# Optimum cereal combine harvester operation by means of automatic machine and threshing speed control

**Promotoren:** ir. A. Moens
hoogleraar in de landbouwkundige aspecten van de landbouwwerktuigkunde alsmede de landbouwbedrijfsmechanisatie

ir. O. H. Bosgra
buitengewoon hoogleraar in de meet-, regel- en systeemtechniek

W. Huisman

# Optimum cereal combine harvester operation by means of automatic machine and threshing speed control

Proefschrift

ter verkrijging van de graad van
doctor in de landbouwwetenschappen,
op gezag van de rector magnificus,
dr. C. C. Oosterlee,
hoogleraar in de veeteeltwetenschap,
in het openbaar te verdedigen
op woensdag 30 november 1983
des namiddags te vier uur in de aula
van de Landbouwhogeschool te Wageningen.

# Abstract

Huisman, W. (1983) Optimum cereal combine harvester operation by means of automatic machine and threshing speed control. Doctoral thesis, Agricultural University, Wageningen.
(xx + 293 p., 156 figs, 46 tables, 132 refs, app., Eng. and Dutch summaries)

The method by which automation of agricultural machinery can be developed is illustrated in the case of cereal combine harvesting. The controlled variables are machine forward speed and threshing cylinder peripheral speed. Four control systems have been developed that optimise these speeds on the basis of harvest costs minimisation, which includes variable and fixed costs of the machine and those of machine- and timeliness losses. The evaluated systems make use of a varying number of input process variables and control the machine speed exclusively, or both machine speed *and* threshing speed. The financial benefits from these control systems were calculated by means of a computer simulation. The research required in developing the models and control systems is discussed in detail. The simulation results demonstrate that control of low-frequency variations in crop properties brings some slight benefit and indicate that timeliness losses are of great importance to optimisation.

FREE DESCRIPTORS: cereal harvest optimisation, combine harvester, automatic control,machine speed control, threshing speed control, simulation.

This thesis is published by the
Department of Agricultural Engineering, Agricultural University
Mansholtlaan 12, 6708 PA Wageningen
The Netherlands

# Stellingen

1. Bij het ontwikkelen van geautomatiseerde systemen voor landbouwmachines dient men zich te laten leiden door een duidelijk en weloverwogen optimalisatie-criterium. Bovendien dient men in een vroeg stadium de te verwachten voordelen kwalitatief en kwantitatief in detail uit te werken om tijdig te kunnen besluiten over voortzetting, stopzetting of ombuiging van het ontwikkelingsonderzoek.

   Dit proefschrift, alsmede M.B. McGechan, C.A. Glasbey.
   J. Agric. Engn. Res. 6 (1982), p. 537-552.

2. Het feit dat gemiddeld per maaidorser in Nederland jaarlijks slechts een geringe oppervlakte wordt bewerkt, kan slechts worden verklaard door de lage machinekosten en het verlangen van de boer om het risico van hoge tijdigheidsverliezen te beperken. De lage machinekosten zijn een gevolg van de lange economische levensduur van maaidorsers.

   R.K. Oving, E. van Elderen, R.L. de Vries.
   IMAG publikatie 143, Wageningen 1980.

3. De graanverliesmeetsystemen die thans in de handel zijn, bieden alleen een economisch voordeel indien de gebruiker zich rekenschap heeft gegeven van het verliesniveau dat hij wenst aan te houden. Bovendien moet de gebruiker het meetsysteem zeer frequent ijken.

   Dit proefschrift.

4. Het ontwikkelen van geautomatiseerde systemen voor landbouwmachines vereist een multidisciplinaire aanpak. Vooral een intensieve samenwerking tussen onderzoekers uit de vakgebieden van de Landbouwtechniek en de Meet-, Regel- en Systeemtechniek is wenselijk.

   Dit proefschrift

5. Automatisering bij maaidorsers levert arbeidsplaatsen op.

Dit proefschrift.

6. Bij optimalisatie van het verschil tussen opbrengsten en kosten van een landbouwproductiesysteem, zoals bijvoorbeeld de bietsuikerproductie, moeten de productiemethoden op het landbouwbedrijf en in de fabriek als een samenhangend systeem worden beschouwd. Indien premies en boetes als sturingsmechanisme worden toegepast moeten deze ook op de korte termijn worden aangepast aan zich wijzigende omstandigheden.

7. Bij de vergelijking van de diverse methoden van groenvoederwinning, worden de aspecten kwaliteit en verlies ten onrechte minder nauwkeurig gekwantificeerd dan de machinekosten.

8. Indien adviezen en voorschriften omtrent energiebesparing in woon- en werkomgeving en in openbare voorzieningen onvoldoende effect sorteren, dienen de mogelijkheden van automatisering daartoe met spoed te worden onderzocht.

9. In de discussie over de invoering van werktijdverkorting moeten argumenten die betrekking hebben op inmateriële waarden een zwaarder gewicht krijgen dan ze thans veelal hebben. Bij de economische argumenten dient men meer aandacht te geven aan de flexibiliteit van de arbeidsmarkt en de grotere arbeidsprestatie.

10. Macro-economisch onderzoek moet zich minder richten op de economie van de groei en meer op een economie waarin de verdeling van welvaart centraal staat.

W. Huisman
Optimum cereal combine harvester operation by means of automatic machine and threshing speed control
Wageningen, 19 september 1983

*Wie steeds op de wind let,*
*zal niet zaaien;*
*en wie steeds naar de wolken ziet,*
*zal niet maaien.*

*Prediker 11:4*

# Voorwoord

In dit proefschrift is een belangrijk deel van de resultaten verwerkt van ongeveer 15 jaar onderzoek aan maaidorsers, uitgevoerd in het kader van het onderzoekprogramma van de vakgroep Landbouwtechniek van de Landbouwhogeschool. In die periode hebben velen een bijdrage geleverd aan dit onderzoek, die ik op deze plaats daarvoor gaarne mijn dank wil betuigen.

In de eerste plaats wil ik mijn promotoren bedanken.

Professor Moens, jou ben ik vooral dankbaar voor de ruime gelegenheid die je me hebt geboden dit onderzoek uit te voeren en voor de stimulans om het met een proefschrift af te ronden. Je opmerkingen betreffende inhoud en tekst en de nadruk die je legde op de algemene toepasbaarheid van het onderzoek, zijn erg belangrijk voor mij geweest.

Professor Bosgra, jou wil ik vooral bedanken voor de intensieve begeleiding met betrekking tot de aanpak van het onderzoek en de vormgeving. Je onvermoeibare inzet bij het overdragen van de nodige kennis uit jouw vakgebied was een onmisbare steun. Het heeft de kwaliteit van dit proefschrift zeer verbeterd.

De medewerkers van de vakgroep Landbouwtechniek waren degenen die dit onderzoek uiteindelijk hebben mogelijk gemaakt.

Oscar Bergman en Jan van Loo, jullie enthousiasme en steun waren onontbeerlijk. Jullie hebben vooral de periode van het veldonderzoek samen met Leen de Boer van de ir. A.P. Minderhoudhoeve, tot een fijne tijd gemaakt.

Egbert van der Wal, Eef van Donselaar en Piet Rijpma, jullie waren bij de assistentie in het veld zeer betrouwbaar en onvermoeibaar.

Geurt van de Scheur, Willem van Brakel en Jordan Charitoglou, jullie steun vanuit de werkplaats was de basis van veld- en laboratoriumonderzoek.

Voor de ontwerpadviezen voor apparatuur ben ik professor Quast, Jaap Heyning en Henk de Vries zeer dankbaar.

Jan Meuleman, jou dank ik vooral voor het overnemen van de taken die ik liet liggen tijdens het schrijven van dit proefschrift. Ook de andere collega's die taken overnamen ben ik daarvoor dankbaar.

Guus Tergast, Karen den Outer en Elly Faber, jullie wil ik vooral bedanken voor de prettige en correcte wijze waarop jullie mijn werk ondersteunen.

In de lange periode van onderzoek hebben 44 doctoraal studenten en een 10-tal praktijkstudenten aan onderwerpen gewerkt die samenhingen met dit onderzoek. Ik heb met plezier met allen samengewerkt en ben dankbaar voor hun inzet.

De student-assistenten Leo van Geel, Henk van Dongen, Frans Reumkens en Bert van 't Ooster ben ik dankbaar voor het maken van en het werken met het simulatieprogramma. Jullie hebben mij veel werk uit handen genomen. Vooral Bert dank ik voor zijn steun in de avonden en nachten achter de terminal.

Van de medewerkers van de sectie Meet-, regel- en systeemtechniek van de vakgroep Natuur- en Weerkunde wil ik met name bedanken Alexander Udink ten Cate en tevens zijn oud collega's Jimmy Lengkeek, professor van Dixhoorn en Gerrit van Zee. Voor de steun bij computerwerk en signaalanalyse ben ik tevens Dimitri van den Akker en Willem Driessen dank verschuldigd.

Dit onderzoek zou niet mogelijk geweest zijn zonder de bijdrage van diverse instellingen en bedrijven zoals

Fa. Sperry New Holland

Fa. Van Driel & van Dorsten

Rijksdienst voor de IJsselmeerpolders

Instituut voor Mechanisatie, Arbeid en Gebouwen

Technische en Fysische Dienst voor de Landbouw

De vakgroepen Informatica, Wiskunde, Landbouwplantenteelt en graslandkunde, het rekencentrum van de Landbouwhogeschool en de ir. A.P. Minderhoudhoeve.

Tenslotte wil ik voor de vormgeving van dit proefschrift gaarne bedanken: Eef van Donselaar voor de figuren; mr. Smith Hardy voor de correctie van het Engels; Hans Sytsma voor vertaalwerk; Karen den Outer, Ciska den Herder en mevrouw L.J. Müller voor het typen van de diverse concepten en Jakke van der Sluis voor het typen en afwerken van de gedrukte versie.

Lieve Jannie, zonder jouw steun was dit werk niet tot stand gekomen; lieve Geertje en Jan Willem, zonder jullie geduld was het niet klaargekomen; lieve vader en moeder, zonder jullie opvoeding was ik er niet aan begonnen.

Wageningen, 29 augustus 1983

# Contents

# List of symbols

| | | |
|---|---|---|
| *a* | regression coefficient; constant in loss-to-feed rate relationship | |
| *A* | ratio of peak values of even straw feed (*TE*) and irregular straw feed (*TI*) | - |
| *AA* | harvested area per combine harvester per year | $ha \cdot yr^{-1}$ |
| *AAN* | *AA* in normal or manually controlled situation | $ha \cdot yr^{-1}$ |
| *ACAV* | average of the absolute values of machine forward speed accelerations | $m \cdot s^{-2}$ |
| *AFC* | annual fixed machine costs | $fl \cdot yr^{-1}$ |
| *AFS* | straw feed rate per m width of threshing cylinder (straw = material other than grain, m.o.g. dry matter) | $kg \cdot s^{-1} \cdot m^{-1}$ |
| *AFST* | *AFS* at the threshing cylinder entrance | $kg \cdot s^{-1} \cdot m^{-1}$ |
| *AFSW* | *AFS* at the straw walker entrance | $kg \cdot s^{-1} \cdot m^{-1}$ |
| *AP* | period over which measured signals are averaged | s |
| *b* | regression coefficients; constant in loss-to-feed rate relationship | |
| *BETA* | threshing coefficient | - |
| *BL* | breakage loss in the grain | $kg \cdot s^{-1}$ |
| *BLF* | fraction of breakage loss | - |
| *c* | constant in various expressions | |
| *C* | correction factor in the calculation of *MFC* | - |
| *CD* | mass of crop (= straw+grain) in the field | $kg \cdot m^{-2}$ |
| *CL* | length of cutter bar | m |
| *CLO* | costs of grain losses arising in the process in the machine | $fl \cdot ha^{-1}$ |
| *CM* | total machine costs (*MVC*+*HVC*+*MFC*) | $fl \cdot ha^{-1}$ |
| *CONA* | concave to threshing cylinder adjustment front/rear | mm/mm |
| *CRL* | level coefficient in rotary separation equation | - |
| *CRS* | slope coefficient in rotary separation equation | $kg^{-1} \cdot s$ |
| *CS* | concave separation (grain) | kg |
| *CTI* | costs of timeliness losses | $fl \cdot ha^{-1}$ |
| *CV* | coefficient of variation | % |

| | | |
|---|---|---|
| $G_o$ | amount of grain in the straw at the front of walkers | $kg \cdot s^{-1}$ |
| $G_\ell$ | amount of grain in the straw at the end of walkers | $kg \cdot s^{-1}$ |
| $G_w$ | amount of grain in the straw at a given place on walkers | $kg \cdot s^{-1}$ |
| *GY* | grain yield | $kg \cdot ha^{-1}$ |
| *HVC* | machine variable costs proportional to working time | $fl \cdot ha^{-1}$ |
| $I_m$ | moment of inertia of motor | $kg \cdot m^2$ |
| $I_t$ | moment of inertia of threshing cylinder | $kg \cdot m^2$ |
| $k$ | constant in various expressions | |
| $K_1, K_2$ | constant in optimum speed calculations | |
| *L* | length of V-belt of threshing cylinder varidrive | m |
| *LA* | concave length factor | - |
| *LT* | length of threshing cylinder | m |
| *LW* | functional length of walkers | m |
| *MCCS* | multiple correlation coefficient | |
| *MCS* | straw moisture content | - |
| *MCG* | grain moisture content | - |
| *MFC* | fixed costs machine | $fl \cdot ha^{-1}$ |
| *ML* | total grain losses arising in machine process | $kg \cdot s^{-1}$ |
| *MVC* | machine variable costs proportional to harvested area | $fl \cdot ha^{-1}$ |
| $n$ | number of trials | |
| *NE* | time during combine harvesting that combine is not cutting and threshing | $h \cdot ha^{-1}$ |
| *NU* | densification factor in threshing model | - |
| *NV* | purchase price of combine harvester | fl |
| *OMOUT* | threshing cylinder angular velocity | $rad \cdot s^{-1}$ |
| *OMWT* | set value threshing cylinder speed control | $rad \cdot s^{-1}$ |

