13 melding gemaak word, kan in die roosternotasie van Figuur 1 soos in Figuur 3 voorgestel word.

Stelling 13 is só sentraal in ons werk dat ons kortliks 'n indruk van een rigting van die bewys daarvan gee. Gestel vrou  $L_{ij}$  is die spanmaat van man  $i$  wanneer hy in 'n OBGRTT van orde  $n$  teen

$i$	$j$
$L_{ij}$	$L_{ji}$

**Figuur 3:** Die pot in 'n GGRTT van orde  $n$  waarin mans  $i$  en  $j$  teen mekaar te staan kom, en waar  $L_{ij}$  die  $(i, j)$ -te inskrywing van 'n self-ortogonale Latynse vierkant van orde  $n$  is.

man  $j$  te staan kom ( $i \neq j$ ). Gestel verder dat daar aan voorwaarde (10) voldoen word, en beskou die  $n \times n$  skikking  $\mathbf{L} = [L_{ij}]$  wat so ontstaan. Aangesien elke man in so 'n OBGGRRTT teen elke vrou (behalwe sy eggenote) te staan kom, bevat elke kolom en elke ry van  $\mathbf{L}$  elkeen van die simbole  $0, 1, \dots, n - 1$ . Gevolglik is  $\mathbf{L}$  'n Latynse vierkant. Aangesien elke vrou teen elke ander vrou in so 'n optimale potbeslissing te staan kom, kom die geordende paar  $(L_{ij}, L_{ji})$  een keer voor wanneer die vierkant  $\mathbf{L}$  op  $\mathbf{L}^T$  gesuperponeer word. Daarom is  $\mathbf{L}$  'n self-ortogonale Latynse vierkant.

Deur byvoorbeeld van die self-ortogonale Latynse vierkant in (9) gebruik te maak, volg dit dat die ses potte in Figuur 4 'n GGRTT van orde 4 vorm — hierdie ses potte is presies die ses potte in Figuur 2, hoewel in 'n ander volgorde gelys, en nie in rondtes ingedeel nie.

0   1	0   2	0   3	1   2	1   3	2   3
3   2	1   3	2   1	3   0	0   2	1   0

**Figuur 4:** 'n Lys van ses potte vir 'n GGRTT van orde 4 soos voortgebring deur die self-ortogonale Latynse vierkant van orde 4 in (9).

Die vraag ontstaan hoe die potte van 'n GGRTT optimaal in rondtes beslis kan word, indien hulle gelys kan word. Wallis [19] het opgemerk dat indien die pot waarin man  $i$  en man  $j$  teen mekaar te staan kom, in 'n OBGGRRTT van orde  $n$  in rondte  $S_{ij}$  geskeduleer word, en indien die konvensie in (11) gevolg word, die skikking  $\mathbf{S} = [S_{ij}]$  'n simmetriese Latynse vierkant van orde  $n$  vorm. Die simmetrie van  $\mathbf{S}$  volg uit die uitruilbaarheid van  $i$  en  $j$  in die definisie van  $S_{ij}$ , terwyl die Latynse eienskap van  $\mathbf{S}$  volg uit die feit dat elke man in elke rondte van 'n optimale potbeslissing speel (behalwe as  $n$  onewe is, in welke geval daar aan man  $i$  'n loslootjie in rondte  $i$  toegeken word) en elke ry van  $\mathbf{S}$  dus 'n permutasie van die elemente  $\{0, 1, \dots, n - 1\}$  bevat. Dieselfde geld vir die kolomme van die skikking as gevolg van die simmetrie van  $\mathbf{S}$ . Aangesien elke vrou ook een keer in elke rondte van 'n optimale potbeslissing speel (behalwe as  $n$  onewe is), is die posisies waarin daar 'n spesifieke simbool in die self-ortogonale Latynse vierkant  $\mathbf{L}$  in Stelling 13 voorkom, presies een van die elemente  $0, 1, \dots, n - 1$  in  $\mathbf{S}$ . Daarom is  $\mathbf{L}$  en  $\mathbf{S}$  ortogonaal (en dieselfde geld vir  $\mathbf{L}^T$  en  $\mathbf{S}$ ), en vorm dus 'n SLVSOM van orde  $n$ .

## 4 ORDES NIE DEUR DIE VOORAFGAANDE TEORIE GEDEK

In die inleiding word gemeld dat dit een van die doelstellings in hierdie artikel is om 'n maklik interpreteerbare lys van GGRTT'e van orde hoogstens 20 vir administrateurs van tennisklubs daar te stel. Toernooi-ordes binne hierdie interval waarvoor GGRTT potte optimaal in rondtes deur Stelling 10 beslis kan word, is  $n = 4, 8$  en  $16$ . Stelling 11 kan verder gebruik word om GGRTT potte vir toernooie van ordes  $n = 5, 7, 9, 11, 13, 17$  en  $19$  binne hierdie interval optimaal in rondtes te beslis. (Die potte van GGRTT'e van ordes  $n = 5, 7, 11, 13, 17$  en  $19$  is trouens ook volgens Stelling 12 optimaal in rondtes beslisbaar.) Waardes van  $n$  in die bogenoemde interval wat dus nie deur die voorafgaande teorie gedek word nie, is  $1, 2, 3, 6, 10, 12, 14, 15, 18$  en  $20$ .

GGRTT'e van ordes  $n = 1, 2$  en  $3$  bestaan duidelik nie, aangesien minstens vier getroude pare benodig word om 'n enkele pot in so 'n toernooi te speel. In die lig van Stellings 6 en 13 kan die potte van 'n GGRTT van orde 6 nie eers gelys word nie, wat nog te sê optimaal in rondtes beslis word. Dit is egter wel moontlik om spelskedules vir die geval  $n = 6$  te vind waarby daar oortolligheid ingebou word in die sin dat sommige spelers meer as een keer teen mekaar te staan moet kom of in 'n span

saam met mekaar moet speel. Dit kan gedoen word deur die woord “presies” in vereistes (V3)–(V5) in §1 met die frase “ten minste” te vervang. Twee spelskedules word later in hierdie afdeling vir  $n = 6$  onder hierdie toernooireëlverslappings gevind.

#### 4.1 OBGGRIT’e vir $n = 12, 15, 18$ en 20

Die reguliere SLVSOM

$$L(12) = \begin{bmatrix} 0 & 2 & 7 & 9 & 6 & b & a & 3 & 5 & 8 & 1 & 4 \\ 3 & 1 & 8 & 6 & a & 7 & 2 & b & 9 & 4 & 5 & 0 \\ 5 & b & 2 & 0 & 8 & 1 & 4 & 9 & 3 & 6 & 7 & a \\ a & 4 & 1 & 3 & 0 & 9 & 8 & 5 & 7 & 2 & b & 6 \\ 9 & 0 & 5 & 8 & 4 & 6 & b & 1 & a & 3 & 2 & 7 \\ 1 & 8 & 9 & 4 & 7 & 5 & 0 & a & 2 & b & 6 & 3 \\ 7 & a & b & 2 & 9 & 3 & 6 & 4 & 0 & 5 & 8 & 1 \\ b & 6 & 3 & a & 2 & 8 & 5 & 7 & 4 & 1 & 0 & 9 \\ 2 & 7 & 6 & b & 1 & 4 & 9 & 0 & 8 & a & 3 & 5 \\ 6 & 3 & a & 7 & 5 & 0 & 1 & 8 & b & 9 & 4 & 2 \\ 4 & 9 & 0 & 5 & b & 2 & 3 & 6 & 1 & 7 & a & 8 \\ 8 & 5 & 4 & 1 & 3 & a & 7 & 2 & 6 & 0 & 9 & b \end{bmatrix}, S(12) = \begin{bmatrix} b & a & 7 & 6 & 5 & 1 & 2 & 4 & 9 & 0 & 3 & 8 \\ a & b & 6 & 7 & 0 & 5 & 4 & 3 & 1 & 9 & 8 & 2 \\ 7 & 6 & b & a & 3 & 4 & 5 & 0 & 2 & 8 & 9 & 1 \\ 6 & 7 & a & b & 4 & 2 & 1 & 5 & 8 & 3 & 0 & 9 \\ 5 & 0 & 3 & 4 & b & a & 9 & 8 & 7 & 1 & 2 & 6 \\ 1 & 5 & 4 & 2 & a & b & 8 & 9 & 0 & 7 & 6 & 3 \\ 2 & 4 & 5 & 1 & 9 & 8 & b & a & 3 & 6 & 7 & 0 \\ 4 & 3 & 0 & 5 & 8 & 9 & a & b & 6 & 2 & 1 & 7 \\ 9 & 1 & 2 & 8 & 7 & 0 & 3 & 6 & b & a & 5 & 4 \\ 0 & 9 & 8 & 3 & 1 & 7 & 6 & 2 & a & b & 4 & 5 \\ 3 & 8 & 9 & 0 & 2 & 6 & 7 & 1 & 5 & 4 & b & a \\ 8 & 2 & 1 & 9 & 6 & 3 & 0 & 7 & 4 & 5 & a & b \end{bmatrix}$$