| | | |
|---|---|---|
| p | probability function | - |
| $P_c$ | gain in integration action of machine speed control | $mm \cdot m^{-1} \cdot s$ |
| $P_g$ | gear box gain | $m \cdot rad^{-1}$ |
| $P_h$ | hydraulic drive gain of machine B | $rad \cdot s^{-1} \cdot mm^{-1}$ |
| $P_m$ | power generated by combine engine | W |
| $P_{tn}$ | power needed for threshing | W |
| $P_v$ | variator gain of machine A | $rad \cdot s^{-1} \cdot mm^{-1}$ |
| *PBL* | grain breakage loss in percentage of grain feed rate | % |
| *PCTC* | gain in integration action of threshing speed control | $rad^{-1} \cdot m$ |
| *PF* | gain in integration action of auger torque feedback control system | $mm \cdot mV^{-1} \cdot s$ |
| *PT* | harvested area | $ha \cdot h^{-1}$ |
| | | |
| *r* | correlation coefficient | |
| $R_{in}$ | working radius of pulley in threshing cylinder vari-drive at engine side | m |
| $R_{out}$ | working radius of pulley in threshing cylinder vari-drive at threshing cylinder side | m |
| *RAH* | relative air humidity | - |
| *RPS* | charge coefficient in threshing model | |
| *RSE* | rotary separator efficiency | - |
| *RT* | transmission ratio of threshing cylinder varidrive | - |
| *RV* | residual value of combine harvester B | fl |
| | | |
| s | complex variable of the Laplace transform | $s^{-1}$ |
| $S_w$ | grain separation at given place at walkers | $kg \cdot s^{-1} \cdot m^{-1}$ |
| *SD* | straw density in the field | $kg \cdot m^{-2}$ |
| *SDAV* | average straw density of test run | $kg \cdot m^{-2}$ |
| *SDM* | straw density calculated by measured auger torque and machine speed | $kg \cdot m^{-2}$ |
| *SL* | sieve loss | $kg \cdot s^{-1}$ |
| *SVTA* | set value auger torque of auger torque feedback control system | mV |
| *SVTS* | set value threshing separation efficiency in control system 4 | % |

| | | |
|---|---|---|
| *D* | displacement of the variator discs of the threshing cylinder varidrive | m |
| *D0, D1* | parameters in loss-to-straw feed rate relationship | |
| *DE* | displacement straw elevator chain | cm |
| *DT* | sample interval of the digital control | s |
| *DTI* | derivate to *VW* from *CTI* | $fl \cdot ha^{-1} \cdot m^{-2} \cdot s$ |
| *DV* | controlled position of the variator discs of the threshing cylinder varidrive | m |
| *e* | Naperian constant; error value | |
| *EF* | combine harvesting efficiency factor | - |
| $f_b$ | breakpoint frequency of filters | $rad \cdot s^{-1}$ |
| *FGM* | grain feed rate measured by monitor | $kg \cdot s^{-1}$ |
| *FGT* | grain feed rate at threshing cylinder | $kg \cdot s^{-1}$ |
| *FGTD* | delayed grain feed rate at threshing cylinder | $kg \cdot s^{-1}$ |
| *FGR* | grain feed rate at rotary separator | $kg \cdot s^{-1}$ |
| *FGW* | grain feed rate at walkers | $kg \cdot s^{-1}$ |
| *FOB* | force in the threshing cylinder driving V-belt | N |
| *FOM* | value of *FOB* below which wear costs are zero | N |
| *FS* | feed rate of straw leaving the combine harvester | $kg \cdot s^{-1}$ |
| *FSA* | straw feed rate at auger | $kg \cdot s^{-1}$ |
| *FSAV* | average straw feed rate over a given period | $kg \cdot s^{-1}$ |
| *FSC* | straw feed rate at cutter bar | $kg \cdot s^{-1}$ |
| *FSE* | straw feed rate at elevator chain | $kg \cdot s^{-1}$ |
| *FSM* | straw feed rate signal measured by monitor | $kg \cdot s^{-1}$ |
| *FSR* | straw feed rate at rotary separator | $kg \cdot s^{-1}$ |
| *FST* | straw feed rate at threshing cylinder | $kg \cdot s^{-1}$ |
| *FSW* | straw feed rate at walkers | $kg \cdot s^{-1}$ |
| *FSWA* | straw feed rate on walkers after redistribution | $kg \cdot s^{-1}$ |
| $F_v$ | frequency of pulsewise variation in feed rate | $s^{-1}$ |
| $GF_1$ | gain in exponential filter of control system 1 | - |
| $GF_2$ | gain in exponential filter of control system 2 | - |
| *GS* | grain-to-straw ratio | - |

| | | |
|---|---|---|
| $t, T$ | time | s |
| $T_d$ | torque caused by engine inertia | Nm |
| $T_{in}$ | torque available for threshing | Nm |
| $T_m$ | torque from motorshaft | Nm |
| $T_{out}$ | torque into threshing cylinder | Nm |
| $T_{tn}$ | torque needed for threshing | Nm |
| *TA* | auger torque | Nm |
| *TAUW* | time constant in first-order transfer of redistribution of straw on walkers | s |
| *TE* | average value of peaks in feed rate at even straw feed | - |
| *TI* | average value of peaks in feed rate at irregular straw feed | - |
| *TILF* | timeliness loss fraction as function of *VW* | |
| *TL* | threshing loss | $kg \cdot s^{-1}$ |
| *TLF* | threshing loss fraction | - |
| *TNSE* | fraction of grain, not separated from the straw after threshing | - |
| *TOC* | total costs of harvesting | $fl \cdot ha^{-1}$ |
| *TSE* | threshing separation efficiency | - |
| *TSEM* | threshing separation efficiency measured by monitor | % |
| *TT* | task time for harvesting | $h \cdot ha^{-1}$ |
| *TYT* | total working time for harvesting per year | $h \cdot yr^{-1}$ |
| $v$ | proportional factor | |
| $V_1$ | value of grain loss (except breakage loss) | $fl \cdot kg^{-1}$ |
| $V_2$ | value of breakage loss | $fl \cdot kg^{-1}$ |
| $V_3$ | value of the V-belt wear | $fl \cdot N^{-1} s^{-1}$ |
| *VBL* | value of grain breakage loss | $fl \cdot s^{-1}$ |
| *VE* | speed of straw elevator chain | $m \cdot s^{-1}$ |
| *VFL* | level factor in threshing speed-to-feed rate relationship | $m^2 \cdot s^{-1}$ |
| *VFS* | slope factor in threshing speed-to-feed rate relationship | $m^2 \cdot kg^{-1}$ |
| *VFSC* | adapted slope factor in threshing speed-to-feed rate relationship | $m^2 \cdot kg^{-1}$ |
| *VM* | machine forward speed | $m \cdot s^{-1}$ |

| | | |
|---|---|---|
| $VM_a$ | actual machine forward speed | $m \cdot s^{-1}$ |
| $VM_o$ | optimum machine forward speed calculated by cost minimisation | $m \cdot s^{-1}$ |
| *VMAV* | average forward speed | $m \cdot s^{-1}$ |
| *VML* | value of machine loss (*ML*) | $fl \cdot s^{-1}$ |
| *VMN* | average machine speed in a manually controlled situation | $m \cdot s^{-1}$ |
| *VT* | threshing cylinder rotation speed | $m \cdot s^{-1}$ |
| $VT_a$ | actual threshing speed | $m \cdot s^{-1}$ |
| $VT_o$ | optimum threshing speed, calculated by cost minimisation | $m \cdot s^{-1}$ |
| *VW* | harvested area per time unit (= $VM \cdot CL$) | $m^2 \cdot s^{-1}$ |
| *VWC* | costs of wear of threshing cylinder drive | $fl \cdot ha^{-1}$ |
| *WA* | wages of combine harvester operator | $fl \cdot h^{-1}$ |
| *WE* | walker (grain) separation efficiency | $kg \cdot s^{-1} \cdot m^{-1}$ |
| *WE*(s) | *WE* for a certain length of walkers measured from front of walkers | $kg \cdot s^{-1} \cdot m^{-1}$ |
| *WE*(ℓ) | local *WE* for a certain length of walkers at any arbitrarily chosen place | $kg \cdot s^{-1} \cdot m^{-1}$ |
| *WEP* | walker efficiency parameter in walker separation model | $kg \cdot s^{-1}$ |
| *WL* | walker loss | $kg \cdot s^{-1}$ |
| *WLAV* | average walker loss | $kg \cdot s^{-1}$ |
| *WLM* | walker loss measured by monitor | |
| *WS* | walker separation | $kg \cdot s^{-1} \cdot m^{-2}$ |
| *WS4* | walker separation in tray 4 | kg |
| *WW* | width of walkers | m |
| *YIELD* | average grain yield | $kg \cdot ha^{-1}$ |

GREEK SYMBOLS

| | | |
|---|---|---|
| $\underline{\eta}$ | angle between the two sides of the threshing cylinder varidrive discs; regression coefficient | |
| $\underline{\gamma}$ | angle in V-belt length calculation | |
| $\underline{\varepsilon}$ | difference | |
| $\underline{\sigma}$ | standard deviation | |
| $\underline{\tau}$ | time constant | s |
| $\underline{\mu}$ | mean value | |
| $\underline{\omega}$ | angular velocity (see subscripts of *T*) | $rad \cdot s^{-1}$ |

# 1. Introduction

## 1.1. GENERAL

In the progress of agricultural mechanisation in the technically highly developed countries during the last century, some successive stages can be distinguished: improvement of tools and implements for animal traction, the introduction of machines and mechanical power, of hydraulic and pneumatic systems and increasing machine sizes. The application of automation and electronics in agricultural machinery will increase in future owing to the availability of greater technical possibilities: microprocessors, electronic sensors and hydraulic drives. When applied, it will be with the aim of increasing the financial returns by improving the quality of the agricultural product and reducing production costs.

The aim of this thesis is to establish the methodology by which the contribution of automated agricultural machinery to the improved returns can be evaluated.

The cereal combine harvester has been taken as a case in which we can consider how cost minimisation by automation can be achieved and assess the extent to which costs can be reduced.

The method followed in this study is to develop a detailed optimisation criterion and translate this in terms of the technical requirements as to the design and adjustment of the control system. The process and the cost criteria have therefore been investigated in order to gather the required knowledge.

In order to estimate the influence of the choice and adjustment of a specific control system on the total costs, a simulation model has been made of a combine harvester equipped with various control systems. The models have been based on data from field studies carried out from 1969 to 1978 inclusive. This method of study was chosen to be able to compare different possible but not yet realised automatic systems to each other and to manual control under identical conditions.

The method is worked out in the following chapters. The harvesting process is so complex a matter, that many simplifications have to be introduced in order to be able to solve the complicated problems involved. These will be briefly explained here and worked out in detail in the chapters dealing with the models.

Many models are based on investigations not yet published. It was found practical to put the details into an appendix in order to illustrate the systematics and the method of the study in the main text. This information is located under the same chapter numbering as is used in the main report, preceded by the letter "A".

For readers unacquainted with combine harvesting of cereals, the process and organisation is described briefly in the appendix (A 1.1.a). Drawings and machine specifications are also presented there. For those not familiar with control theory a very short explanation of the terms used in this study is also given in the appendix (A 1.1.b).

## 1.2. LITERATURE

Automation in cereal combine harvesters has been a subject of research since 1956. In some cases the purpose is to reduce the operator work load. Systems have been developed to follow the rim of the crop (edge-guide steering system). Others adjust the header height either by sensing the surface of the ground or by controlling the mowed straw for length. Systems have also been developed to control the load of the threshing cylinder so as to utilize the available engine power to the maximum. For many years now combine harvesters have been available with systems for levelling the machine on slopes in the longitudinal as well as the transversal direction. Research is being done on systems which adapt the adjustment of the fan to the crop properties in order to reduce sieve losses. These systems will not be discussed in this publication.

Our main attention will be centred on systems which control the forward speed of the combine and the peripheral speed of the threshing cylinder. Actually the purpose of these systems is to control the losses and in particular the walker loss. In the appendix a review is given of the references dealing with these systems. The conclusions are presented in this section.

When the crop throughput is controlled by adjustment of the driving speed to variation in the straw input, measured by a variable which is closely related to the straw input, this type of system is known as a straw feed rate control system (A 1.2.2).

When the driving speed is controlled via loss indications, the system is known as loss control system (A 1.2.3).

When the driving speed is controlled by both loss measurement and feed rate measurement the system is known as loss-feed rate control system.

Influencing the losses by controlling the speed of the threshing cylinder has also been researched (A 1.2.4). These systems are known as threshing speed control systems.

Thorough knowledge of the dynamics of the threshing and separation processes for design of the control systems is required. Towards this end, model studies of the processes in the combine harvester have been carried out (A 1.2.5).

The aim of keeping the losses at a constant level, as formulated in literature, is based on research into optimisation of the cereal harvest. The idea of one optimum loss level, however, is based on an incomplete theory. This theory can be described briefly as follows: An increase in driving speed results in a rise in straw input as this is determined by the product of working width, driving speed and the crop mass per unit area. An increasing straw input causes an exponentially rising loss. A reduction in driving speed not only results in a lower machine loss, but also in a smaller area harvested by the machine, resulting in higher machine and labour costs per hectare. With a given acreage per combine per season, a lower speed will result in harvest delay, causing higher timeliness losses. Therefore there is always an optimum loss level. Loss control can thus be favourable if we are to maintain the loss at that optimum level.

The calculation of the optimum loss level has been done by model studies of harvesting. In these model studies just one loss-to-feed rate relationship is used, resulting also in just one optimum loss level, given by the cost factors and constraints of the studied situation. One single-feed rate level is optimum for this loss level also. However, when the loss feed rate relation changes, not only does the feed rate level change but also the optimum loss level itself.

All writers on the subject are aware of the fact that a changing loss-to-feed rate relation indicates that the mean straw feed rate or the set value of a feed control has to be changed as well, but no one realized that the optimum loss level in that case can change, too. This will be explained in 1.4.1 of this study.

The advantages expected of the automatic control are, lower mental load on the operator, a smoother feed into the combine resulting in less jamming, lower fuel consumption, less wear and lower loss levels. The extent of the benefit is expressed in the literature in terms of reduction in the variation in straw feed rate and rise in the feed rate level. The increase in feed rate level is only correctly calculated if losses are kept at the same level as without the control. Benefits of 5 - 30% are mentioned. This wide range is due to the circumstances under which the research is carried out: loss-feed rate relationship, chosen loss level and straw density variation affect the benefit (see A 1.2.7). Only two authors have tried to calculate the benefits in terms of financial returns.

Fekete (1981) studied the benefits of loss feed rate control systems on three combine harvesters in practice in Poland. Reduction in the cost of combine harvesting was found to be 6-7%. This result would enable the costs of the control system to be amortised in 2 years.

McGechan (1982) calculated the benefits of different loss control systems by simulation based on crop variability data. He concluded that the benefit for a 200 ha grain farm in Scotland would be very small, too small to justify the cost of a control system. In the present study, too, a constant loss feed rate relation has been used, so that variation in this relation could not result in a benefit with a control system adapted to crop variability. In our opinion this possibly causes the benefit to be underestimated.

Eimer (1973) reported on a threshing cylinder speed control in combination with a feed rate control. His aim was to compensate the effect of straw feed rate fluctuations on losses by controlling the speed of the threshing cylinder in order to improve its separation efficiency. He states that this control system allowed an increase in feed rate of 40% in rye and 25% in wheat for the same loss level. How this was measured was not explained.

Comparison of automatic control systems to manual control in practice is very difficult. The machine, its adjustments and the crop properties must be the same throughout the tests. Besides, when different systems are working close together, the operator of the manually controlled machine will be influenced by the speed of the automatically controlled machines. Another problem is that systems that include loss control need adequate loss measuring devices. The acoustic sensors used for this purpose at present are not yet accurate enough.

The following conclusions have been reached from the study of literature. The control systems described,control a level of loss or feed rate or machine power. The level to be chosen is not argued on optimisation criteria and is though to be constant. Adaption of these levels to changing conditions has not been considered until now. It will be necessary therefore to investigate the criteria for optimum control and incorporate the calculation of the set values in the control system.

The different control systems introduced are not compared and cannot be compared in the field because the loss measuring devices are inadequate. Before designing the systems, the economic benefits have to be estimated and compared to those obtained with manual control.

## 1.3. AIM OF THE STUDY

The conclusions drawn in the literature review are restated briefly below:

- None of the known control systems are designed from the viewpoint of optimising harvest operation as a function of varying crop and weather conditions.
- The inadequacy of the available loss monitors makes it difficult to estimate the real benefits of existing control systems.
- The various known systems control threshing speed and machine forward speed in different ways but the benefits of these systems have not yet been compared.

*The aim of the present study will therefore be to develop different control systems, optimising the forward speed and the threshing cylinder speed of the cereal combine harvester and reacting to variations of the crop properties, each system applying different combinations of input signals and controlled outputs. In addition, the* *benefits of each system compared to those obtained with manual control will be assessed.*

With this end in view, the requirement is to

- develop an optimisation criterion,
- quantify the important process disturbances that affect machine performance,
- investigate the way in which the criterion can be optimised,
- develop control systems that optimise the criterion,
- assess the benefits of the systems compared to those of manual control by simulation.

Models of the process, machine drives measurement systems and control systems have to be developed for the simulation.

## 1.4. METHOD OF THE STUDY

In this section the method of the study will be presented in condensed form. Details are explained in the following chapters and in the appendix, but the fundamental approach will be described here. This approach includes simplification in order to allow the very complex process of control in combine harvesting to be researched. The simplifying assumptions will be indicated in the text in italics.

### 1.4.1. *Optimisation criterion*

The objective of farming is to produce agricultural products profitably. Innovations in farming are made to maximise or maintain profit levels. Harvest optimisation calculations are made on the basis of harvest models to assess the optimum size or number of the combine harvesters for given conditions (Kampen, 1969; Boyce, 1972; Philips 1974). Once the decision on the number and size is taken, the various machine variables must be adapted to the varying crop and walker conditions.

If we take the harvestable mass of grain and straw as determined at the moment of combine ripeness (see A 1.1.a) and denote the decrease of harvestable grain from that moment as opportunity costs, the maximum profit can be converted into minimum costs. The decrement of straw mass will be *assumed* to be economically negligible.

We will further only take into consideration the costs affected by the variation in machine forward speed and peripheral speed of the threshing cylinder. The sum of these costs is the cost function, or total costs.

The cost function has to be expressed in such a way that the sum of all important cost elements can be clearly shown and calculated as a function of time. This is done so that

- it can be shown why benefits can be expected from control systems;
- the extent of the benefits obtained from the control system can be easily calculated;
- the optimum settings of the machine speed and threshing speed controls can be calculated continuously, adapting to the specific combine harvester and crop conditions. It is *assumed* that this will be done continuously by means of a microprocessor on the machine.

The various cost elements that go to make up the cost function are worked out extensively in chapter 2 but will be summed up here. The costs are expressed in guilders per unit area ($fl \cdot ha^{-1}$) and not per unit time ($fl \cdot s^{-1}$) as the total area to be harvested is usually fixed and therefore the total harvesting costs can easily be calculated. They are: the total machine costs *CM*, made up out of:

*MVC* = Machine variable costs, such as technical wear, required fuel and lubricants. They are *assumed* to be proportional to the harvested area;

*HVC* = Machine and labour costs that are proportional to the work time but are recalculated in $fl \cdot ha^{-1}$;

*MFC* = Annual fixed machine costs such as depreciation and interest;

the machine loss costs resulting from the financial value of sieve loss (*SL*), threshing loss (*TL*), grain breakage loss (*BL*), walker loss (*WL*); the timeliness losses costs *TILC* and the costs of extra wear of the V-belt, driving the threshing cylinder.

The way in which costs are affected by control of machine and threshing speeds will be shown below.

*The effect of machine speed on costs*

A change in the forward speed of the combine harvester brings about a change in the capacity, that is the amount of grain harvested or the area harvested per unit of time. An increase in the driving speed will result in a change in the following cost-determining factors. (The details are given in 2.2.)

Costs will then increase because the grain loss increases.

Costs will decrease because

1. the harvesting period becomes shorter and labour and timeliness costs will be cut down.
2. The actual harvesting time can be reduced so that the combine starts when the crop has reached an adequate level of grain moisture content naturally, thus reducing drying costs.
3. A larger area can be harvested in one season, resulting in lower machine costs per hectare.
4. The number of machines to be used in a specific area can be diminished.

These four factors are to some extent interchangeable. Factors 1 and 2 show short-term effects on costs while factors 3 and 4 show long-term effects.

It is advisable to study the effect of control on both levels. For this reason two ways of using combine harvesters will be considered in which both effects are clearly evident.

In the first case we consider *cereal farmers who work with a variable harvesting period and a fixed area, a fixed number of combine harvesters and fixed maximum grain moisture content*. Here in particular, the determinants are timeliness loss costs and labour costs. The grain drying costs are fixed because the timeliness loss curve is determined by the workable hours resulting from fixed grain-moisture levels (see 2.2).

In the second case we have *a contractor or cereal farmer with such a large area that the number of machines in use can be varied*. The harvesting period, the mean grain moisture content, thus grain drying costs are *assumed* to be fixed. In this case it is the machine costs that are the determinants.

The cost elements are calculated for these two ways of using the combine on the basis of data relating to the year 1982. The timeliness loss calculations are based on two levels of weather risk, i.e. 25% and 16 2/3% referring to the percentage of years in which the number of workable hours, used in the calculation of the timeliness loss curve, will not be available due to the weather conditions.

When we study these costs as a function of machine speed then we must first realise that straw feed rate ($FS$ in $kg \cdot s^{-1}$) arises from the straw density ($SD$ in $kg \cdot m^{-2}$), that is the amount of straw on the field per unit of area, the cutting width ($CL$ in m) and the forward speed ($VM$ in $m \cdot s^{-1}$) of the combine harvester, namely

$$FS = SD \cdot VM \cdot CL \quad kg \cdot s^{-1} \qquad (1.1)$$

Let us *assume* $SD$ and $CL$ to be constant then $FS$ is proportional to $VM$. The relations between losses and straw feed rate are in general as indicated in fig. 1.4.1.1 so that increasing machine speed gives increasing losses.

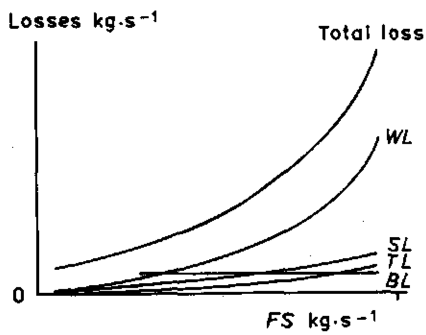



Figure 1.4.1.1. Grain losses related to straw feed rate (straw = m.o.g = material other than grain)

If the cutting width is constant, the harvested area $VW$ is also proportional to the speed of the machine because

$$VW = VM \cdot CL \quad m^2 \cdot s^{-1} \qquad (1.2)$$

All cost factors are then worked out as a function of $VW$ and can be plotted in this way. We then have fig. 1.4.1.2 for the case that the machine is used by a contractor or a cereal farmer who works with a fixed harvest period and a variable area per machine. In this figure, three lines of total value of walker losses are plotted: $VWL(1)$, $VWL(2)$ and $VWL(e)$. This results in three different lines of total costs $TC(1)$, $TC(2)$ and $TC(e)$, each giving cost minima at different cost levels and at different values of $VW$, which means three specific optimum machine speeds.

From this it is clear that there are cost minima that vary with differing loss curves. The objective of speed control is to adjust the actual machine speed to the optimum machine speed that varies with varying loss cost curves. There are two reasons why the loss cost curve varies.

In the first place, crop properties vary because of varying weather and growing conditions and because of the kind and breed of the crop varies. The difference in the curves *VWL*(1) and *VWL*(2) is an example of that. These variations can be considered as mean level and low-frequency variations. In chapter 4 they are quantified.

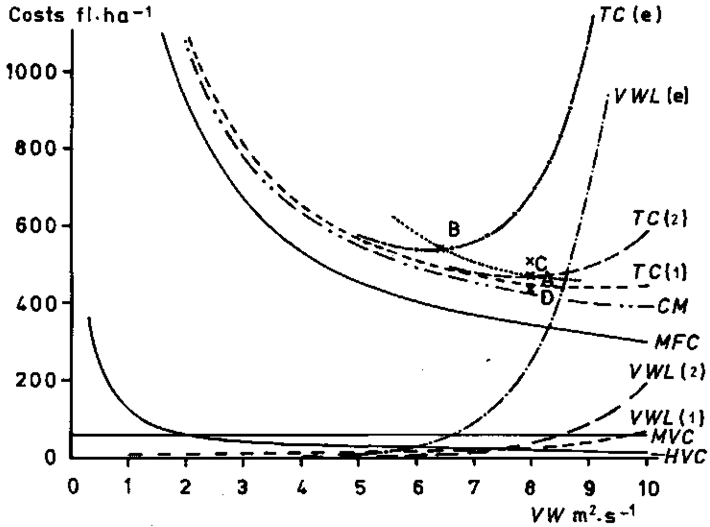



Figure 1.4.1.2. Costs of combine harvesting related to the harvested area *VW* (=*VM*·*CL*) for a fixed harvesting period in which the harvested area varies.
*HVC* = labour costs, *MVC* = machine variable costs, *MFC* = annual fixed machine costs, *CM* = total machine costs, *VWL* = costs of grain losses due to machine performance under the following three conditions with different loss-to-feed rate relations: (1) $WL = 0.0015 \exp(VW \cdot 0.58)$, (2) $WL = 4.5 \cdot 10^{-5} \cdot \exp(VW \cdot 0.40)$, (e) $WL = 4.5 \cdot 10^{-5} \exp(VW \cdot 0.50)$.
A = minimum cost point for *VWL*(2), B = minimum cost point for *VWL*(e), C = total costs for straw density $SD = 1.1 \cdot (SD$ at A), D = total costs for $SD = 0.9 \cdot (SD$ at A) ("*SD* at A" stands for straw density that holds for minimum cost point A).
(............) = line of minimum costs points for *VWL*(2) at differing straw densities.
The lines are calculated, using the values explained in 2.2:
$MVC = 67.--$ fl·ha$^{-1}$, $WA = 40.--$ fl·h$^{-1}$, $AFC = 425000.--$ fl·yr, $V_1 = 0.50$ fl·kg$^{-1}$, $AAN = 100$ ha, $VMN = 1$ m·s$^{-1}$, $NE = 0.25$ h·ha$^{-1}$, $CTI = 0$ fl·ha$^{-1}$

It can be seen in the figure that the optimum is not found at a constant loss level. The optimum is located at that value of *VW* at which the slope of the curve of decreasing total machine costs is equal to the negative value of the slope of the curve of increasing loss costs.

The second reason of varying loss cost curves is the natural variation in straw density. If the loss curve as a function of straw feed rate *FS* does not change, the loss cost curve as a function of harvested area *VW* becomes dependent on the straw density because from (1.1) and (1.2) can be derived that the straw feed rate *FS* can also be written as the product of straw density *SD* and harvested area *VW*

$$FS = SD \cdot VW \quad kg \cdot s^{-1} \qquad (1.3)$$

This also means that if *VW* is constant, then straw feed rate *FS* becomes proportional to straw density *SD*, so that walker loss becomes dependent on *SD*. For instance, for the curve of *VWL*(e) in fig. 1.4.1.2 the same walker loss feed rate relationship is used as for *VWL*(2) but the straw density level is increased by 25%, giving the cost minimum at B instead of A. The cost minima for just one loss-to-feed rate relationship, but for varying straw density levels, are found at the dotted line in fig. 1.4.1.2.

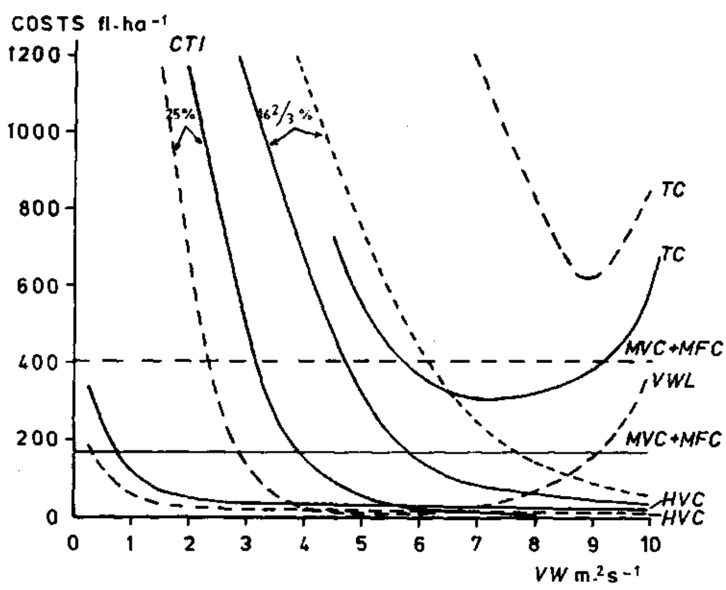



Figure 1.4.1.3. Costs of combine harvesting related to the harvested area *VW*(=*VM*·*CL*) in the case that the harvest period varies with *VW* and the average winter wheat to be harvested per machine is fixed at 100 ha for a farmer (------) and 175 ha for the IJsselmeerpolders Development Authority large-scale grain farm (———).
*CTI* = costs of timeliness loss calculated for two levels of weather risk given by the percentage years in which the number of workable hours, used in the calculation, that is respectively 25% and 16 2/3%, are not available due to the weather. *TC* = total costs for the 16 2/3% risk. For the other cost factors see figure 1.4.1.2.

The task of a machine speed control system is to calculate the optimum desired machine speed and to adjust the actual speed in order to become identically to the calculated value. The system must then have information about the straw density, the loss-to-feed rate relationship and the other cost functions.