van orde 12 kan uit die nie-reguliere SLVSOM in [7, §III.5, Voorbeeld 5.38] afgelei kan word, terwyl die reguliere SLVSOM

$$L(15) = \begin{bmatrix} 0 & 7 & 3 & 1 & e & 8 & a & c & 4 & 2 & 9 & d & 6 & 5 & b \\ c & 1 & 8 & 4 & 2 & 0 & 9 & b & d & 5 & 3 & a & e & 7 & 6 \\ 7 & d & 2 & 9 & 5 & 3 & 1 & a & c & e & 6 & 4 & b & 0 & 8 \\ 9 & 8 & e & 3 & a & 6 & 4 & 2 & b & d & 0 & 7 & 5 & c & 1 \\ 2 & a & 9 & 0 & 4 & b & 7 & 5 & 3 & c & e & 1 & 8 & 6 & d \\ e & 3 & b & a & 1 & 5 & c & 8 & 6 & 4 & d & 0 & 2 & 9 & 7 \\ 8 & 0 & 4 & c & b & 2 & 6 & d & 9 & 7 & 5 & e & 1 & 3 & a \\ b & 9 & 1 & 5 & d & c & 3 & 7 & e & a & 8 & 6 & 0 & 2 & 4 \\ 5 & c & a & 2 & 6 & e & d & 4 & 8 & 0 & b & 9 & 7 & 1 & 3 \\ 4 & 6 & d & b & 3 & 7 & 0 & e & 5 & 9 & 1 & c & a & 8 & 2 \\ 3 & 5 & 7 & e & c & 4 & 8 & 1 & 0 & 6 & a & 2 & d & b & 9 \\ a & 4 & 6 & 8 & 0 & d & 5 & 9 & 2 & 1 & 7 & b & 3 & e & c \\ d & b & 5 & 7 & 9 & 1 & e & 6 & a & 3 & 2 & 8 & c & 4 & 0 \\ 1 & e & c & 6 & 8 & a & 2 & 0 & 7 & b & 4 & 3 & 9 & d & 5 \\ 6 & 2 & 0 & d & 7 & 9 & b & 3 & 1 & 8 & c & 5 & 4 & a & e \end{bmatrix}, S(15) = \begin{bmatrix} 0 & 2 & 5 & a & d & b & e & 4 & c & 8 & 6 & 9 & 7 & 3 & 1 \\ 2 & 1 & 3 & 6 & b & e & c & 0 & 5 & d & 9 & 7 & a & 8 & 4 \\ 5 & 3 & 2 & 4 & 7 & c & 0 & d & 1 & 6 & e & a & 8 & b & 9 \\ a & 6 & 4 & 3 & 5 & 8 & d & 1 & e & 2 & 7 & 0 & b & 9 & c \\ d & b & 7 & 5 & 4 & 6 & 9 & e & 2 & 0 & 3 & 8 & 1 & c & a \\ b & e & c & 8 & 6 & 5 & 7 & a & 0 & 3 & 1 & 4 & 9 & 2 & d \\ e & c & 0 & d & 9 & 7 & 6 & 8 & b & 1 & 4 & 2 & 5 & a & 3 \\ 4 & 0 & d & 1 & e & a & 8 & 7 & 9 & c & 2 & 5 & 3 & 6 & b \\ c & 5 & 1 & e & 2 & 0 & b & 9 & 8 & a & d & 3 & 6 & 4 & 7 \\ 8 & d & 6 & 2 & 0 & 3 & 1 & c & a & 9 & b & e & 4 & 7 & 5 \\ 6 & 9 & e & 7 & 3 & 1 & 4 & 2 & d & b & a & c & 0 & 5 & 8 \\ 9 & 7 & a & 0 & 8 & 4 & 2 & 5 & 3 & e & c & b & d & 1 & 6 \\ 7 & a & 8 & b & 1 & 9 & 5 & 3 & 6 & 4 & 0 & d & c & e & 2 \\ 3 & 8 & b & 9 & c & 2 & a & 6 & 4 & 7 & 5 & 1 & e & d & 0 \\ 1 & 4 & 9 & c & a & d & 3 & b & 7 & 5 & 8 & 6 & 2 & 0 & e \end{bmatrix}$$

van orde 15 uit die vektornotasie in [7, §III.5, Voorbeeld 5.48] afgelei kan word. Sowel die reguliere SLVSOM

$$L(18) = \begin{bmatrix} 0 & 7 & d & c & b & a & 2 & 1 & 9 & h & e & g & f & 3 & 4 & 6 & 5 & 8 \\ 4 & 1 & 8 & 0 & d & c & b & 3 & 2 & a & h & e & g & f & 5 & 7 & 6 & 9 \\ f & 5 & 2 & 9 & 1 & 0 & d & c & 4 & 3 & b & h & e & g & 6 & 8 & 7 & a \\ g & f & 6 & 3 & a & 2 & 1 & 0 & d & 5 & 4 & c & h & e & 7 & 9 & 8 & b \\ e & g & f & 7 & 4 & b & 3 & 2 & 1 & 0 & 6 & 5 & d & h & 8 & a & 9 & c \\ h & e & g & f & 8 & 5 & c & 4 & 3 & 2 & 1 & 7 & 6 & 0 & 9 & b & a & d \\ 1 & h & e & g & f & 9 & 6 & d & 5 & 4 & 3 & 2 & 8 & 7 & a & c & b & 0 \\ 8 & 2 & h & e & g & f & a & 7 & 0 & 6 & 5 & 4 & 3 & 9 & b & d & c & 1 \\ a & 9 & 3 & h & e & g & f & b & 8 & 1 & 7 & 6 & 5 & 4 & c & 0 & d & 2 \\ 5 & b & a & 4 & h & e & g & f & c & 9 & 2 & 8 & 7 & 6 & d & 1 & 0 & 3 \\ 7 & 6 & c & b & 5 & h & e & g & f & d & a & 3 & 9 & 8 & 0 & 2 & 1 & 4 \\ 9 & 8 & 7 & d & c & 6 & h & e & g & f & 0 & b & 4 & a & 1 & 3 & 2 & 5 \\ b & a & 9 & 8 & 0 & d & 7 & h & e & g & f & 1 & c & 5 & 2 & 4 & 3 & 6 \\ 6 & c & b & a & 9 & 1 & 0 & 8 & h & e & g & f & 2 & d & 3 & 5 & 4 & 7 \\ c & d & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & e & g & h & f \\ 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & c & d & 0 & 1 & h & f & e & g \\ 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & c & d & 0 & 1 & 2 & f & h & g & e \\ d & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & c & g & e & f & h \end{bmatrix}, S(18) = \begin{bmatrix} h & e & c & 5 & 8 & 6 & 3 & f & b & 1 & 4 & 2 & a & g & 7 & 0 & 9 & d \\ e & h & g & d & 6 & 9 & 7 & 4 & f & c & 2 & 5 & 3 & b & 8 & 1 & a & 0 \\ c & g & h & e & 0 & 7 & a & 8 & 5 & f & d & 3 & 6 & 4 & 9 & 2 & b & 1 \\ 5 & d & e & h & g & 1 & 8 & b & 9 & 6 & f & 0 & 4 & 7 & a & 3 & c & 2 \\ 8 & 6 & 0 & g & h & e & 2 & 9 & c & a & 7 & f & 1 & 5 & b & 4 & d & 3 \\ 6 & 9 & 7 & 1 & e & h & g & 3 & a & d & b & 8 & f & 2 & c & 5 & 0 & 4 \\ 3 & 7 & a & 8 & 2 & g & h & e & 4 & b & 0 & c & 9 & f & d & 6 & 1 & 5 \\ f & 4 & 8 & b & 9 & 3 & e & h & g & 5 & c & 1 & d & a & 0 & 7 & 2 & 6 \\ b & f & 5 & 9 & c & a & 4 & g & h & e & 6 & d & 2 & 0 & 1 & 8 & 3 & 7 \\ 1 & c & f & 6 & a & d & b & 5 & e & h & g & 7 & 0 & 3 & 2 & 9 & 4 & 8 \\ 4 & 2 & d & f & 7 & b & 0 & c & 6 & g & h & e & 8 & 1 & 3 & a & 5 & 9 \\ 2 & 5 & 3 & 0 & f & 8 & c & 1 & d & 7 & e & h & g & 9 & 4 & b & 6 & a \\ a & 3 & 6 & 4 & 1 & f & 9 & d & 2 & 0 & 8 & g & h & e & 5 & c & 7 & b \\ g & b & 4 & 7 & 5 & 2 & f & a & 0 & 3 & 1 & 9 & e & h & 6 & d & 8 & c \\ 7 & 8 & 9 & a & b & c & d & 0 & 1 & 2 & 3 & 4 & 5 & 6 & h & f & e & g \\ 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & c & d & f & h & g & e \\ 9 & a & b & c & d & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & e & g & h & f \\ d & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & c & g & e & f & h \end{bmatrix}$$