The cost functions differ from those of fig. 1.4.1.2 in the case that the harvesting period is variable and the area to be harvested is fixed. In that situation the timeliness loss costs are a function of the harvested area *VW*. In this case the curves in fig. 1.4.1.3 have to be used to calculate optimum machine speed. The technique, however, is the same. The timeliness loss cost curve to be used depends on the weather risk, area to be harvested and grain moisture limitations as will be explained in 2.2.

*The effect of threshing speed on costs*

The threshing speed influences the machine losses as indicated in fig. 1.4.1.4. When threshing speed increases, the breakage of grain increases. As straw breakage increases too, the straw load on the sieves increases so that the sieve losses will rise. Threshing loss will also decrease, and as the grain separation through the concave grate increases, the walker loss will also decrease. The damaged seed does not always affect the value of the grain sold but the other loss becomes a cost element whose money value is found by multiplying the actual amount lost, by the market price of the grain minus the costs of drying, transport and storage.

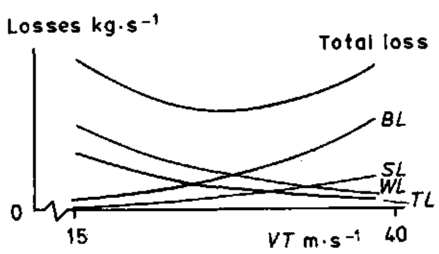



Figure 1.4.1.4. Grain losses related to threshing speed

The shape of the curves is dependent on crop properties and straw feed rate level as in fig. 1.4.1.5. From the figures it is evident that there is always an optimum threshing speed conditioned by the crop properties and the straw feed rate.

Since the crop properties vary slowly as a function of place and time and the straw feed rate varies not only slowly but also quickly, there is a succession of different valid curves and different optimum values for the threshing speed during the movement of the machine. When the threshing speed is kept constant for a number of hours, as is often the case with manual control in practice, the costs are not kept at a minimum.

When the machine speed varies, there is an interaction between the optimum machine speed and the optimum threshing speed that makes optimisation even more complex.

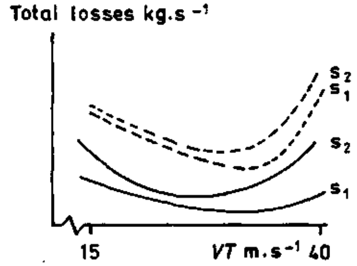



Figure 1.4.1.5. Total grain losses as a function of threshing speed for two different crop-property situations $s_1$, $s_2$ and two different feed rate levels (———) and ( ------ ).

## 1.4.2. *The reason for simulation*

In the previous section the optimisation criterion has been worked out in detail. It has also been shown that the speeds at which minimum costs are found will vary in practice.

The aim of the study is to calculate the benefit of automatic machine and threshing speed control based upon such an optimisation criterion compared to manual control. Computer simulation was thought to be a good calculation technique for the following reasons.

- By simulation alone, one can study the various control systems, including manual control, under known conditions in which disturbances in the process and other harvest conditions are made identical.
- We can check in detail how the various control systems affect harvesting costs. All variables of interest can be studied, so that their role and influence can be assessed.
- The values of parameters can be adjusted separately so that insight into the process can easily be increased. One can exclude the interactions of parameter values.
- The availability of measuring systems and control systems can be assumed so that no investments have to be made beforehand, for improvement or introduction of systems. This is of importance for the control systems and the loss-measurement system.
- It is easy to adjust the control and the machine variables at which the harvesting has to be performed.

For the above reasons the problem will be worked out as a model study using the simulation as the main tool. In this chapter therefore the optimisation problem will be formulated in detail, taking into account the implementation of the simulation. The process and control systems will be worked out in the following chapters.
In chapter 2 the technique of modelling is described and cost data and models of the process worked out.
Chapter 3 describes measurement devices.
In chapter 4 the disturbances are studied and we state which sample of the disturbances is to be selected as an input of the simulation.
The control systems are developed in chapter 5 and in chapter 6 the simulation is considered and the results are given in terms of costs per hectare.
In chapter 7 the general conclusions about the optimisation are summarised.

1.4.3. *Formulation of the optimisation problem*

In order to be able to minimise costs by simulation we have in addition to the cost criterion, to formulate the various conditions under which combine harvesting is carried out. These conditions concern the use made of the combine harvester, the course of the process and the selection of the controlling variables.

1. *Parameter values for the cost model affected by the use made of the combine harvester*

Every owner of a combine harvester uses the machine under his own specific conditions as to area, selection of crops or varieties. He also makes his own assessment of the weather risk affecting the timeliness loss expectation and maximum levels of grain moisture content. Six different cost situations are defined to cover most of the situations in which the combine is used.

The chosen values of the areas to be harvested in 3 situations are in the neighbourhood of the optima given in the literature, based upon harvest optimisation models for grain farms under European conditions (Baumgartner, 1969; Boyce, 1972; Philips, 1974). The harvest situations of the 3 other cost situations agree with the averaged harvesting operation, that is the result of harvest optimisation based upon a harvest simulation model of the IJsselmeerpolders Development Authority. This model is in use and has been improved continuously for about 15 years (Kampen, 1969; Hagting, 1976; Fokkens, 1981).

The area to be harvested per machine has been made variable in some situations in order to study the effects of cost minimisation by controls on long term decisions on such areas.

The details of these cost situations are given in 2.2 but are defined briefly below.

*Cost situation 1:* The length of the harvest period is dependent on machine speed, the area being fixed at 100 ha per machine that can be thought to be in use on one farm or by a group of farms. The timeliness loss risk is set at 25% and the grain is harvested when the grain moisture content is 23% or less.

*Cost situation 2:* The same conditions hold for this situation as used in cost situation 1, except that the farm is the large scale grain farm of the IJsselmeerpolders Development Authority (IJ.D.A.) so that the fixed area per machine is 175 ha wheat and the maximum grain moisture content is 27% or less.

*Cost situation 3:* The same conditions, such as cost situation 1 hold for this situation, except for the timeliness loss risk that is set at 16 2/3%.

*Cost situation 4:* The same conditions as in cost situation 2 (IJ.D.A.) but the timeliness loss risk is set at 16 2/3%.

*Cost situation 5:* The harvested area per season is about 100 ha but is dependent on machine speed, while the harvest period is fixed. The cost factors are calculated for a contractor and harvest conditions are like those of cost situation 1.

*Cost situation 6:* This situation is like cost situation 5 but the cost factors are those of the IJ.D.A. in cost situation 2.

2. *The timeliness loss expectation is not changed during the harvest season*
The harvest cost minimisation in our simulation will not be adapted to a change in expected timeliness loss due to the weather conditions. The two timeliness loss risk levels used in the simulation will give some information about the sensitivity of the cost optimisation to the timeliness loss curves. These curves must be adjustable when a control system is used in practice.

3. *The process of threshing and separation*
The characteristics of the processes in the combine harvester define the relations between loss, and speeds as well as the restrictions in control. In this way the process also defines the cost minimisation.

A dynamic model of the combine harvester, formulated in accordance with the design and dimensions of the combine harvester is needed for the simulation. The process is defined by the design of the machine under consideration and the crops harvested.

In this study the combine harvester is a relatively large machine equipped with threshing cylinder, rotary separator and straw walkers (see A 1.1.a). The process is worked out for wheat (see 2.2). The disturbances in the process caused by the variations in crop properties are defined by the Dutch conditions at the Flevopolders as to crop, soil and weather. They are recorded in the field and a sample is taken for input into the simulation.

4. *The selected controlling variables*
A number of variables has to be adjusted for optimum performance of the process in practice: sieve and fan adjustments, threshing concave adjustment and speeds of machine and threshing cylinder.

After a study of the literature on the threshing process it was concluded that continuous adaption of the concave adjustment to feed rate was not worthwhile, and that adaption to crop properties need not be done continuously. For reasons of limitation, the sieve and fan adjustments are not studied, so that machine and threshing speeds have remained.

Costs and process variables have to be formulated in accordance with these speeds for the simulation.

Cost minimisation by control of these variables depends on the design of the control systems. In designing, account has to be taken of the various possible alternatives.

*Consideration of the optimisation problem*

The objective of automatic control is to influence a process in such a way that the process variables evolve according to a previously defined plan. In our case the plan is to operate the combine harvester at minimum cost according to a previously defined criterion. To achieve this, we must solve an optimum control problem having the following characteristics:

1. This control problem includes a dynamic system that evolves in time. This implies that the differential equations that govern the behaviour of the processes in the combine harvester must be considered as constraints on the optimisation problem under consideration.
2. The optimisation problem must take account of the stochastic nature of the disturbances acting upon the combine harvester. Thus we have a stochastic optimisation problem described by models of the harvester process and by models of the disturbances.
3. Only a limited number of process variables can be measured; the measurements of some variables can only be realized with the aid of a transducer or measuring system which introduces measurement errors or noise. This requires dynamic filtering of some measured variables.
4. Some process characteristics, notably some essential parameters used in the cost function, are not known in advance and must be estimated on line during the operation of the harvester.

The solution of a dynamic optimisation problem for a nonlinear dynamic system having time delays, unknown parameters, stochastic disturbances and measurement noise leads to an intractable situation. The formal solution - if one manages to compute it - should be available on line, that is as an explicitly computable function of the available measured variables. One may expect that such a solution will be much too complex to be of direct practical use. Therefore we will simplify the problem so that an usable sub-optimum solution results.

*Simplifying assumptions in the formulation of the optimum control problem*

The disturbances in the process are stochastic, so that measured signals have to be filtered. For optimum filtering, Kalman filters would be best, but knowledge of the behaviour of the disturbances is too slight to allow their use at present. First-order low-pass filters are used instead.

The main disturbances in our process are mean value and low-frequency variations. Crop properties especially vary slowly but straw density also does so as can be seen, for instance in figure 1.4.3.1. This figure shows the straw density variation measured for the 5.9 m width of the combine harvester header over three different stretches of 25 m of the same, very-homogeneous-looking field.

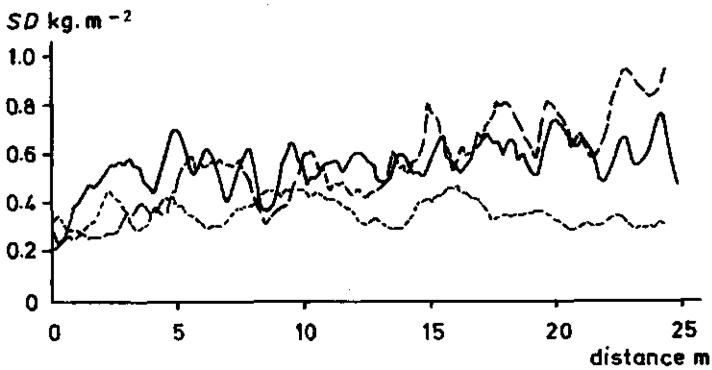



Figure 1.4.3.1. Variation of straw density on three different stretches at the same tield with winter wheat at the IJ.D.A.

In addition the high-frequency variations which occur do not much affect the mean loss level because their effect on losses due to positive-deviations from the mean straw feed rate level are compensated by those of the negative deviations. This is the case, because the exponential relation of loss to straw feed rate applied to a wide range of feed rate, can be considered approximately linear over the short range in which the feed rate varies when the combine harvester only traverses a short distance. This effect is quantified in figure 1.4.1.2 where point C indicates the total costs in the case that the straw density is 10% higher than the density that was the basis of the calculated optimum point A. The cost difference between A and D, referred to costs at a 10% lower straw density, is about the same as the difference of A to C.

The presence of dynamics and delays in the process requires dynamic control. Because of the slowly varying disturbances we can consider the optimisation problem as split up into 1) a quasi steady-state optimisasion problem that yields optimum set-point values for relevant process variables and 2) a control problem by which these set-point values are followed by means of a sufficiently fast feedback control system. In so doing we circumvent the very complicated on-line, nonlinear, dynamic optimisation problem.

The parameters of the process are unknown in practice so they have to be estimated. This ought to be done on-line by means of recursive techniques, using models with more than two parameters. Much more research would then be needed, hence it is approximated by simple one and two-parameter models, estimated afterwards, off-line. Research on this aspect is required when control of speed on combine harvesters is developed for use in practice.

The optimisation of threshing speed and machine speed should be done in mutual dependance. This is however a very complex matter, so it was simplified by adapting the desired threshing speed to the threshing separation efficiency instead of machine loss.

The optimum adjustment of concave, sieves and fan should also be considered in their dependance on adjusted threshing speed and machine speed and vice versa. These aspects could, however, only be considered in this study by calculating threshing loss, breakage loss and sieve loss on the basis of averaged values of model parameters, and including them in the total costs.

The large number of possible control systems is limited to five. Table 1.4.3.1 shows the names, inputs and outputs of these 5 systems.

Table 1.4.3.1. The investigated control systems
*WL* = walker loss, *FS* = straw feed rate, *TSE* = threshing separation efficiency, *VM* = machine speed, *VT* = threshing speed.

| System | | Input variables | | | Output variables | |
|---|---|---|---|---|---|---|
| Symbol | Name | *WL* | *FS* | *TSE* | *VM* | *VT* |
| 0 | manual control | - | - | - | - | - |
| 1 | loss control | x | - | - | x | - |
| 2 | loss-feed rate control | x | x | - | x | - |
| 3 | loss-feed rate-threshing speed control | x | x | - | x | x |
| 4 | loss-feed rate-threshing separation control | x | x | x | x | x |

We will look back to these simplifications when the simulation results are known. A discussion about this matter will be dealt with in 6.4.

# 2. System models

## 2.1. MODEL APPROACH

### 2.1.1. *Introduction*

Modelling and simulation in general comprise the activities involved in constructing a model of a real-world system and simulating it on a computer. The model of the real-world system has to be made smaller and simpler than the real world, as the reality is too complex and too wide, even for a big computer. The possible reductions and simplifications depend on the aim of the research, in which the model is used to solve a problem.

The following steps have to be taken after formulation of the aim:

The boundary between the considered system and the environment has to be formulated, and input/output relations defined. The essential aspects can then be selected, and model hypotheses formulated on the basis of physical laws.

It is desirable to keep the models as simple as possible for the sake of the simulation technique so that the need arises to compare the simulated to the experimental results.

Depending on the results of these activities, the same loop has to be gone over again to get satisfactory results.

This approach will be demonstrated for our problem in the present and following chapters. The model description will be given in two iterations. The general aspects of the total model will be discussed in 2.1.2. The details of the differentiated processes, the control models, the parameter estimation of the models and the comparison of the simulation to experimental results will be discussed in the following sections and chapters. In fact a first step has already been described in chapter 1.

### 2.1.2. *General aspects*

*Aim*

The aim of this study has been described in chapter 1 in terms of assessment of the contribution of control systems in combine harvesters to the minimisation of harvest costs. These costs can possibly reduced by continuous adaptation of the machine speed and threshing cylinder speed to the crop variables. For this purpose control systems, that include continuous calculation of the optimum speeds, have been designed.