van orde 18 as die reguliere SLVSOM

$$L(20) = \begin{bmatrix} 0 & 9 & d & 7 & j & 4 & 1 & 8 & i & 5 & c & g & f & 3 & b & 2 & e & a & 6 & h \\ 7 & 1 & a & e & 8 & j & 5 & 2 & 9 & 0 & 6 & d & h & g & 4 & c & 3 & f & b & i \\ c & 8 & 2 & b & f & 9 & j & 6 & 3 & a & 1 & 7 & e & i & h & 5 & d & 4 & g & 0 \\ h & d & 9 & 3 & c & g & a & j & 7 & 4 & b & 2 & 8 & f & 0 & i & 6 & e & 5 & 1 \\ 6 & i & e & a & 4 & d & h & b & j & 8 & 5 & c & 3 & 9 & g & 1 & 0 & 7 & f & 2 \\ g & 7 & 0 & f & b & 5 & e & i & c & j & 9 & 6 & d & 4 & a & h & 2 & 1 & 8 & 3 \\ 9 & h & 8 & 1 & g & c & 6 & f & 0 & d & g & a & 7 & e & 5 & b & i & 3 & 2 & 4 \\ 3 & a & i & 9 & 2 & h & d & 7 & g & 1 & e & j & b & 8 & f & 6 & c & 0 & 4 & 5 \\ 5 & 4 & b & 0 & a & 3 & i & e & 8 & h & 2 & f & j & c & 9 & g & 7 & d & 1 & 6 \\ 2 & 6 & 5 & c & 1 & b & 4 & 0 & f & 9 & i & 3 & g & j & d & a & h & 8 & e & 7 \\ f & 3 & 7 & 6 & d & 2 & c & 5 & 1 & g & a & 0 & 4 & h & j & e & b & i & 9 & 8 \\ a & g & 4 & 8 & 7 & e & 3 & d & 6 & 2 & h & b & 1 & 5 & i & j & f & c & 0 & 9 \\ 1 & b & h & 5 & 9 & 8 & f & 4 & e & 7 & 3 & i & c & 2 & 6 & 0 & j & g & d & a \\ e & 2 & c & i & 6 & a & 9 & g & 5 & f & 8 & 4 & 0 & d & 3 & 7 & 1 & j & h & b \\ i & f & 3 & 0 & d & 7 & b & a & h & 6 & g & 9 & 5 & 1 & e & 4 & 8 & 2 & j & c \\ j & 0 & g & 4 & e & 1 & 8 & c & b & i & 7 & h & a & 6 & 2 & f & 5 & 9 & 3 & d \\ 4 & j & 1 & h & 5 & f & 2 & 9 & d & c & 0 & 8 & i & b & 7 & 3 & g & 6 & a & e \\ b & 5 & j & 2 & i & 6 & g & 3 & a & e & d & 1 & 9 & 0 & c & 8 & 4 & h & 7 & f \\ 8 & c & 6 & j & 3 & 0 & 7 & h & 4 & b & f & e & 2 & a & 1 & d & 9 & 5 & i & g \\ d & e & f & g & h & i & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & c & j \end{bmatrix}, S(20) = \begin{bmatrix} j & 1 & d & c & 8 & 3 & g & 6 & f & e & 5 & 7 & i & a & h & 4 & 9 & b & 0 & 2 \\ 1 & j & 2 & e & d & 9 & 4 & h & 7 & g & f & 6 & 8 & 0 & b & i & 5 & a & c & 3 \\ d & 2 & j & 3 & f & e & a & 5 & i & 8 & h & g & 7 & 9 & 1 & c & 0 & 6 & b & 4 \\ c & e & 3 & j & 4 & g & f & b & 6 & 0 & 9 & i & h & 8 & a & 2 & d & 1 & 7 & 5 \\ 8 & d & f & 4 & j & 5 & h & g & c & 7 & 1 & a & 0 & i & 9 & b & 3 & e & 2 & 6 \\ 3 & 9 & e & g & 5 & j & 6 & i & h & d & 8 & 2 & b & 1 & 0 & a & c & 4 & f & 7 \\ g & 4 & a & f & h & 6 & j & 7 & 0 & i & e & 9 & 3 & c & 2 & 1 & b & d & 5 & 8 \\ 6 & h & 5 & b & g & i & 7 & j & 8 & 1 & 0 & f & a & 4 & d & 3 & 2 & c & e & 9 \\ f & 7 & i & 6 & c & h & 0 & 8 & j & 9 & 2 & 1 & g & b & 5 & e & 4 & 3 & d & a \\ e & g & 8 & 0 & 7 & d & i & 1 & 9 & j & a & 3 & 2 & h & c & 6 & f & 5 & 4 & b \\ 5 & f & h & 9 & 1 & 8 & e & 0 & 2 & a & j & b & 4 & 3 & i & d & 7 & g & 6 & c \\ 7 & 6 & g & i & a & 2 & 9 & f & 1 & 3 & b & j & c & 5 & 4 & 0 & e & 8 & h & d \\ i & 8 & 7 & h & 0 & b & 3 & a & g & 2 & 4 & c & j & d & 6 & 5 & 1 & f & 9 & e \\ a & 0 & 9 & 8 & i & 1 & c & 4 & b & h & 3 & 5 & d & j & e & 7 & 6 & 2 & g & f \\ h & b & 1 & a & 9 & 0 & 2 & 5 & c & i & 4 & 6 & e & j & 3 & 2 & 1 & b & 7 & 3 & g \\ 4 & i & c & 2 & b & a & 1 & 3 & e & 6 & d & 0 & 5 & 7 & f & j & g & 9 & 8 & h \\ 9 & 5 & 0 & d & 3 & c & b & 2 & 4 & f & 7 & e & 1 & 6 & 8 & g & j & h & a & i \\ b & a & 6 & 1 & e & 4 & d & c & 3 & 5 & g & 8 & f & 2 & 7 & 9 & h & j & i & 0 \\ 0 & c & b & 7 & 2 & f & 5 & e & 4 & 6 & h & 9 & g & 3 & 8 & a & i & j & 1 & 0 \\ 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & a & b & c & d & e & f & g & h & i & 0 & 1 & j \end{bmatrix}$$

van orde 20 kan soortgelyk uit die vektornotasië in [7, §III.5, Voorbeeld 5.48] afgelei word. Die bogenoemde vier matrikspre kan gebruik word om GGRTT'e van ordes  $n = 12, 15, 18$  en  $20$  optimaal in rondtes te beslis, soos ons in die aanhangsel aan die einde van die artikel doen.

**4.2 Lyste van GGRTT potte vir die uitstaande gevalle  $n = 10$  en  $14$**

Die kleinste orde waarvoor dit tot nog toe onbekend is of die potte van 'n GGRTT optimaal in rondtes beslisbaar is, is dus  $n = 10$ . Dit is wel moontlik om die potte van so 'n GGRTT volgens Stelling 13 op minstens drie verskillende maniere te lys, gebaseer op die nie-isotopiese self-ortogonale Latynse vierkante

$$L(10) = \begin{bmatrix} 0 & 2 & 8 & 6 & 9 & 7 & 1 & 5 & 4 & 3 \\ 5 & 1 & 3 & 0 & 7 & 9 & 8 & 2 & 6 & 4 \\ 7 & 6 & 2 & 4 & 1 & 8 & 9 & 0 & 3 & 5 \\ 4 & 8 & 7 & 3 & 5 & 2 & 0 & 9 & 1 & 6 \\ 2 & 5 & 0 & 8 & 4 & 6 & 3 & 1 & 9 & 7 \\ 9 & 3 & 6 & 1 & 0 & 5 & 7 & 4 & 2 & 8 \\ 3 & 9 & 4 & 7 & 2 & 1 & 6 & 8 & 5 & 0 \\ 6 & 4 & 9 & 5 & 8 & 3 & 2 & 7 & 0 & 1 \\ 1 & 7 & 5 & 9 & 6 & 0 & 4 & 3 & 8 & 2 \\ 8 & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 9 \end{bmatrix}, L'(10) = \begin{bmatrix} 0 & 2 & 5 & 8 & 6 & 3 & 1 & 9 & 7 & 4 \\ 7 & 1 & 6 & 5 & 3 & 9 & 0 & 4 & 2 & 8 \\ 1 & 4 & 2 & 9 & 8 & 7 & 3 & 0 & 6 & 5 \\ 6 & 8 & 0 & 3 & 7 & 2 & 9 & 5 & 4 & 1 \\ 2 & 0 & 9 & 1 & 4 & 8 & 5 & 6 & 3 & 7 \\ 9 & 6 & 3 & 4 & 1 & 5 & 7 & 8 & 0 & 2 \\ 3 & 5 & 8 & 7 & 9 & 4 & 6 & 2 & 1 & 0 \\ 4 & 3 & 1 & 2 & 5 & 0 & 8 & 7 & 9 & 6 \\ 5 & 9 & 7 & 0 & 2 & 6 & 4 & 1 & 8 & 3 \\ 8 & 7 & 4 & 6 & 0 & 1 & 2 & 3 & 5 & 9 \end{bmatrix} \text{ en } L''(10) = \begin{bmatrix} 0 & 2 & 5 & 8 & 6 & 3 & 1 & 9 & 7 & 4 \\ 8 & 1 & 3 & 6 & 0 & 7 & 4 & 2 & 9 & 5 \\ 9 & 0 & 2 & 4 & 7 & 1 & 8 & 5 & 3 & 6 \\ 4 & 9 & 1 & 3 & 5 & 8 & 2 & 0 & 6 & 7 \\ 7 & 5 & 9 & 2 & 4 & 6 & 0 & 3 & 1 & 8 \\ 2 & 8 & 6 & 9 & 3 & 5 & 7 & 1 & 4 & 0 \\ 5 & 3 & 0 & 7 & 9 & 4 & 6 & 8 & 2 & 1 \\ 3 & 6 & 4 & 1 & 8 & 9 & 5 & 7 & 0 & 2 \\ 1 & 4 & 7 & 5 & 2 & 0 & 9 & 6 & 8 & 3 \\ 6 & 7 & 8 & 0 & 1 & 2 & 3 & 4 & 5 & 9 \end{bmatrix} \tag{13}$$

van orde 10 wat in onderskeidelik [7, §III.5, Voorbeeld 5.6], [10, Tabel 1] en [20, Figuur 1] verskyn. Die lys van 45 potte vir 'n GGRTT van orde 10 wat uit  $L(10)$  ontstaan, is:

$\begin{bmatrix} 0 & 1 \\ 2 & 5 \end{bmatrix}$	$\begin{bmatrix} 0 & 2 \\ 8 & 7 \end{bmatrix}$	$\begin{bmatrix} 0 & 3 \\ 6 & 4 \end{bmatrix}$	$\begin{bmatrix} 0 & 4 \\ 9 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 5 \\ 7 & 9 \end{bmatrix}$	$\begin{bmatrix} 0 & 6 \\ 1 & 3 \end{bmatrix}$	$\begin{bmatrix} 0 & 7 \\ 5 & 6 \end{bmatrix}$	$\begin{bmatrix} 0 & 8 \\ 4 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 9 \\ 3 & 8 \end{bmatrix}$	$\begin{bmatrix} 1 & 2 \\ 3 & 6 \end{bmatrix}$
$\begin{bmatrix} 1 & 3 \\ 0 & 8 \end{bmatrix}$	$\begin{bmatrix} 1 & 4 \\ 7 & 5 \end{bmatrix}$	$\begin{bmatrix} 1 & 5 \\ 9 & 3 \end{bmatrix}$	$\begin{bmatrix} 1 & 6 \\ 8 & 9 \end{bmatrix}$	$\begin{bmatrix} 1 & 7 \\ 2 & 4 \end{bmatrix}$	$\begin{bmatrix} 1 & 8 \\ 6 & 7 \end{bmatrix}$	$\begin{bmatrix} 1 & 9 \\ 4 & 0 \end{bmatrix}$	$\begin{bmatrix} 2 & 3 \\ 4 & 7 \end{bmatrix}$	$\begin{bmatrix} 2 & 4 \\ 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 2 & 5 \\ 8 & 6 \end{bmatrix}$
$\begin{bmatrix} 2 & 6 \\ 9 & 4 \end{bmatrix}$	$\begin{bmatrix} 2 & 7 \\ 0 & 9 \end{bmatrix}$	$\begin{bmatrix} 2 & 8 \\ 3 & 5 \end{bmatrix}$	$\begin{bmatrix} 2 & 9 \\ 5 & 1 \end{bmatrix}$	$\begin{bmatrix} 3 & 4 \\ 5 & 8 \end{bmatrix}$	$\begin{bmatrix} 3 & 5 \\ 2 & 1 \end{bmatrix}$	$\begin{bmatrix} 3 & 6 \\ 0 & 7 \end{bmatrix}$	$\begin{bmatrix} 3 & 7 \\ 9 & 5 \end{bmatrix}$	$\begin{bmatrix} 3 & 8 \\ 1 & 9 \end{bmatrix}$	$\begin{bmatrix} 3 & 9 \\ 6 & 2 \end{bmatrix}$
$\begin{bmatrix} 4 & 5 \\ 6 & 0 \end{bmatrix}$	$\begin{bmatrix} 4 & 6 \\ 3 & 2 \end{bmatrix}$	$\begin{bmatrix} 4 & 7 \\ 1 & 8 \end{bmatrix}$	$\begin{bmatrix} 4 & 8 \\ 9 & 6 \end{bmatrix}$	$\begin{bmatrix} 4 & 9 \\ 7 & 3 \end{bmatrix}$	$\begin{bmatrix} 5 & 6 \\ 7 & 1 \end{bmatrix}$	$\begin{bmatrix} 5 & 7 \\ 4 & 3 \end{bmatrix}$	$\begin{bmatrix} 5 & 8 \\ 2 & 0 \end{bmatrix}$	$\begin{bmatrix} 5 & 9 \\ 8 & 4 \end{bmatrix}$	$\begin{bmatrix} 6 & 7 \\ 8 & 2 \end{bmatrix}$
$\begin{bmatrix} 6 & 8 \\ 5 & 4 \end{bmatrix}$	$\begin{bmatrix} 6 & 9 \\ 0 & 5 \end{bmatrix}$	$\begin{bmatrix} 7 & 8 \\ 0 & 3 \end{bmatrix}$	$\begin{bmatrix} 7 & 9 \\ 1 & 6 \end{bmatrix}$	$\begin{bmatrix} 8 & 9 \\ 2 & 7 \end{bmatrix}$					

terwyl dié wat uit die self-ortogonale Latynse vierkant  $L'(10)$  ontstaan, gegee word deur:

0	1
2	7

0	2
5	1

0	3
8	6

0	4
6	2

0	5
3	9

0	6
1	3

0	7
9	4

0	8
7	5

0	9
4	8

1	2
6	4

1	3
5	8

1	4
3	0

1	5
9	6

1	6
0	5

1	7
4	3

1	8
2	9

1	9
8	7

2	3
9	0

2	4
8	9

2	5
7	3

2	6
3	8

2	7
0	1

2	8
6	7

2	9
5	4

3	4
7	1

3	5
2	4

3	6
9	7

3	7
5	2

3	8
4	0

3	9
1	6

4	5
8	1

4	6
5	9

4	7
6	5

4	8
3	2

4	9
7	0

5	6
7	4

5	7
8	0

5	8
0	6

5	9
2	1

6	7
2	8

6	8
1	4

6	9
0	2

7	8
9	1

7	9
6	3

8	9
3	5

Die lys van 45 potte

0	1
2	8

0	2
5	9

0	3
8	4

0	4
6	7

0	5
3	2

0	6
1	5

0	7
9	3

0	8
7	1

0	9
4	6

1	2
3	0

1	3
6	9

1	4
0	5

1	5
7	8

1	6
4	3

1	7
2	6

1	8
9	4

1	9
5	7

2	3
4	1

2	4
7	9

2	5
1	6

2	6
8	0

2	7
5	4

2	8
3	7

2	9
6	8

3	4
5	2

3	5
8	9

3	6
2	7

3	7
0	1

3	8
6	5

3	9
7	0

4	5
6	3

4	6
0	9

4	7
3	8

4	8
1	2

4	9
8	1

5	6
7	4

5	7
1	9

5	8
4	0

5	9
0	2

6	7
8	5

6	8
2	9

6	9
1	3

7	8
0	6

7	9
2	4

7	9
3	5

ontstaan laastens uit die Latynse vierkant  $L''(10)$ . Dit is egter maklik om aan te toon dat geen simmetriese maats vir enigeen van die self-ortogonale Latynse vierkante  $L(10)$ ,  $L'(10)$  of  $L''(10)$  in (13) gevind kan word nie; daarom kan geneen van die bostaande lysste van 45 potte optimaal (in nege rondtes van vyf potte elk) beslis word nie. Dit is ook nie bekend of 'n ander self-ortogonale Latynse vierkant van orde 10 as dié in (13) gevorm kan word (m.a.w. of die bogenoemde lysste potte effens anders gekies kan word) om die bestaan van so 'n simmetriese maat te bewerkstellig nie. Die grootste aantal Latynse vierkante van orde 10 bekend wat onderling in pare ortogonaal is, is trouens twee [7, §III.4, Tabel 4.14] — die ontdekking van 'n SLVSOM van orde 10 sal hierdie ondergrens op die grootste aantal Latynse vierkante van orde 10 wat in pare ortogonaal is, met een opskuif.