The machine and threshing cylinder will react as a dynamic system to input signals from the control as to optimum speed. In order to do so, consideration has to be given in the model to

- cost factors of the grain harvest with the combine harvester,
- speed of machine and threshing cylinder,
- effect of these speeds on costs,
- crop variables: straw density and process parameters affecting losses (= costs), especially walker loss, which is the main loss,
- dynamic behaviour of the transmissions for machine speed and threshing speed,
- control systems, including the optimisation calculations.

*System border*

This study will be limited to those factors that affect harvest costs by alteration of machine and threshing speed. The costs of grain harvesting are not only those of the combine harvester. The straw left in the field also has a certain value in the Netherlands and will give yields and costs, both affected by speeds in combine harvesting. Even harvesting other crops for instance seed potatoes, is sometimes in competition with combine harvesting, and thus affects the total costs and financial yields of a farm. These factors, however, *will not be included* in the model. Other *restrictions* introduced in the model are stated below:

- the harvest conditions refer only to the IJsselmeerpolders;
- the influence of competing crops and costs of grain drying can only be found in the 4 different timeliness loss curves;
- no adaption of timeliness loss expectations are encountered;
- costs and yields of straw are not considered;
- one type of combine harvester is taken into consideration, that is a

machine with threshing cylinder, rotary separator and straw walkers;

- the only crop to be considered is wheat;
- the harvest conditions are varied at 8 different levels;
- the control systems are considered as representing four systems using an increasing number of input variables and for controlled outputs. The necessary input variables were assumed to be available, that is measured speed, measured feed rate, measured walker loss and measured threshing separation efficiency;
- costs of transport of the grain will not be encountered.

*Inputs*

The following will be the inputs from the environment to the system:

- straw density variations,
- variations in the values of crop-property parameters affecting threshing separation efficiency and walker separation efficiency,
- constant parameter values are used in the calculation of:
  rotary separator efficiency, sieve, threshing and breakage loss,
  process dynamics, such as time delays and time constants of first-order transfers and machine and threshing-cylinder transmission dynamics,
- levels and nature of measurement errors (noise),
- choice of the control,
- choice of feed rate measurement device,
- choice as to use of the combine harvester,
- choice of the timeliness curve.

*Outputs*

The total costs will be estimated out of:

- the speed of the machine, from which the machine costs and timeliness losses will be derived,
- the machine losses, that is from sieves, threshing, grain breakage and walkers. The walker losses will be the main ones, so they have to be calculated most accurately. The other loss components have to be known to check any unusual circumstances,
- the wear of the V-belt driving the threshing cylinder, because it can be expected that such wear will increase, owing to the threshing speed controls,
- a check will also have to be made of the machine speeds and acceleration.

*General model hypotheses*

Important *assumptions* have been made with regard to the feed rates.

On the basis of field test and laboratory test results the conclusion was reached that the feed rate would have to be *considered* on a dry-matter basis in order to separate the effect of feed rate levels and moisture content. The moisture content will be *regarded* as a crop property.

The straw feed rate in the process is *not* divided into feed rates for chaff and short and long pieces of straw. The total mass of straw, including chaff and weeds, often indicated as m.o.g. (material other than grain), is used as a functional variable. The straw feed rate can be expressed in $kg \cdot s^{-1}$ or $kg \cdot s^{-1} \cdot m^{-1}$. The last-mentioned unit is the feed rate per standard width of threshing cylinder or walkers of 1 m.

Although, most effects of straw feed rate on the process are caused by the volume of the straw in the model,the dry matter mass flow will be regarded as the transfer factor. It is therefore *assumed* that the ratio between mass and volume is constant for one and the same functional element of the process, but can differ from one element to the other. If this assumption is incorrect, the *deviation will be regarded* as a change in a crop property, resulting in a change of the crop parameter value for that element.

The grain feed rate is *assumed* to be directly dependent on straw feed rate. It will be calculated from the grain-to-straw ratio, which is regarded as a crop property.

The varying crop property inputs in the model are derived from tests made in various fields on different days. By comparing results of measurements on combines over several years with literature, a selection of data was made to create an input-data file that *can be considered* as a good representation of the harvest conditions that a combine harvester will meet during its operational life.

*Physical relations used*

The physical relations used in the models are very simple and most of them are empirical. They are shown in detail in the following chapters. The general relations concern mass and energy flows.

- There is no loss of mass (straw or grain).
- The energy used for threshing and acceleration of the threshing

cylinder depends on the power available from the engine.

- The cut area is calculated from the product of the width of the cutter bar and the traversed distance, this being the integral of the speed of the machine. The width is kept constant.

*Mathematical simplifications*

- Due importance should be given to the fact that the crop flow through the combine harvester has no width or height, so that in space it is one-dimensional ($kg \cdot s^{-1}$). This means that an uneven distribution in width and height will be an important source of variation in feed rate effect.
- The effects of crop-property parameters on the process transfers in the combine harvester are very complex. It is very difficult to find relations that explain all input-output transfers. It was therefore necessary to reduce the number of crop-property parameters in the models. As we will see in the chapters to come, this *lumped-parameter approach* has led to just one steady-state parameter for each submodel and, in addition to several time delays, one first-order transfer in the separation process. The delays are *assumed* to be constant.
- The control systems are considered as linear around the working point, that is around the mean level of operation. No hysteresis occurs in the models.
- Random processes are only considered to be apparent in the input variable, that is in the straw density and in the measuring device noise. In the measuring device they occur as coloured noise. In the straw density these random processes are put into the model by a deterministic variation of the so-called apparent straw density, calculated from feed rates and speeds, measured on a machine in the field. This apparent straw density is calculated and stored in data files for intervals of 0.25 m.

*Comparison of simulated to experimental data*

This comparison was done by simulating parts of the model, the complete model and a previous control system and comparing the simulation results with field-experiment data. This will be shown in chapter 6.

### 2.1.3. *Method used in this study*

The steps taken to transfer the conceptual model into a physical model and then into a mathematical model and finally the mathematical model into the simulation model should be clearly separated so that the simplifications become visible. In the following sections, however, it will be shown that in many cases a deterministic model was built, allowing the conceptual model to be translated into a mathematical model in one step, while this model could be used without adaption in the simulation model. In most cases, therefore just one symbol is used for each parameter.

The assessment of the parameter values is also given in these sections, because this is included in the way the model was built. In most cases the approach has been as follows:
Knowledge to build a theoretical model was obtained from literature; sometimes a conceptual model and sometimes a physical one. If no literature was available, experiments were carried out. With the results of new experiments, parameters were estimated and literature was used to verify the results.

Of the experiments and simulations that were compared, one was performed with machine A, so that a model of this machine also had to be developed.

## 2.2. COST MODEL

As explained in chapter 1 six different cost situations referring to the way the variation of machine speed affects the various cost factors are considered. The cost factors will all be expressed in $fl \cdot ha^{-1}$. They are:
a) Variable machine costs proportional to the harvested area (*MVC*)
b) Machine and labour costs proportional to the working time (*HVC*).
c) Annual fixed costs (*AFC*).
These three together are also called machine costs (*CM*).
d) Costs of machine losses (*CLO*).
e) Costs of extra wear of the threshing cylinder drive (*VWC*).
f) Costs of timeliness losses (*CTI*).
The cost factors will be calculated for the 100 ha wheat harvested by the cereal farmer, the 175 ha wheat of the IJsselmeerpolders Development Authority large-scale grain farm and the harvest of roughly 100 ha wheat

by the contractor per year per machine. The calculated values will be mentioned in this order.

### 2.2.1. *Variable costs proportional to the harvested area: MVC fl·ha$^{-1}$*

Costs, such as technical wear, maintenance, lubricants, fuel are proportional to the harvested area. The calculation is given in the appendix and the calculated values are 58.-- fl·ha$^{-1}$, 54.-- fl·ha$^{-1}$, 66.-- fl·ha$^{-1}$.

### 2.2.2. *Variable costs proportional to the working time: HVC fl·ha$^{-1}$*

The only important cost proportional to the working time is the labour cost (*WA* fl·h$^{-1}$). In this cost factor the hours not workable, training and overheads have to be included, so that the rate is higher than the payment. In addition, calculation of this factor per hectare is complicated, as not only the effective time, but also machine down time and extra allowances have to be taken into consideration. This means that at higher capacities the effective time is inclined to decrease in proportion to the other times.

The time elements are given in h·ha$^{-1}$ and the definitions are (Lint, 1974):

1) Effective time = Machine is cutting and threshing.
2) Auxiliary time = Actions required in the course of the work: discharging the grain tank, turning the machine and driving to the end of the field, extra time for the corners and the headlanes of the fields, road time to other fields and time allowance for breakdown of the machine.
3) Relaxation allowance = rest allowance for the sum of the effective time and the auxiliary time together.

The 3 elements mentioned above are together considered as the net working time.

The task time (*TT*) can be presented as the net working time plus preparation time, road time and disturbance allowance. It is *assumed* in this study that the task time minus the effective time, that is the not-effective time (*NE*) is proportional to the harvested area. In this *assumption*, the field size and distance to the farm, etc. are fixed. In 1982 the *NE* for wheat at the IJ.D.A. was 0.27 h·ha$^{-1}$. For contractors and grain farms it is lower and was *estimated* at 0.2 h·ha$^{-1}$ thanks to shorter road time and waiting time and the fact that the grain tanks are discharged while the combine is mowing and threshing.

For the reduction in proportion of the effective time to the total working time a correction factor $EF$ has to be introduced, dependent on the product of the speed of the machine and the cutting width, $VW$ ($m^2 \cdot s^{-1}$) and the not effective time $NE$ ($h \cdot ha^{-1}$). The efficiency factor $EF$ can be defined as

$$EF = \frac{\text{effective time}}{\text{task time}} = \frac{\text{effective time}}{\text{effective time} + NE} \qquad (2.1)$$

Knowing that effective time = $1/0.36 \cdot VW$ $h \cdot ha^{-1}$

(the factor 0.36 is for the conversion of $m \cdot s^{-1}$ to $ha \cdot h^{-1}$) we can now define

$$EF = \frac{1/0.36 \cdot VW}{1/0.36 \cdot VW + NE} = \frac{1}{NE \cdot VW \cdot 0.36 + 1} \qquad (2.2)$$

The area capacity of the machine in $ha \cdot h^{-1}$ then is

$$PT = EF \cdot VW \cdot 0.36 = \frac{VW \cdot 0.36}{NE \cdot VW \cdot 0.36 + 1} \cdot (ha \cdot h^{-1}) \qquad (2.3)$$

Therefore the costs per hectare are

$$HVC = \frac{WA}{PT} = \frac{WA(NE \cdot VW \cdot 0.36 + 1)}{VW \cdot 0.36} \ (fl \cdot ha^{-1}) \qquad (2.4)$$

The calculation set out in the appendix shows that

$WA$ = 40.-- $fl \cdot h^{-1}$, 20.-- $fl \cdot h^{-1}$, 32.60 $fl \cdot h^{-1}$.

### 2.2.3. *Fixed costs: MFC* $fl \cdot ha^{-1}$

The annual fixed costs $AFC$ are depreciation, interest, insurance, housing and, in the case of contractors also include general costs. They were calculated as being

20 387.50; 35 280.--; 36 350.-- $fl \cdot yr^{-1}$.

These costs should be related to the yearly harvested area $AA$ $ha \cdot yr^{-1}$. If this is fixed, then the costs per hectare are constant and yield $MFC = AFC/AA$.

If the area is variable, then the costs per hectare are not known before the end of the season. In order to calculate the momentaneous costs a correction factor $C$ is introduced, based on the area harvested in a *"normal"* situation. In this situation we *assume* that the harvest is $AAN$ $ha \cdot yr^{-1}$, and this can be completed during the effective time by working at a constant speed of $VMN$ $m \cdot s^{-1}$ and a header working width of $CL$ m. This case yields $AA = C \cdot AAN$ $ha \cdot yr^{-1}$ (2.5)

If we *assume* that the available yearly working time is $TYT$ h·yr$^{-1}$ then $AA$ and $AAN$ are each equal to $TYT \cdot PT$.

As $VM$ is the actual machine speed m·s$^{-1}$, and

$$VW = VM \cdot CL \ \mathrm{m^2 \cdot s^{-1}} \tag{2.6}$$

$$\text{then } C = \frac{AA}{AAN} = \frac{TYT \cdot VW \cdot 0.36 \cdot EF(VM)}{TYT \cdot VMN \cdot CL \cdot 0.36 \cdot EF(VMN)} \tag{2.7}$$

Together with the definition (2.2) of $EF$, this becomes

$$C = \frac{VW \cdot (NE \cdot VMN \cdot CL \cdot 0.36 + 1)}{VMN \cdot CL(NE \cdot VW \cdot 0.36 + 1)} \tag{2.8}$$

The fixed costs are then

$$MFC = \frac{AFC}{AA} = \frac{AFC}{AAN} \cdot \frac{VMN \cdot CL}{VW} \cdot \frac{(NE \cdot VW \cdot 0.36 + 1)}{(NE \cdot VMN \cdot CL \cdot 0.36 + 1)} \ \mathrm{fl \cdot ha^{-1}} \tag{2.9}$$

For the IJ.D.A. we then have $AAN$ = 175 ha and $VMN$ is 0.9 m·s$^{-1}$.
For the farmer and contractor we have $AAN$ = 100 ha and $VMN$ is 1.0 m·s$^{-1}$.

### 2.2.4. *Costs of machine losses: CLO fl·ha$^{-1}$*

The grain losses are calculated by the model in kg·s$^{-1}$ as worked out in the next sections. It should be noted that there are four types of losses: sieve loss, threshing loss, walker loss and breakage loss. The financial value of the lost crop, $V_1$, due to the first three kinds of loss is taken as the market price minus transport and drying costs. In the appendix they are calculated in case of the IJ.D.A. to be 0.505 fl·kg$^{-1}$ and in that of the farmer and contractor 0.534 fl·kg$^{-1}$.