Die self-ortogonale Latynse vierkant

$$L(14) = \begin{bmatrix} 0 & 8 & 3 & c & 9 & 2 & 5 & a & 6 & b & 1 & 4 & d & 7 \\ d & 1 & 9 & 4 & 0 & a & 3 & 6 & b & 7 & c & 2 & 5 & 8 \\ 6 & d & 2 & a & 5 & 1 & b & 4 & 7 & c & 8 & 0 & 3 & 9 \\ 4 & 7 & d & 3 & b & 6 & 2 & c & 5 & 8 & 0 & 9 & 1 & a \\ 2 & 5 & 8 & d & 4 & c & 7 & 3 & 0 & 6 & 9 & 1 & a & b \\ b & 3 & 6 & 9 & d & 5 & 0 & 8 & 4 & 1 & 7 & a & 2 & c \\ 3 & c & 4 & 7 & a & d & 6 & 1 & 9 & 5 & 2 & 8 & b & 0 \\ c & 4 & 0 & 5 & 8 & b & d & 7 & 2 & a & 6 & 3 & 9 & 1 \\ a & 0 & 5 & 1 & 6 & 9 & c & d & 8 & 3 & b & 7 & 4 & 2 \\ 5 & b & 1 & 6 & 2 & 7 & a & 0 & d & 9 & 4 & c & 8 & 3 \\ 9 & 6 & c & 2 & 7 & 3 & 8 & b & 1 & d & a & 5 & 0 & 4 \\ 1 & a & 7 & 0 & 3 & 8 & 4 & 9 & c & 2 & d & b & 6 & 5 \\ 7 & 2 & b & 8 & 1 & 4 & 9 & 5 & a & 0 & 3 & d & c & 6 \\ 8 & 9 & a & b & c & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & d \end{bmatrix}$$

van orde 14 is in 1975 deur Hedayat [11, Tabel 1] gevind. Die lys van 91 potte vir 'n GGRIT van orde 14 wat op hierdie manier ontstaan, is:

0	1
8	d

0	2
3	6

0	3
c	4

0	4
9	2

0	5
2	b

0	6
5	3

0	7
a	c

0	8
6	a

0	9
b	5

0	a
1	9

0	b
4	1

0	c
d	7

0	d
7	8

1	2
9	d

1	3
4	7

1	4
1	4

1	5
a	3

1	6
3	c

1	7
6	4

1	8
b	0

1	9
7	b

1	a
c	6

1	b
2	a

1	c
5	2

1	d
8	9

2	3
a	d

2	4
5	8

2	5
1	6

2	6
b	4

2	7
4	0

2	8
7	5

2	9
c	1

2	a
8	c

2	b
0	7

2	c
3	b

2	d
9	a

3	4
b	d

3	5
6	9

3	6
2	7

3	7
c	5

3	8
5	1

3	9
8	6

3	a
0	2

3	b
9	0

3	c
1	8

3	d
a	b

4	5
c	d

4	6
7	a

4	7
3	8

4	8
0	6

4	9
6	2

4   a 9   7	4   b 1   3	4   c a   1	4   d b   c	5   6 0   d	5   7 8   b	5   8 4   9	5   9 1   7	5   a 7   3	5   b a   8
5   c 2   4	5   d c   0	6   7 1   d	6   8 9   c	6   9 5   a	6   a 2   8	6   b 8   4	6   c b   9	6   d 0   1	7   8 2   d
7   9 a   0	7   a 6   b	7   b 3   9	7   c 9   5	7   d 1   2	8   9 3   d	8   a b   1	8   b 7   c	8   c 4   a	8   d 2   3
9   a 4   d	9   b c   2	9   c 8   0	9   d 3   4	a   b 5   d	a   c 0   3	a   d 4   5	b   c 6   d	b   d 5   6	c   d 6   7

**4.3 Rondte-beslissings vir GGRTT'e van ordes  $n = 10$  en 14**

Deur al  $\binom{45}{5} = 1\,221\,759$  kombinasies van vyf potte in elkeen van die lyste van 45 potte vir GGRTT'e van orde 10 in (14)–(16) rekenaarmatig te ondersoek, is dit maklik om aan te toon dat geen enkele rondte bestaande uit vyf potte in enigeen van die drie lyste gevind kan word nie. Daarom bestaan elke rondte in enigeen van hierdie drie lyste potte noodwendig uit hoogstens vier potte. Gevolglik word minstens  $\lceil \frac{45}{4} \rceil = 12$  rondtes in elke geval benodig. Die mees gebalanseerde manier om 45 potte in twaalf rondtes van hoogstens vier potte elk in te deel, is wanneer nege van die twaalf rondtes uit vier potte elk bestaan (ons noem sulke rondtes *groot rondtes*), en die oorblywende drie rondtes elk uit drie potte bestaan (ons noem sulke rondtes *klein rondtes*), soos in Tabel 2 gesien kan word.

**TABEL 2:** Die maniere waarop 45 potte in 12 rondtes, elk met hoogstens 4 potte, vir 'n toernooi van orde  $n = 10$  ingedeel kan word.

# Groot Rondtes	# Potte per Rondte												Maks – min Afwyking	← beste	
	0	1	2	3	4	5	6	7	8	9	a	b			
9	4	4	4	4	4	4	4	4	4	4	3	3	3	1	
10	4	4	4	4	4	4	4	4	4	4	4	3	2	2	
11	4	4	4	4	4	4	4	4	4	4	4	4	1	3	

Om rondte-beslissings bestaande uit nege groot rondtes en drie klein rondtes te vind, kan daar vir elkeen van die potlyste (14)–(16) 'n sogenaamde *uitsluitingsgrafiek vir die groot rondtes* opgestel word. Elke punt in so 'n uitsluitingsgrafiek is 'n toelaatbare groepering van vier potte uit die lys (m.a.w. vier potte waarin geen speler meer as een keer voorkom nie), en twee punte in die grafiek word deur vier middel van 'n lyn aan mekaar verbind indien daar minstens een pot is wat in beide die ooreenstemmende potgroeperings voorkom. Die potgroeperings is dus potensieël groot rondtes, en geen twee van hierdie rondtes kan natuurlik beide in 'n uiteindelijke rondtebeslissing geskeduleer word as die ooreenstemmende punte in die uitsluitingsgrafiek naasliggend is nie. Vir die potlyste (14)–(16) is die ordes van hierdie uitsluitingsgrafieke almal 99, terwyl die groottes daarvan onderskeidelik 1 287, 1 197 en 1 197 is (die grafieke is paarsgewys nie-isomorf).

Enige onafhanklike versameling **A** van kardinaliteit 9 in die uitsluitingsgrafiek vir groot rondtes stem ooreen met 'n geldige indeling van 36 van die 45 potte in nege groot rondtes. Vir enige sodanige onafhanklike versameling in die uitsluitingsgrafiek vir groot rondtes kan daar op 'n soortgelyke wyse 'n verdere *uitsluitingsgrafiek vir klein rondtes* vir die oorblywende nege potte opgestel word. In die uitsluitingsgrafiek vir klein rondtes stem die punte ooreen met toelaatbare groeperings van drie potte uit die oorblywende lys van nege potte (m.a.w. drie potte waarin geen speler meer as een keer voorkom nie), en die naasliggendheid van punte in die grafiek is soortgelyk aan dié in die uitsluitingsgrafiek vir groot rondtes. Indien 'n onafhanklike versameling **B** van kardinaliteit 3 in die uitsluitingsgrafiek vir klein rondtes gevind kan word, kan al 45 potte volgens die versamelings **A** en **B** in nege groot rondtes en drie klein rondtes geskeduleer word. Ons skeduleringsbenadering vir elkeen van die potlyste (14)–(16) was dus om alle onafhanklike versamelings van kardinaliteit 9 in die uitsluitingsgrafiek vir groot rondtes opeenvolgens te ondersoek totdat 'n onafhanklike versameling van kardinaliteit 3 in die ooreenstemmende uitsluitingsgrafiek vir klein rondtes gevind kon word. Hierdie ondersoek is



rekenaarmatig deur middel van 'n algoritme in [4] uitgevoer en het by die 103-de oorweging van 'n onafhanklike versameling van kardinaliteit 9 in die uitsluitingsgrafiek vir groot rondtes die spelskedule

Rondte 0:	<table border="1"><tr><td>0</td><td>1</td></tr><tr><td>2</td><td>5</td></tr></table>	0	1	2	5	<table border="1"><tr><td>2</td><td>5</td></tr><tr><td>8</td><td>6</td></tr></table>	2	5	8	6	<table border="1"><tr><td>3</td><td>8</td></tr><tr><td>1</td><td>9</td></tr></table>	3	8	1	9	<table border="1"><tr><td>4</td><td>9</td></tr><tr><td>7</td><td>3</td></tr></table>	4	9	7	3	Rondte 1:	<table border="1"><tr><td>0</td><td>2</td></tr><tr><td>8</td><td>7</td></tr></table>	0	2	8	7	<table border="1"><tr><td>1</td><td>5</td></tr><tr><td>9</td><td>3</td></tr></table>	1	5	9	3	<table border="1"><tr><td>3</td><td>9</td></tr><tr><td>6</td><td>2</td></tr></table>	3	9	6	2	<table border="1"><tr><td>6</td><td>8</td></tr><tr><td>5</td><td>4</td></tr></table>	6	8	5	4
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vir die potlys (15) by die 26-ste oorweging van 'n onafhanklike versameling van kardinaliteit 9 in die uitsluitingsgrafiek vir groot rondtes gevind is. Die spelskedule

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is laastens vir die potlys (16) by die 34-ste oorweging van 'n onafhanklike versameling van kardinaliteit 9 in die uitsluitingsgrafiek vir groot rondtes gevind.

Deur soortgelyk al  $\binom{91}{7} = 8\,093\,990\,190$  kombinasies van sewe potte in die lys van 91 potte vir 'n GGRTT van orde 14 in §4 rekenaarmatig te ondersoek, kan daar aangetoon word dat geen enkele rondte bestaande uit sewe potte gevind kan word nie. Daarom bestaan elke rondte uit hoogstens ses potte. Gevolglik word minstens  $\lceil \frac{91}{6} \rceil = 16$  rondtes benodig. Die mees gebalanseerde manier om 91 potte in sestien rondtes van hoogstens ses potte elk in te deel, is wanneer elf van die sestien rondtes uit ses potte elk bestaan (ons noem sulke rondtes weereens *groot rondtes*), en die oorblywende vyf rondtes elk uit vyf potte bestaan (weereens bekend as *klein rondtes*), soos in Tabel 3 gesien kan word.

Om 'n rondte-beslissing bestaande uit elf groot rondtes en vyf klein rondtes te vind, het ons weer 'n *uitsluitingsgrafiek* vir die groot rondtes opgestel, maar hierdie keer van orde 541 (omdat daar 541 verskillende maniere is om ses potte saam in 'n rondte te groepeer) en van grootte 44365. Elke punt in hierdie uitsluitingsgrafiek is dus 'n toelaatbare groepering van ses potte uit die lys van 91 potte. 'n

**TABEL 3:** Die maniere waarop 91 potte in 16 rondtes, elk met hoogstens 6 potte, vir 'n toernooi van orde  $n = 14$  ingedeel kan word.

# Groot Rondtes	# Potte per Rondte														Maks – min Afwyking		
	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f	
11	6	6	6	6	6	6	6	6	6	6	6	5	5	5	5	5	1
12	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	4	2
13	6	6	6	6	6	6	6	6	6	6	6	6	6	5	4	4	2
13	6	6	6	6	6	6	6	6	6	6	6	6	6	5	5	3	3
14	6	6	6	6	6	6	6	6	6	6	6	6	6	6	4	3	3
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← beste

Soortgelyke benadering as vir  $n = 10$  is gevolg, waar ons gesoek het na 'n onafhanklike versameling **A** van kardinaliteit 11 in die uitsluitingsgrafiek vir groot rondtes en 'n onafhanklike versameling **B** van kardinaliteit 5 in die ooreenstemmende uitsluitingsgrafiek vir klein rondtes. 'n Rekenaarmatige soektog na sulke versamelings **A, B** het by die 117-de oorweging van 'n onafhanklike versameling van kardinaliteit 11 in die uitsluitingsgrafiek vir groot rondtes die spelskedule

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opgelewer.

#### 4.4 Alternatiewe GGRTT-beslissings vir $n = 6, 10, 14$ d.m.v. reëlverslapping

Dit is natuurlik moontlik om gebalanseerde, maar sub-optimale spelskedules (in terme van oortollighe) vir alle waardes van  $n$  (insluitend  $n = 6$ ) op te stel indien die toernooireëls (V3)–(V5) in §1 verslap word na:

- (V3)' elke speler *minstens* een keer teen elke ander speler van dieselfde geslag te staan kom,  
 (V4)' elke speler *minstens* een keer saam met elke speler van die teenoorgestelde geslag in 'n span afgepaar word, en  
 (V5)' elke speler *minstens* een keer teen elke speler van die teenoorgestelde geslag te staan kom.

Ons het byvoorbeeld die onderstaande spelskedule bestaande uit ses rondtes van drie potte elk vir  $n = 6$  gevind deur na drie rondtes (Rondtes 0, 2 en 4) te soek waarvoor al  $\binom{6}{2} = 15$  pare van dieselfde geslag voorkom (m.a.w. alle ongeordende, horisontale pare in die roosternotasie van Figuur 1) en waarvoor elke ongeordende paar  $(a, b)$  (van teenoorgestelde-geslag spelers) in minstens een van die volgende kombinasies voorkom: (i)  $(a, b)$  en  $(b, a)$  verskyn beide in 'n kolom of in 'n diagonaal, of (ii)  $(a, b)$  of  $(b, a)$  verskyn beide in 'n kolom en in 'n diagonaal. Daarna het ons die volgende drie rondtes (Rondtes 1, 3 en 5) gevorm deur in elke pot van die bogenoemde drie rondtes alle mans met hul vrouens om te ruil en dan weer die twee vrouens in elke pot om te ruil. Tydens hierdie omruiling vervul mans dus die rolle van vrouens, terwyl opponerende pare die rol van spanpare vervul. Op hierdie manier word daar aan die toernooireëls (V1)–(V2), (V3')–(V5') voldoen:

Rondte 0:	$\begin{array}{ c c } \hline 0 & 1 \\ \hline 2 & 3 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 2 & 4 \\ \hline 0 & 5 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 3 & 5 \\ \hline 1 & 4 \\ \hline \end{array}$	Rondte 1:	$\begin{array}{ c c } \hline 2 & 3 \\ \hline 1 & 0 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 0 & 5 \\ \hline 4 & 2 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 1 & 4 \\ \hline 5 & 3 \\ \hline \end{array}$
Rondte 2:	$\begin{array}{ c c } \hline 0 & 2 \\ \hline 3 & 5 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 1 & 5 \\ \hline 4 & 0 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 3 & 4 \\ \hline 2 & 1 \\ \hline \end{array}$	Rondte 3:	$\begin{array}{ c c } \hline 3 & 5 \\ \hline 2 & 0 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 4 & 0 \\ \hline 5 & 1 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 2 & 1 \\ \hline 4 & 3 \\ \hline \end{array}$
Rondte 4:	$\begin{array}{ c c } \hline 0 & 2 \\ \hline 4 & 1 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 1 & 3 \\ \hline 2 & 5 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 4 & 5 \\ \hline 0 & 3 \\ \hline \end{array}$	Rondte 5:	$\begin{array}{ c c } \hline 4 & 1 \\ \hline 2 & 0 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 2 & 5 \\ \hline 3 & 1 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 0 & 3 \\ \hline 5 & 4 \\ \hline \end{array}$

Die nadeel van die bogenoemde rondtebeslissing is dat daar oortolligheid in die spelskedule a.g.v. die reëlverslapping voorkom (die skedule bevat meer as die minimum aantal rondtes waarvoor daar in 'n OBGRTT gesoek word, en sommige pare spelers kom meer as een keer teen mekaar te staan en sommige ander pare speel weer meer as een keer saam met mekaar), maar 'n voordeel is dat elke rondte dieselfde aantal potte bevat (en die skedule dus gebalanseerd voorkom). Die skedule is verder ook gebalanseerd in die sin dat elke speler presies een keer in elkeen van die drie soorte oortollighede waarvoor daar in (V3')–(V5') voorsiening gemaak word, ter sprake is. Die outeurs is nie bewus van 'n soortgelyke skedule vir  $n = 6$  in die literatuur waar daar gepoeg word om 'n beslissing (natuurlik met oortolligheid) in die minimum aantal rondtes te bewerkstellig nie. In die (ontwerp-teorie-) literatuur word daar gewoonlik volstaan met 'n opmerking dat die skedulering van 'n OBGRTT vir  $n = 6$  onmoontlik is; tog is dit prakties gesproke denkbaar dat tennisklubs daarin mag belangstel om GGRTT'e onder een of ander soort reëlverslapping vir ses getroude pare te skeduleer.