The broken grain depreciation $V_2$ is low. For wheat it is 0.00027 fl·kg$^{-1}$ for every 0.1% broken grain above 4%, so that the cost of broken grain is

$$VBL = V_2 \cdot BL \cdot 1000 \cdot (BLF - 0.04) \ \mathrm{fl \cdot s^{-1}} \quad \text{if } BLF > 0.04 \tag{2.10a}$$

$$VBL = 0.0 \quad \text{if } BLF \leqslant 0.04 \tag{2.10b}$$

The sum of the financial value of the machine loss is therefore

$$VML = V_1(WL + SL + TL) + VBL \ \ \mathrm{fl \cdot s^{-1}} \tag{2.11}$$

These loss costs only incur when the machine is harvesting and then they amount to

$$CLO = VML \cdot 10.000/VM \ \ \mathrm{fl \cdot ha^{-1}} \tag{2.12}$$

2.2.5. *Costs of the extra wear of the threshing cylinder drive: VWC* $fl{\cdot}ha^{-1}$

In the case that a threshing cylinder speed control is used, intensive acceleration and deceleration increases the V-belt wear. In comparing costs of control systems these costs may not be neglected. This wear is *assumed* to be proportional to the V-belt tension *FOB* above a certain minimum level *FOM* that is (*FOB-FOM*) N, which can be calculated in the model.
If the value $V_3$ (in $fl{\cdot}N^{-1}s^{-1}$) is known, then the costs in $fl{\cdot}ha^{-1}$ are

$$VWC = V_3 \cdot (FOB-FOM) \cdot 10000/VW \ fl{\cdot}ha^{-1} \qquad (2.13)$$

$$V_3 = 1.0 \cdot 10^{-6} \ fl{\cdot}N^{-1}{\cdot}s^{-1} \text{ and } FOM = 1250 \text{ N}$$

It should be noted here that the extra wear of the machine speed control is not calculated, *assuming* that the costs are relatively small.

2.2.6. *Costs of the timeliness losses CTI* $fl{\cdot}ha^{-1}$

These are the cost of shatter loss caused by wind and precipitation, wild life, sprouting and dry matter decrease prior to mowing, counted from harvesting ripeness and including header loss in mowing. In the Netherlands the average time of harvest ripeness of winter wheat is around August 15th (Fokkens, 1983). These losses occur about 15 days after this time and increase more than linearly.

The time when a certain area of crop can be harvested depends on the number of workable hours in the previous days and the working rate during these hours. Moreover, the crop will be *considered* as lost if it has not been harvested before a certain date in accordance with the IJ.D.A. harvesting model. We *assume* this date to be October 1st. This is a theoretical risk because in practice extra machines are hired when harvest is delayed that much. Still this gives extra costs. Based on data from the IJ.D.A. for winter wheat, a relation for timeliness losses has been derived and is given in figure 2.2.6.1 (for details see appendix).

Based on this relation and the data on the workable hours for the cereal harvest in the Netherlands, the total timeliness losses were calculated for a range of machine speeds and different *assumptions*. The *assumptions* concern the size of the area that has to be harvested (100 ha for the grain farm and 175 ha for the IJ.D.A.), the cereal moisture contents at the time of harvest (< 23% for the farm and < 28% for IJ.D.A.) and the uncertainty

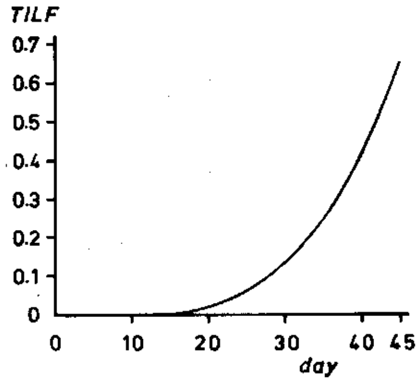



Figure 2.2.6.1. The fraction of the grain yield (*TILF*) lost when harvested at the indicated number of days after date of "combine ripeness" (about August 15th)

of workable hours availability due to the weather. For the last-named, called the weather risk, we took the percentage of years in which the number of workable hours, used in our calculations, was not available in the period until October 1st, due to unfavourable weather (25% or 16 2/3%) (see appendix). This already shows that the timeliness loss curves that arise in this way, and are shown in fig. 1.4.1.3, strongly depends on the conditions and, in our case, on the *assumptions*.

## 2.3. PROCESS MODEL

The combine-harvester process is split up into elements as shown in figure 2.3.1. The submodels referring to walker loss were worked out in more detail than the other submodels. They are dealt with in the next sections.

The desired speed of the machine and the threshing cylinder can be adjusted by the combine harvester operator (= manual control) or by one of the control systems (= automatic control).

### 2.3.1. *Header and conveyer*

The crop is cut by the cutter bar in the header and is then pushed by the next cut and the reel to the auger. The auger transports it laterally towards the centre (see fig. A 1.1.1 and A 1.1.2). At the centre of the auger there are retracting fingers that transport the crop to the con-

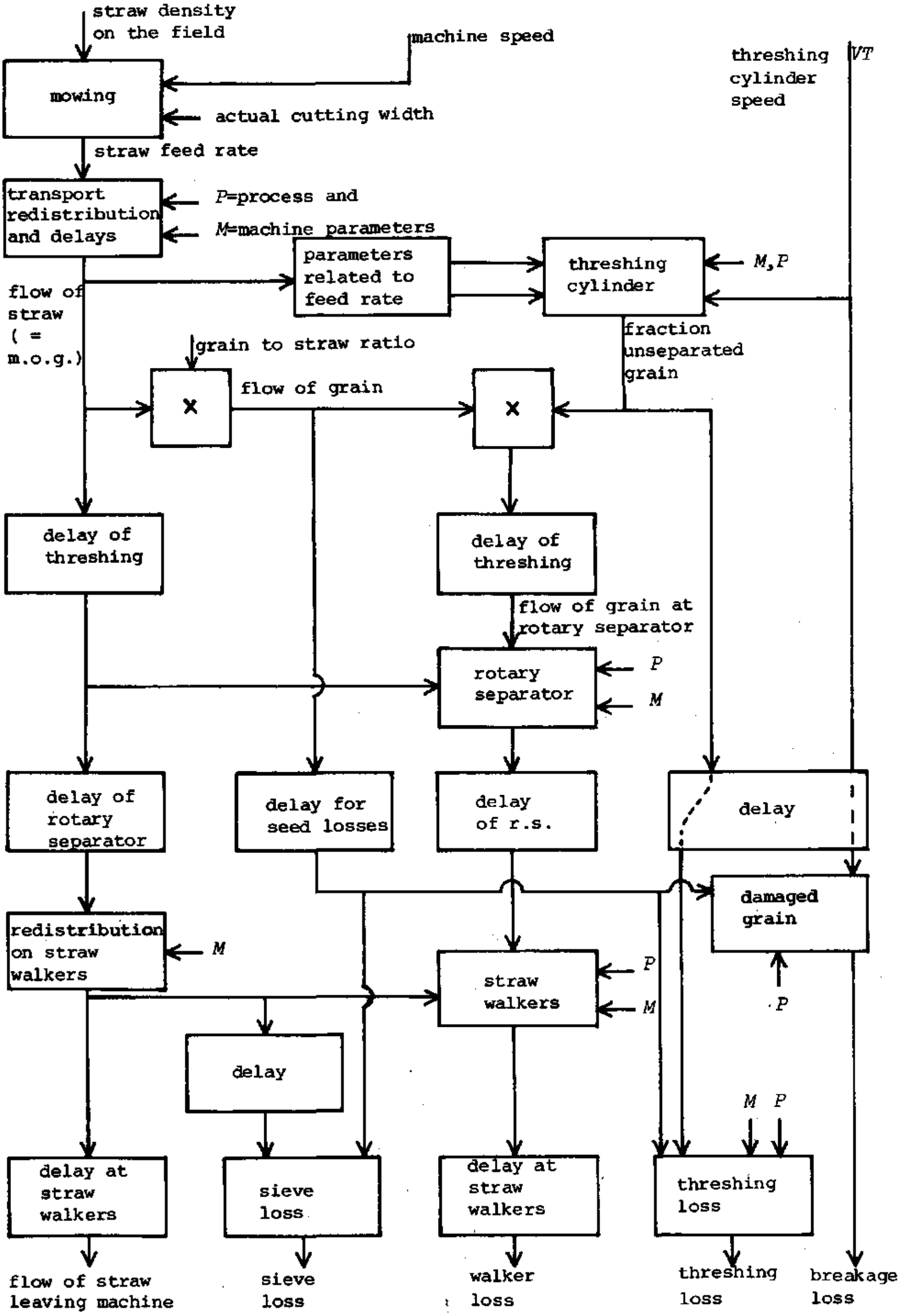



Figure 2.3.1. Flow chart of the combine harvester process for loss calculation

veyor. The conveyor or elevator chain transports the crop to the threshing cylinder in a continuous layer.

The cutting is done over the width of the cutter bar *CL* m, defined by the distance between the crop dividers at both sides of the header. The combine harvester has a certain speed *VM* $m \cdot s^{-1}$, at which speed cutting is done. If in front of the cutter bar the average amount of straw in a stretch is *SD* $kg \cdot m^{-2}$ then the amount of straw cut per time unit, the straw feed rate and the cutter bar *FSC* $kg \cdot s^{-1}$ will be.

$$FSC = SD \cdot VM \cdot CL \quad kg \cdot s^{-1} \qquad (2.14)$$

It is *assumed* in this mathematical relation that no material is lost, that means the material not gathered was not harvestable.

In transportation of the straw to the auger (and further) no material is lost either. Only a delay occurs. Based on an average machine speed of 1 $m \cdot s^{-1}$ and the dimensions of the header, these delays are calculated as 0.3 s for machine A and 0.4 s for machine B (see A 2.3.1). The transportation of the straw by means of the auger is a complicated process because there has to be a certain amount of straw accumulated before it is moved. Moreover, the crop is collected continuously over the full width of the auger and added to the sideways-moving mass.

At first this process was described by a first-order transfer based on a theoretical step function. This theory is worked out in A 2.3.1. However, the idea has been rejected, because in such transfer the high-frequency variations in the straw feed rate would be suppressed, which they are not when the process is continuous. The high-frequency variations will remain present (see 4.2) since they can be introduced by the auger as there is some mass redistribution caused by accumulation and there are also lateral straw-density variations in the strip. These variations reach the elevator in the way explained below.

Schematically the crop feed rate can be split up into three flows: (see figure 2.3.1.1) C moves straight ahead; A + B are added to C, but come later. The various crop mass flows are joined and taken over by the elevator chain at D. The variations in crop density are arrived at similarly.

The simulation model was defined by the condition that simulation of each control system must take place under constant conditions with regard to the disturbances in the process.

Variation in feed rate is such a disturbance and becomes important only at threshing and separation. Since the origin of the disturbances are the crop density variation in the field, the variation will be defined and recorded in terms of straw density ($kg \cdot m^{-2}$).

The transfer of the header and conveyer only will be expressed by equation 2.14 and time delays. All deviations from this expression are included in the calculation of the straw density input in the simulation.

The calculation of this straw density input is done by using the measured signal of the auger torque *TA*. This signal relates to the mass flow under the retracting fingers in the centre of the auger just before it reaches D (in fig. 2.3.1.1) as will be explained in 3.1.1. Also, the machine speed and cutter bar width are needed in the calculation of the apparent straw density. The equation can be derived from (2.14) and is

$$SD = TA/(VM \cdot CL) \quad kg \cdot m^{-2} \qquad (2.15)$$

Hence the disturbances in the measurement of feed rate and machine speed, the variations in cutting width and cutting height during the experiments, the variations in the redistribution in the header are all included in the calculated values of the apparent straw density.

It is only the measurement disturbances that *should not be* represented in the calculated values, all others may remain, as they are due to the process in the header and are the same for all simulations.

There is, however, a complication caused by an eventual difference in machine speed in the simulations and the experiments that will be explained below with the help of fig. 2.3.1.1.

If we consider a crop flow carried over to the conveyer at D during $\Delta t = 0.2$ s then it can be calculated that this crop mass was present as unmowed on the hatched strip E, about 1.7 seconds before, if the combine harvester is moving at a speed of 1 $m \cdot s^{-1}$. Hence the crop feed rate at D has to be related to a strip of crop roughly of shape E. If the machine speed had been 0.8 $m \cdot s^{-1}$, then the feed rate at D in $\Delta t$ would originate from strip F.

In the case that the machine speed varies in the simulation, the original position of the uncut crop must thus be thought if as varying. When the apparent straw density value derived from measurements with a driving speed of 1.0 $m \cdot s^{-1}$, is used in simulations at a driving speed of 0.8 $m \cdot s^{-1}$ then this straw density value corresponds as a matter of fact

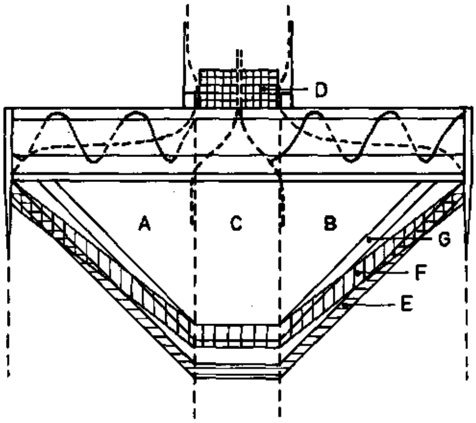



Figure 2.3.1.1. Origin of crop on the field as measured at D, in situations with different machine speeds (see text)

to strip G in figure 2.3.1.1 (which is namely equal to E in shape and area).

This gives a special character to the feed rate variation that cannot be separated from the original variation of straw density, and will therefore be *neglected*. This is allowed because the deviation is relatively slight and the kind of feed rate variation is not changed in principle.

On this assumption the transportation process is only a matter of time delays. These are deduced from the dimensions in the machine and the flow speeds and are established by measurements (see A 2.3.1).

The conveyer consists of an elevator capable of moving in the vertical direction at the front. Since this movement has been used for mass flow measurements it will receive separate consideration (see 3.1.2).

Consequently the model of the header and the conveyer is given for both machines by:

| *Description* | *Mathematical expression* | *Parameter* | *Value for machine* A | B |
|---|---|---|---|---|
| Straw feed rate at the cutter bar | $FSC=SD \cdot CL \cdot VM$ (kg·s$^{-1}$) | $CL$ (m) | 4.5 | 5.9 |
| Straw feed rate at the auger | $FSA=FSC \cdot e^{-\underline{T}_1 s}$ (kg·s$^{-1}$) | $\underline{T}_1$ (s) | 0.3 | 0.4 |
| Straw feed rate at the elevator | $FSE=FSA \cdot e^{-\underline{T}_2 s}$ (kg·s$^{-1}$) | $\underline{T}_2$ (s) | 0.2 | 0.3 |
| Straw feed rate at the threshing cylinder | $FST=FSE \cdot e^{-\underline{T}_3 s}$ (kg·s$^{-1}$) | $\underline{T}_3$ (s) | 0.7 | 0.6 |

$$TSE = 1 - \exp(-LA \cdot NU \cdot RPS \cdot (VT - VE)^{BETA}) \quad (2.16)$$

in which

*TSE* = Fraction concave separation of the grain feed rate.

*BETA* = Threshing coëfficient. This factor only depends on the crop being threshed and amounts to between 1.1 and 1.8.

*RPS* = The reciprocal value of the charge coëfficient (= $1/\psi$ of Caspers). This factor depends on the feed rate.

*NU* = Densification factor. This factor gives an indication of the densification of the product in the threshing space. Consequently the value of this factor depends on the concave adjustment and the straw feed rate.

*LA* = Concave length factor. This is the quotient of the real concave length and a reference concave length (680 mm for Caspers)(in our own case 0.9).

*VT* = Peripheral velocity of the threshing cylinder (threshing speed) $m \cdot s^{-1}$.

*VE* = Velocity elevator $m \cdot s^{-1}$ i.e. the crop intake speed (in our case 2.6 $m \cdot s^{-1}$),

Since the concave length, the concave adjustment and the intake speed are fixed in this study, the value for *LA* is calculated as 0.862 for machine A and 0.9 for machine B. For *NU* and *RPS* values are calculated with reference to the concave adjustment and the specific straw feed rate (= straw feed rate in $kg \cdot s^{-1}$ dry matter per metre concave width)(see A 2.3.2.a)

During simulations these values can be introduced by a function generator with linear interpolation and, since they are a function of the specific feed rate, that is specified for a standard width of 1 m, they are valid for machine A as well as machine B.

Separation is thus dependent on the feed rate, the threshing speed, the threshing coëfficient and the chosen concave adjustment. In figure 2.3.2.1 an example is given of this relationship for the values of variables: *BETA* = 1.7, the concave adjustment of 8/4, which means a space between threshing bar and concave of 8 mm at the front side and 4 mm at the rear, and *NU* and *RPS* for spring wheat.

This relation is also close to the results obtained by other researchers, for instance Arnold (1964), Cooper (1971) and Eimer (1977) and the present writer's own laboratory research (see A 2.3.2.b). In the model that Pickering

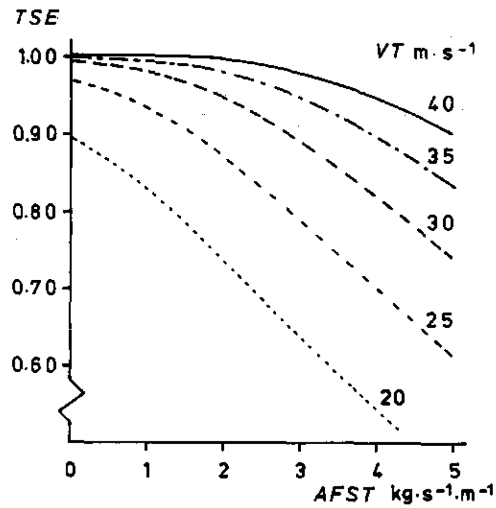



Figure 2.3.2.1. Relation between threshing separation efficiency (*TSE*) and specific straw feed rate (*AFST*) for different levels of threshing cylinder speed (*VT*) according to the model of Caspers for *BETA* = 1.7 and concave adjustment 8/4 mm/mm

(1974) used in simulations, the concave separation is suggested to be linearly dependent on the straw and grain feed rate. The present writer's own field research shows this to be a good estimate in case there is a slight variation in feed rate (see A 2.3.2.c). For such a small range of feed rate the model of Caspers shows also an almost linear relation, so there is no real difference between these models. A dependence on the threshing cylinder speed is not indicated in the model of Pickering, so the model of Caspers was preferred.

From the present research (see A 2.3.2.d) it has been established that the separation doesn't depend on the frequencies in feed rate variations in the researched bandwidth lower then 12 rad·s$^{-1}$. It is *assumed* therefore that every feed rate variation that occurs in the simulation will have effect in accordance with the indicated relationship between straw feed rate and concave separation. In the model of Pickering this is the case, too.

In the straw density input only frequencies lower than about 6 rad·s$^{-1}$ exist, so that variations above this level are in fact *assumed* to have no impact. The threshing separation fraction (*TSE*) has to be multiplied by the grain feed rate at the threshing cylinder (*FGT*) to calculate the amount of separated grain in kg·s$^{-1}$. This grain feed rate is calculated from the straw feed rate *FS* on multiplication by the grain-to-straw ratio (*GS*). This *simplification* is permitted as the variation within one field is slight and the value will differ for each field just as other crop properties do. See also appendix 4.2.1.

*Threshing loss*

The threshing loss depends on the threshing cylinder speed, the concave adjustment, the intake speed and the feed rate level. Caspers didn't make a model of it, he only presented some measurement results. Based on these results and those of Eimer (1977) a *simplified model* has been derived using the non-concave separation of the model of Caspers. The fraction of threshing loss of grain feed: $TLF = (1-TSE)\cdot 0.025$ that holds for a concave adjustment of 8/4. The use of this simple model is justified because the contribution to the total losses is slight.

In this way the threshing loss becomes

$$TL = TLF\cdot FGT \text{ kg}\cdot\text{s}^{-1} \qquad (2.17)$$

*Breakage loss*

The breakage of grain strongly depends on the crop variety, moisture content and the drum speed. Especially dry grain is vulnerable, while the influence of the concave adjustment is small. In figure 2.3.2.2 some data are plotted from tests with wheat carried out by Arnold (1964), Caspers (1966, 1973) and Kolganov (1956). The tests done by Arnold showed that the wheat variety Capella Desprez is particularly sensitive to grain damage. All other observations are below 2%. King (1960) published data from New Zealand where visible damage percentages up to 28% at $VT$=28 m$\cdot$s$^{-1}$ and 14% grain moisture content were measured.

In the field in Western Europe the damage percentages are found to be quite lower. For normal straw feed rates of 1.7 and 2.4 kg$\cdot$s$^{-1}$, field measurements (Van Oosten, 1970) showed damage percentages of 1.0 and 1.1% at $VT$ = 25 m$\cdot$s$^{-1}$. Several test reports by IMAG and DLG (Anonymus, 1976, 1967) generally present very low damage percentages, sometimes with an upwards peak caused by special conditions. From information of the Dutch cereal trade it appears that damage percentages higher than 1% are rarely encountered in the Netherlands (Schrier, 1982).

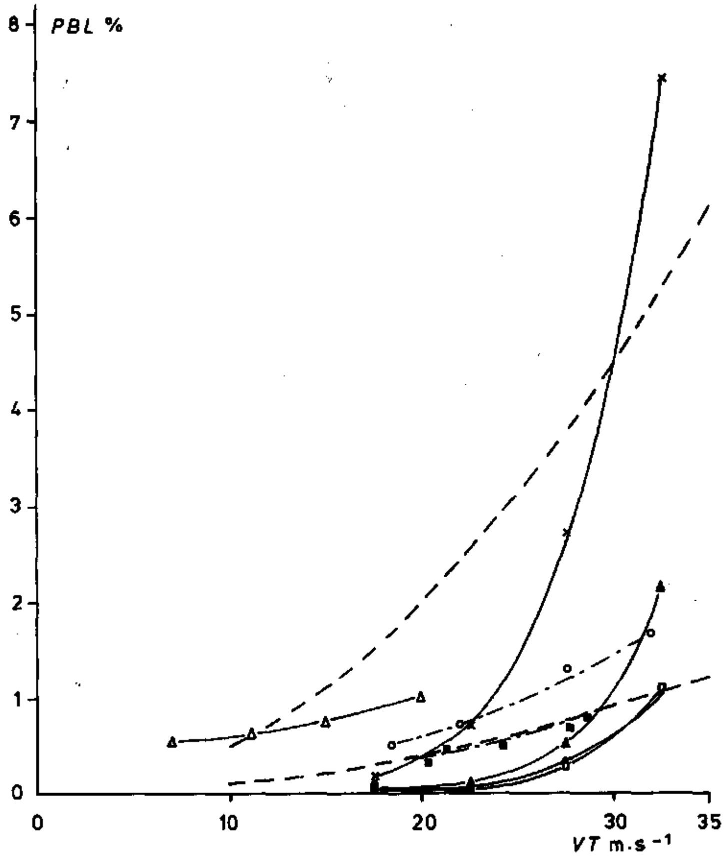



Figure 2.3.2.2. Grain breakage % (*PBL*) related to threshing cylinder speed (*VT*) $m \cdot s^{-1}$. Data from Arnold (1964), 2 $kg \cdot s^{-1}$, winter wheat: Capelle Desprez: × *MCG* = 15%, ▲ *MCG* = 19%, ◘ *MCG* = 30%, Koga 2: ● *MCG* = 14%; Data Kolganov (1956), △ winter wheat; Data Caspers (1966, 1973), 3 $kg \cdot s^{-1}$: o winter wheat, ■ spring wheat;
— — – – Model $PBL = 0.001 \cdot (VT)^2$ and $0.005 \cdot (VT)^2$

The influence of the straw feed rate on grain damage is, according to Wieneke (1964), slight and slowly decreasing with rising feed rate.

Eimer (1977) presents a figure with lines showing a minimum amount of damaged grain at $\pm$ 3 $kg \cdot s^{-1}$, but the measurement points give just as many reasons for concluding that there is no dependence.

However as the quantity of damaged grain is an important criterion for selection of the threshing cylinder speed, it is important to apply such a relation in the simulation model.

On the basis of the above mentioned data, *only a* relation with the threshing cylinder speed is considered, namely the fraction of damaged grain $BLF = 1 \cdot 10^{-5} \cdot (VT)^2$, for a normal, favourable situation and five times as much in an unfavourable situation. These relations are shown in fig. 2.3.2.2. Thus the amount of grain breakage loss is

$$BL = BLF \cdot FGT \text{ kg} \cdot \text{s}^{-1} \qquad (2.18)$$

*Separation of small straw parts by the concave*

Though it is known that a higher threshing intensity (higher $VT$, a lower cylinder-to-concave distance or a lower straw feed rate), induces the separation of a higher percentage of small straw parts, this will *not be taken into consideration* by the model as

1) the effect is *relatively* small and has little impact on the losses;
2) it was *assumed* that the effects on walker losses and sieve losses compensate one another.

*Straw breakage*

At higher threshing intensity the straw is beaten harder and split and broken to a greater extent. This can cause a raise in walker loss. As there were no experimental data on this effect available, and the effect was *thought* to be small under Dutch conditions, no model of this factor was made.

*Delay in straw and grain flow*

Because of the length of the concave (0.63 m) and the speed of the crop flow which, according to Gasparetto (1977) is 7-11 m$\cdot$s$^{-1}$ with an average value of 9 m$\cdot$s$^{-1}$, a delay of the straw and grain conveyance of approximately 0.1 s has to be taken into consideration. This includes the slowing down by the cylinder beater.

### 2.3.3. *Rotary separator*

The task of the rotary separator differs from that of the threshing cylinder. It separates and does not thresh. For that reason the separation characteristic differs, too. Figure 2.3.3.1 shows the measurement points of laboratory tests with stored winter wheat and rye. This figure shows that the fraction grain separated at the rotary separator (*RSE*) decreases fairly linearly with straw feed rate at the separator (*FSR*) and that the slope is the same for the different crops. During harvesting, the crop is usually wetter than in the laboratory and thus separation is reduced, so that the line drawn in the figure *was found to be more realistic* for our simulation. The mathematical model used in our simulation will be therefore

$$RSE = CRL - 0.05 \cdot FSR \tag{2.19}$$

*CRL* will vary depending on crop properties. In our case, where only wheat is considered, *CRL* will be 0.6.

The delay at the rotary separator is *estimated* to be 0.1 s.

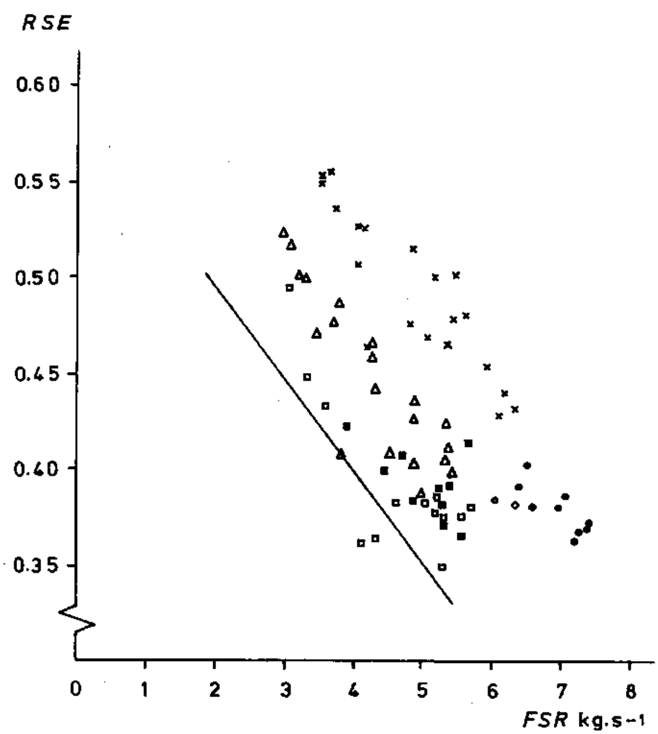



Figure 2.3.3.1. Relation between rotary separator efficiency (*RSE*) and straw feed at separator (*FSR*)
×,●,○ different trials with winter wheat
△,■,□ different trials with rye
(——) Model: $RSE = 0.6 - 0.05 \cdot FSR$

### 2.3.4. *Straw walkers*

*Steady state model*

The material leaving the threshing cylinder or the rotary separator at a speed of about 10 $m \cdot s^{-1}$ is slowed down by a baffle curtain to a speed of almost zero. This curtain is fixed above the walkers 0.61 m from the front walkers for machine A and 0.65 m for machine B. The process of separation before and behind the curtain is different in principle.

From laboratory research (see A 2.3.4.a) it was found that the separation before the curtain is approximately linearly proportional to the concave separation in the threshing cylinder. In the model this separation is *thought to be included* in the threshing separation or rotary separation. Just the separation behind the curtain will be considered to be walker separation, so that the active walker length is 2.75 m and 2.65 m for machines A and B, respectively. The speed of the mixture of straw and grain behind the curtain will increase to approximately 0.5 $m \cdot s^{-1}$. However, the speed will vary as will the time in which the straw is accumulated in front of and under the curtain.

The separation of the grain and the straw is activated by tossing up the material, thus increasing the distance between the straw parts, so that the grain can fall further down when the straw is tossed up again by the walkers.

The density of the material can also be decreased by having side-by-side walker parts that carry out phase-shifted movements, by mounting walker steps and sawtooth cams, or by mounting moving parts above the walkers.

From research by Baader (1969), Sonnenberg (1970), Reed (1972) and Souter (1967) the optimal frequencies and amplitudes for the movement of the walkers can be deduced. In our machines A and B these items are fixed at practically the optimum levels.