Ten slotte wys ons daarop dat Jooste [12, §5] opgemerk het dat rondtebeslissings vir GGRTT'e van ordes  $n = 6, 10, 14$  ook onder die reëlverslapping (V1)–(V2), (V3')–(V5') uit OBGRTT'e van ordes  $n = 7, 11, 15$  onderskeidelik afgelei kan word. 'n Rondte-beslissing kan byvoorbeeld vir 'n GGRTT van orde 6 uit 'n OBGRTT van orde 7 afgelei word deur in die laasgenoemde spelskedule die paar (man 6, vrou 6) te vervang met die paar wat in elke rondte 'n loslootjie ontvang, in welke geval die volgende rondte-beslissing ontstaan:

Rondte 0:	$\begin{array}{ c c } \hline 1 & 0 \\ \hline 3 & 4 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 2 & 5 \\ \hline 0 & 1 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 3 & 4 \\ \hline 2 & 5 \\ \hline \end{array}$	Rondte 1:	$\begin{array}{ c c } \hline 0 & 2 \\ \hline 5 & 4 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 3 & 1 \\ \hline 0 & 2 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 4 & 5 \\ \hline 3 & 1 \\ \hline \end{array}$
Rondte 2:	$\begin{array}{ c c } \hline 0 & 4 \\ \hline 3 & 1 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 1 & 3 \\ \hline 2 & 5 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 5 & 2 \\ \hline 4 & 0 \\ \hline \end{array}$	Rondte 3:	$\begin{array}{ c c } \hline 0 & 3 \\ \hline 1 & 5 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 1 & 5 \\ \hline 4 & 2 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 2 & 4 \\ \hline 0 & 3 \\ \hline \end{array}$
Rondte 4:	$\begin{array}{ c c } \hline 0 & 1 \\ \hline 4 & 2 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 2 & 4 \\ \hline 5 & 3 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 3 & 5 \\ \hline 1 & 0 \\ \hline \end{array}$	Rondte 5:	$\begin{array}{ c c } \hline 0 & 3 \\ \hline 4 & 5 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 1 & 2 \\ \hline 0 & 3 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 4 & 5 \\ \hline 2 & 1 \\ \hline \end{array}$
Rondte 6:	$\begin{array}{ c c } \hline 0 & 5 \\ \hline 2 & 3 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 1 & 4 \\ \hline 5 & 0 \\ \hline \end{array}$	$\begin{array}{ c c } \hline 2 & 3 \\ \hline 1 & 4 \\ \hline \end{array}$				

In die bogenoemde rondtebeslissing is daar weereens oortolligheid in die spelskedule a.g.v. die bogenoemde reëlverslapping, maar bevat elke rondte weer dieselfde aantal potte (en kom die skedule dus gebalanseerd voor). 'n Soortgelyke, gebalanseerde spelskedule (met oortollighede) kan vir  $n = 10$  uit 'n OBGGRIT van orde  $n = 11$  afgelei word, en sien soos volg daaruit:

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Let op dat die bogenoemde spelskedule uit een minder rondte bestaan as die ongebalanseerde spelskedule vir  $n = 10$  in §4.4 (waarin daar geen oortollighede is nie). 'n Soortgelyke skedule met oortollighede kan ten slotte vir  $n = 14$  uit 'n OBGGRIT van orde  $n = 15$  afgelei word:

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Weereens bestaan die bogenoemde spelskedule uit een minder rondte as die ongebalanseerde spelskedule vir  $n = 14$  in §4.4 (waarin daar geen oortollighede is nie).

## 5 SLOTOPMERKINGS

In hierdie artikel het ons ondersoek watter tegnieke uit ontwerpteorie gebruik kan word om op 'n wiskundig verantwoordbare wyse met OBGGRIT'e vorendag te kom. Hierdie tegnieke is gebaseer op die eienskappe en konstruksie van Latynse vierkante en spesifiek SLVSOM'e, soos in §2–3 verduidelik. Ons het hierdie tegnieke vir OBGGRIT'e van ordes hoogstens 20 toegepas en die resultate van hierdie toepassings op 'n gebruikersvriendelike manier in die aanhangsel aan die einde van hierdie artikel gedokumenteer. Die speelskedules in die aanhangsel is op 'n naslaanbasis toeganklik vir administrateurs van tennisklubs (wat tipies nie wiskundiges is nie).

Ons kon nie daarin slaag om OBGGRIT'e van ordes  $n = 6, 10$  en  $14$  te vind nie — in eersgenoemde geval omdat so 'n OBGGRIT nie bestaan nie, maar in laasgenoemde twee gevalle mag dit wees dat OBGGRIT'e wel bestaan. Ons het wel in §4 vir hierdie drie GGRTT ordes goeie (maar nie noodwendig optimale) rondte-beslissings daargestel. In die lig van die suboptimaliteit van hierdie drie gevalle stel ons die volgende twee beroemde oop probleme as uitdagings aan die leser.

**Oop Probleem 1** *Bestaan daar 'n SLVSOM van orde 10? Indien so 'n matrikspaar gevind kan word, sou dit gebruik kon word om op die rondte-beslissing vir 'n GGRTT van orde 10 wat in §4.4–4.5 gegee is, te verbeter. Indien nie, kan 'n speelskedule bestaande uit 10 rondtes nogtans vir die geval  $n = 10$  gevind word?*

**Oop Probleem 2** *Bestaan daar 'n SLVSOM van orde 14? Indien so 'n matrikspaar gevind kan word, sou dit gebruik kon word om op die rondte-beslissing vir 'n GGRTT van orde 14 wat in §4.4–4.5 gegee is, te verbeter. Indien nie, kan 'n speelskedule bestaande uit 14 rondtes nogtans vir die geval  $n = 14$  gevind word?*

Ten slotte wys ons weer daarop dat Stelling 9 die uitspraak lewer dat OBGGRIT'e van alle ordes  $n > 20$  gevind kan word. Dus stem die *enigste* probleemgevalle ooreen met die ordes  $n = 6, 10$  en  $14$ .

## Dankbetuigings

Die outeurs bedank Professor Dirk Laurie van die Departement Wiskundige Wetenskappe aan die Universiteit Stellenbosch wat die probleem van gade-vermydende gemengde-dubbels rondomtalientennistoernooie onder ons aandag gebring het. Die NNS het hierdie navorsingsprojek onder toekenning nr. 2072999 befonds.

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## AANHANGSEL

Die doel van hierdie aanhangsel is, soos in die inleiding genoem, om ter wille van naslaandoeleindes voorstelle te maak vir die skedulering van GGRTT'e wat vir bestuurders van tennisklubs maklik interpreteerbaar is.

### OBGGRTT'e

Volgens die stellings en resultate in §3 is GGRTT'e van ordes  $n = 4, 5, 7, 8, 9, 11, 12, 13, 15, 16, 17, 18, 19$  en 20 optimaal in rondtes beslisbaar. Besliste toernooie van hierdie ordes word volgens die potnotasie in Figuur 1 in hierdie afdeling gelys. SLVSOM'e waarvolgens hierdie spelskedules gegeneer is, kan in [5] nageslaan word.

$n = 4$  (volgens Stellings 7 en 10 met  $p = 2$  en  $q = 2$ ):

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$n = 7$  (volgens Stellings 7 en 11 met  $p = 7$  en  $q = 1$ ):

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$n = 8$  (volgens Stellings 7 en 10 met  $p = 2$  en  $q = 3$ ):

Rondte 0:	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">0</td><td style="padding: 0 5px;">1</td></tr><tr><td style="padding: 0 5px;">7</td><td style="padding: 0 5px;">6</td></tr></table>	0	1	7	6	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">2</td><td style="padding: 0 5px;">3</td></tr><tr><td style="padding: 0 5px;">5</td><td style="padding: 0 5px;">4</td></tr></table>	2	3	5	4	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">4</td><td style="padding: 0 5px;">5</td></tr><tr><td style="padding: 0 5px;">3</td><td style="padding: 0 5px;">2</td></tr></table>	4	5	3	2	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">6</td><td style="padding: 0 5px;">7</td></tr><tr><td style="padding: 0 5px;">1</td><td style="padding: 0 5px;">0</td></tr></table>	6	7	1	0	Rondte 1:	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">0</td><td style="padding: 0 5px;">2</td></tr><tr><td style="padding: 0 5px;">3</td><td style="padding: 0 5px;">1</td></tr></table>	0	2	3	1	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">1</td><td style="padding: 0 5px;">3</td></tr><tr><td style="padding: 0 5px;">2</td><td style="padding: 0 5px;">0</td></tr></table>	1	3	2	0	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">4</td><td style="padding: 0 5px;">6</td></tr><tr><td style="padding: 0 5px;">7</td><td style="padding: 0 5px;">5</td></tr></table>	4	6	7	5	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">5</td><td style="padding: 0 5px;">7</td></tr><tr><td style="padding: 0 5px;">6</td><td style="padding: 0 5px;">4</td></tr></table>	5	7	6	4
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$n = 9$  (volgens Stellings 7 en 11 met  $p = 3$  en  $q = 2$ ):

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Rondte 5:	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">0</td><td style="padding: 0 5px;">7</td></tr><tr><td style="padding: 0 5px;">1</td><td style="padding: 0 5px;">6</td></tr></table>	0	7	1	6	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">1</td><td style="padding: 0 5px;">6</td></tr><tr><td style="padding: 0 5px;">7</td><td style="padding: 0 5px;">0</td></tr></table>	1	6	7	0	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">2</td><td style="padding: 0 5px;">8</td></tr><tr><td style="padding: 0 5px;">4</td><td style="padding: 0 5px;">3</td></tr></table>	2	8	4	3	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">3</td><td style="padding: 0 5px;">4</td></tr><tr><td style="padding: 0 5px;">2</td><td style="padding: 0 5px;">8</td></tr></table>	3	4	2	8	(Paar 5 loslootjie)
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Rondte 8:	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">0</td><td style="padding: 0 5px;">4</td></tr><tr><td style="padding: 0 5px;">3</td><td style="padding: 0 5px;">1</td></tr></table>	0	4	3	1	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">1</td><td style="padding: 0 5px;">3</td></tr><tr><td style="padding: 0 5px;">0</td><td style="padding: 0 5px;">4</td></tr></table>	1	3	0	4	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">2</td><td style="padding: 0 5px;">5</td></tr><tr><td style="padding: 0 5px;">6</td><td style="padding: 0 5px;">7</td></tr></table>	2	5	6	7	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">6</td><td style="padding: 0 5px;">7</td></tr><tr><td style="padding: 0 5px;">5</td><td style="padding: 0 5px;">2</td></tr></table>	6	7	5	2	(Paar 8 loslootjie)
0	4																				
3	1																				
1	3																				
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2	5																				
6	7																				
6	7																				
5	2																				

$n = 11$  (volgens Stellings 7 en 11 met  $p = 11$  en  $q = 1$ ):

Rondte 0:	<table style="border-collapse: collapse;"><tr><td style="padding: 0 5px;">1</td><td style="padding: 0 5px;">a</td></tr><tr><td style="padding: 0 5px;">3</td></tr></table>	1	a	3
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Rondte 3:	<table border="1"><tr><td>0</td><td>6</td></tr><tr><td>5</td><td>1</td></tr></table>	0	6	5	1	<table border="1"><tr><td>1</td><td>5</td></tr><tr><td>8</td><td>9</td></tr></table>	1	5	8	9	<table border="1"><tr><td>2</td><td>4</td></tr><tr><td>0</td><td>6</td></tr></table>	2	4	0	6	<table border="1"><tr><td>7</td><td>a</td></tr><tr><td>4</td><td>2</td></tr></table>	7	a	4	2	<table border="1"><tr><td>8</td><td>9</td></tr><tr><td>7</td><td>a</td></tr></table>	8	9	7	a	(Paar 3 loslootjie)
0	6																									
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0	6																									
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8	9																									
7	a																									
Rondte 4:	<table border="1"><tr><td>0</td><td>8</td></tr><tr><td>3</td><td>5</td></tr></table>	0	8	3	5	<table border="1"><tr><td>1</td><td>7</td></tr><tr><td>6</td><td>2</td></tr></table>	1	7	6	2	<table border="1"><tr><td>2</td><td>6</td></tr><tr><td>9</td><td>a</td></tr></table>	2	6	9	a	<table border="1"><tr><td>3</td><td>5</td></tr><tr><td>1</td><td>7</td></tr></table>	3	5	1	7	<table border="1"><tr><td>9</td><td>a</td></tr><tr><td>8</td><td>0</td></tr></table>	9	a	8	0	(Paar 4 loslootjie)
0	8																									
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1	7																									
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Rondte 5:	<table border="1"><tr><td>0</td><td>a</td></tr><tr><td>1</td><td>9</td></tr></table>	0	a	1	9	<table border="1"><tr><td>1</td><td>9</td></tr><tr><td>4</td><td>6</td></tr></table>	1	9	4	6	<table border="1"><tr><td>2</td><td>8</td></tr><tr><td>7</td><td>3</td></tr></table>	2	8	7	3	<table border="1"><tr><td>3</td><td>7</td></tr><tr><td>a</td><td>0</td></tr></table>	3	7	a	0	<table border="1"><tr><td>4</td><td>6</td></tr><tr><td>2</td><td>8</td></tr></table>	4	6	2	8	(Paar 5 loslootjie)
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Rondte 6:	<table border="1"><tr><td>0</td><td>1</td></tr><tr><td>a</td><td>2</td></tr></table>	0	1	a	2	<table border="1"><tr><td>2</td><td>a</td></tr><tr><td>5</td><td>7</td></tr></table>	2	a	5	7	<table border="1"><tr><td>3</td><td>9</td></tr><tr><td>8</td><td>4</td></tr></table>	3	9	8	4	<table border="1"><tr><td>4</td><td>8</td></tr><tr><td>0</td><td>1</td></tr></table>	4	8	0	1	<table border="1"><tr><td>5</td><td>7</td></tr><tr><td>3</td><td>9</td></tr></table>	5	7	3	9	(Paar 6 loslootjie)
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Rondte 7:	<table border="1"><tr><td>0</td><td>3</td></tr><tr><td>8</td><td>6</td></tr></table>	0	3	8	6	<table border="1"><tr><td>1</td><td>2</td></tr><tr><td>0</td><td>3</td></tr></table>	1	2	0	3	<table border="1"><tr><td>4</td><td>a</td></tr><tr><td>9</td><td>5</td></tr></table>	4	a	9	5	<table border="1"><tr><td>5</td><td>9</td></tr><tr><td>1</td><td>2</td></tr></table>	5	9	1	2	<table border="1"><tr><td>6</td><td>8</td></tr><tr><td>4</td><td>a</td></tr></table>	6	8	4	a	(Paar 7 loslootjie)
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Rondte 9:	<table border="1"><tr><td>0</td><td>7</td></tr><tr><td>4</td><td>3</td></tr></table>	0	7	4	3	<table border="1"><tr><td>1</td><td>6</td></tr><tr><td>7</td><td>0</td></tr></table>	1	6	7	0	<table border="1"><tr><td>2</td><td>5</td></tr><tr><td>a</td><td>8</td></tr></table>	2	5	a	8	<table border="1"><tr><td>3</td><td>4</td></tr><tr><td>2</td><td>5</td></tr></table>	3	4	2	5	<table border="1"><tr><td>8</td><td>a</td></tr><tr><td>6</td><td>1</td></tr></table>	8	a	6	1	(Paar 9 loslootjie)
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$n = 12$  (volgens die reguliere SLVSOM  $L(12), S(12)$  van orde 12 in §4.1):

Rondte 0:	<table border="1"><tr><td>0</td><td>9</td></tr><tr><td>8</td><td>6</td></tr></table>	0	9	8	6	<table border="1"><tr><td>1</td><td>4</td></tr><tr><td>a</td><td>0</td></tr></table>	1	4	a	0	<table border="1"><tr><td>2</td><td>7</td></tr><tr><td>9</td><td>3</td></tr></table>	2	7	9	3	<table border="1"><tr><td>3</td><td>a</td></tr><tr><td>b</td><td>5</td></tr></table>	3	a	b	5	<table border="1"><tr><td>5</td><td>8</td></tr><tr><td>2</td><td>4</td></tr></table>	5	8	2	4	<table border="1"><tr><td>6</td><td>b</td></tr><tr><td>1</td><td>7</td></tr></table>	6	b	1	7
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Rondte 1:	<table border="1"><tr><td>0</td><td>5</td></tr><tr><td>b</td><td>1</td></tr></table>	0	5	b	1	<table border="1"><tr><td>1</td><td>8</td></tr><tr><td>9</td><td>7</td></tr></table>	1	8	9	7	<table border="1"><tr><td>2</td><td>b</td></tr><tr><td>a</td><td>4</td></tr></table>	2	b	a	4	<table border="1"><tr><td>3</td><td>6</td></tr><tr><td>8</td><td>2</td></tr></table>	3	6	8	2	<table border="1"><tr><td>4</td><td>9</td></tr><tr><td>3</td><td>5</td></tr></table>	4	9	3	5	<table border="1"><tr><td>7</td><td>a</td></tr><tr><td>0</td><td>6</td></tr></table>	7	a	0	6
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$n = 17$  (volgens Stellings 7 en 11 met  $p = 17$  en  $q = 1$ ):

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**GGRTT rondte-beslissings vir die uitstaande gevalle**

Daar bestaan trouens geen OBGRTT van orde  $n = 6$  nie (sien Stelling 9), maar vir  $n = 10$  en 14 is dit nie bekend of 'n OBGRTT bestaan of nie. In hierdie afdeling gee ons dus goeie (maar nie noodwendig optimale) GGRTT rondte-beslissings vir hierdie drie uitstaande gevalle.

$n = 6$  (met oortolligheid, soos beskryf in §4.4)

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