For our model we need the relationship between separation efficiency and feed rate as well as the impact of crop properties. For this a separation model (given below) was studied as used by Filatov (1967), Reed (1970) and Glaser (1976):

$$G_w = G_o \exp(-WE \cdot x) \text{ in which} \qquad (2.20)$$

$G_w$ = quantity of grain in the straw passing the walkers at $x$ ($kg \cdot s^{-1} \cdot m^{-1}$);

$G_o$ = quantity of grain in the straw passing the walkers at the start of the separation process ($kg \cdot s^{-1} \cdot m^{-1}$);

$WE$ = separation factor called walker efficiency $m^{-1}$

$x$ = distance from the beginning of the separation process m

This equation is the solution of a first-order differential equation

$$dG_w/dx = - WE \cdot G_w \qquad (2.21)$$

In this equation it is *assumed* that the straw layer on the walkers is homogeneous and doesn't change while on the walkers, and that the grain is homogeneously distributed in the straw layer, causing the separation to be proportional to the grain content of the grain/straw mixture.

The grain content just mentioned has the dimension $kg \cdot s^{-1} \cdot m^{-1}$, because the grain/straw mass moves backward at a given speed. If the mass transport is recalculated for the specific width of 1 m, the dimension becomes $kg \cdot s^{-1} \cdot m^{-2}$.

Though these assumptions cannot be completely justified, the result can be used for our purpose (see appendix b). The process is so complex that the disturbances in the process due to unknown variables cannot be distinguished from incorrect assumptions. In the next paragraph the effect of straw feed rate on straw separation will be worked out. All other variables are lumped together in one parameter *WEP*. In this parameter the effects of a large number of crop properties and harvest conditions are included, the most important of which are:

- The crop properties that can be measured in terms of physical properties like: elasticity; friction; dimensions before threshing and after threshing, when breakage and splitting occurs; the ratio of leaves and chaff to longer pieces of straw; moisture content of straw or grain. These properties are defined by the kind of crop, variety, growing conditions, state of ripeness, cutting height, disease and weather conditions.
- Amount of weeds in the harvested crop.
- Machine adjustments.

Each of the mentioned factors can vary and influences the walker separation in a way which is not always predictable while there are several interactions between these variables themselves and with straw feed rate.

The value of *WE* depends on the quantity of straw in which the grain is embedded and the crop properties in a way that is modelled by

$$WE = WEP/AFSW \qquad (2.22)$$

In this form *AFSW* is the straw feed rate per m width of the walkers and *WEP* the lumped parameter.

The value of *WEP* varies in general between 1 and 4 (see appendix b). The influence of design parameters is left out of consideration as the parameters are constant here. Figure 2.3.4.1 shows how some data from field and laboratory measurements relate to this equation. The scatter of measuring points can be due to measuring faults but also to the lumped parameter model.

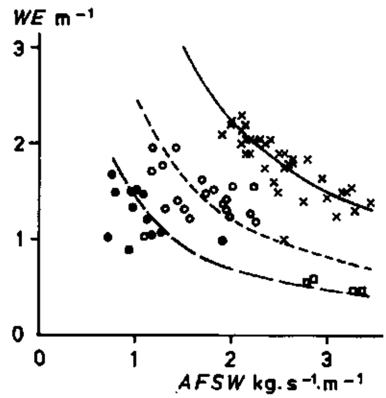



Figure 2.3.4.1. Walker efficiency related to straw feed rate for machine A ($LW$ = 2.75): × = wheat 1976, ● = oats 1975, o = spring wheat 1975, □ = winter wheat, laboratory tests 1973.
——— : $WE = 4.5/AFSW$; ----- $WE = 2.5/AFSW$; — — : $WE = \frac{1.4}{AFSW}$

Pickering (1974), too, originally applied this type of model, but with the exception that he didn't use the feed rate of m.o.g., but only the feed rate of the longer straw pieces. However, because m.o.g. was split up into straw and chaff at a fixed ratio, an adaption of *WEP* would have had the same result.

After comparison of one feed rate-to-loss curve with field measurements, Pickering changed the model into

$$G_w = G_o(1 - \exp(-WE \cdot AFSW)^{-1}) \qquad (2.23)$$

In our model this adaption wouldn't be necessary, because $G_o$ increases exponentially with the straw feed rate and not linearly as in Pickering's model, so that the first model will be maintained.

As mentioned earlier, the speed of the grain and straw mixture is slowed down by the curtain. As a matter of fact, a thin layer of straw is transformed here at high speed to a slow-moving thick, dense straw layer. In this way the material is redistributed depending on its speed, the straw feed rate and the properties of the straw.

The rotational movements of the walker parts result in a movement of the straw to the rear. The speed of the straw will depend on the contact of the walkers with the straw which in turn depends on the mass and coherence of the straw. On the walkers, too, there is a redistribution of material when the feed rate varies.

From a physical point of view *it can be perceived* that highly frequent variations in the throughput over the walkers are reduced by averaging, while low-frequent variations remain. This *can be described* by a first-order process in feed rate transfer giving

$$FSWA = FSR \cdot (1 + \underline{\tau} \cdot s)^{-1} \qquad (2.24)$$

Pickering (1974) also applied a first-order process initially with $\underline{\tau} = 2.0$, but later on used $\underline{\tau}=1.0$.

It is difficult to ascertain which value should be taken. That is also the reason why a possibly more accurate model doesn't make sense. From field observation of step functions (see figure 2.3.4.2 and A 2.3.4.c) and

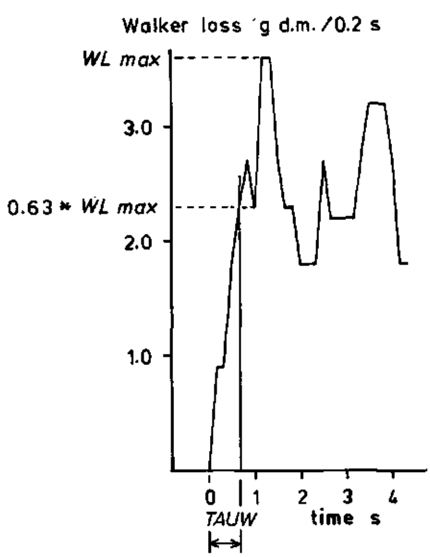



Figure 2.3.4.2. Response of walker loss to a step in feed rate, giving an indication of the time constant (*TAUW*) in the first order transfer at the walkers.

laboratory tests, the most acceptable value of $\tau$ has been ascertained to be 0.8. The delay, caused by the transport of the straw from curtain to the end of the walkers, is calculated to be 8.2 s (see A 2.3.4.d). In the field this delay varies a great deal, due apparently to accumulation at the curtain.

### 2.3.5. *Sieve loss*

In calculating the total costs the sieve losses will also be taken into consideration. The sieve loss model is not worked out extensively. These losses are low in general under Dutch harvest conditions and in relation to walker losses. Just the relation to straw feed rate will be worked out as this is the main factor.

The influence of the threshing cylinder speed on sieve losses *will be neglected.* A higher threshing-cylinder speed will give a higher separation of straw through the concave grate and influences the sieve losses negatively in general. However, in this case the walker loss is influenced positively owing to the reduced amount of straw on the walkers. It is *assumed* in this study that the two effects compensate one another.

The number of factors influencing the level of the sieve loss is large: type of straw, straw feed rate, moisture content of the straw, amount of weeds, ripeness of the straw, etc. as in 2.3.4. In addition, the adjustment of the sieves (the opening and the airflow), is also very important, but only the straw feed rate will be used as a variable. The reason for this is that the other factors are either beyond the influence of the operator or fully controlled by him (for instance machine adjustments), while the object of the present research is the straw feed rate as a result of the machine speed.

The model for the sieve loss will be derived from field experiments.

In figure 2.3.5.1 field measurements with machine A during the years 1969 ... 1972 are shown. The stretches were about 25 m in length in those tests. The extreme values are also presented in table 2.3.5.1 to make comparisons with the walker losses possible (Van Oosten, 1970; Klein Hesselink, 1971; Loorbach, 1972; Wevers, 1972). Data of measurements with machine B on grain farms in 1980 are also presented (Van Dongen, 1981). Here the length of the stretches was 10 m. The averages of measurements

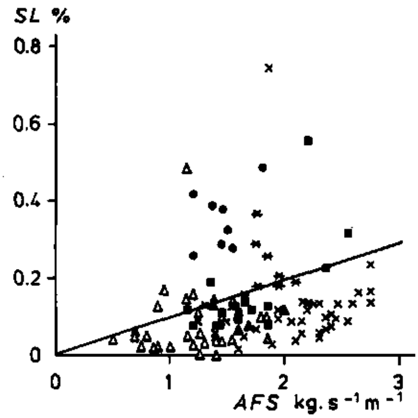



Figure 2.3.5.1. Sieve losses; measured at machine A in winter wheat field trials: ■ 1969, ✳ 1970, × 1971, ● 1972; at farmers' machines B: Δ 1980 and at machine B of the IJsselmeerpolders Development Authority from 1977 up to 1982: ▲

with machine B at the IJ.D.A. are available from the year 1977. The table shows the variation over the years and the tendency for sieve losses to be much smaller than walker losses.

Table 2.3.5.1. Losses measured in field tests

| Year | Specific straw feed rate $kg \cdot s^{-1} \cdot m^{-1}$ | | | Walker loss % | | | Sieve loss % | | |
|---|---|---|---|---|---|---|---|---|---|
| | min | mean | max | min | mean | max | min | mean | max |
| 1969 | 1.1 | | 2.6 | 0.3 | | 5.5 | 0.08 | | 0.3 |
| 1970 | 1.3 | | 2.2 | 0.06 | | 2.6 | 0.13 | | 0.4 |
| 1971 | 1.3 | | 2.8 | 0.2 | | 5.2 | 0.02 | | 0.8 |
| 1972 | 1.2 | | 1.7 | 0.7 | | 9.1 | 0.3 | | 1.7 |
| 1980 | 0.7 | | 1.9 | 0.01 | | 3.1 | 0.005 | | 0.5 |
| 1977 | | 1.4 | | | 0.07 | | | 0.14 | |
| 1978 | | 2.0 | | | 0.30 | | | 0.12 | |
| 1979 | | 1.4 | | | 0.23 | | | 0.13 | |
| 1980 | | 1.7 | | | 0.10 | | | 0.08 | |
| 1981 | | 1.6 | | | 0.08 | | | 0.11 | |
| 1982 | | 1.6 | | | 0.10 | | | 0.07 | |

The general tendency is indicated by the line in figure 2.3.5.1 and the formula of the fraction sieve losses of grain feed rate will be

$$SLF = 0.001 \cdot AFS \qquad (2.25)$$

Almost the same conclusion is reached in the literature. There is a linear increase of the sieve losses by ± 0.1% per $kg \cdot s^{-1} \cdot m^{-1}$ increase in the feed rate. Pickering's model doesn't contain a sieve and Kirk (1977) doesn't give any details. In this model the straw feed rate after the redistribution on the walkers *AFSW will be applied* to the straw feed rate, because the measurement points in the figure refer to averaged feed rates covering a longer stretch and *AFSW* constitutes a better approach than *AFS*.

Further more $SL = SLF \cdot FGT$. Actually *FGT* should have been diminished by *WL*, but this *is neglected*.

## 2.4. TRANSMISSION MODELS

If the driving speed or the threshing-cylinder speed is controlled automatically the dynamic behaviour of the transmissions will have an impact on the actual speeds so these transmissions have to be modelled for the simulation.

### 2.4.1. *Transmission in machine A*

On machine A the driving speed is adjusted by a V-belt varidrive. The rotational speed of the engine has to remain nearly constant, as the speed of the various parts of the machine has to be constant. There is a clutch and a gearbox behind the varidrive. The varidrive is adjusted by means of a hydraulic cylinder with an adjustment range of 113 mm. Measurements showed that the adjustment time over this range is 2.4 s during the continuous maximum acceleration of the machine (Werkman, 1972; Naaktgeboren, 1976). See also figure 2.4.1.1.

A hydraulic cylinder can be modelled as an integrator with limited extreme values. The displacement of the cylinder in time $dy/dt$ is proportional to the flow of oil ($x$) into the cylinder

$$dy/dt = k \cdot x \ \mathrm{m \cdot s^{-1}} \quad (2.31)$$

or after Laplace transformation

$$s \cdot y = k \cdot x \ \mathrm{m \cdot s^{-1}} \quad (2.32)$$

so that

$$y = k \cdot x / s \ \mathrm{m} \quad (2.33)$$

The value of $k \cdot x = PF$ is given by the dimensions of the cylinder, the oil flow characteristics, and the adjustment needed for correct behaviour of the control.

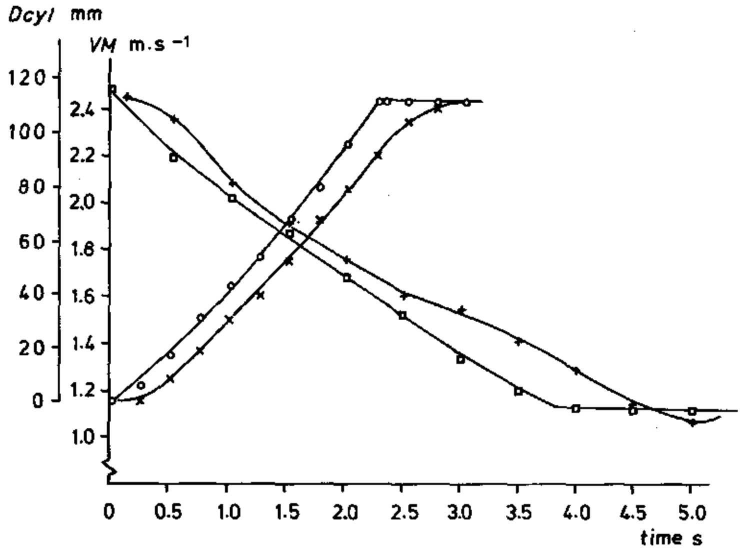



Figure 2.4.1.1. Forward speed (*VM*) of machine A at acceleration and deceleration actuated by the displacement of the cylinder of the varidrive (*Dcyl*).
Acceleration: o Cylinder displacement, × Measured speed
Deceleration: ◻ Cylinder displacement, + Measured speed

In an auger torque feedback control system with which field tests have been carried out, the adjustment of the oil flow has been done by means of a pulsating oil flow with a varying passing time (Loo, 1977).

In figure 2.4.1.1. the relation of the position of the cylinder to the driving speed is shown. The model is a linear equation dynamically *approximated* by means of a first-order process with $\tau_2$=0.3. This is because there are inertnesses in the adjustment of the variator in consequence of the acceleration of the mass of the machine and the deformation of the V-belt.

The transfer of the gearbox and the wheels is linear and depends on the gear selected. Thus variation in driving speed arising from slipping wheels and sagging tyres is *neglected*.

In figure 2.4.1.2. the transfers are quantified. $P_v$ is the gain of the varidrive. $P_g$ is the gain of the gearbox.

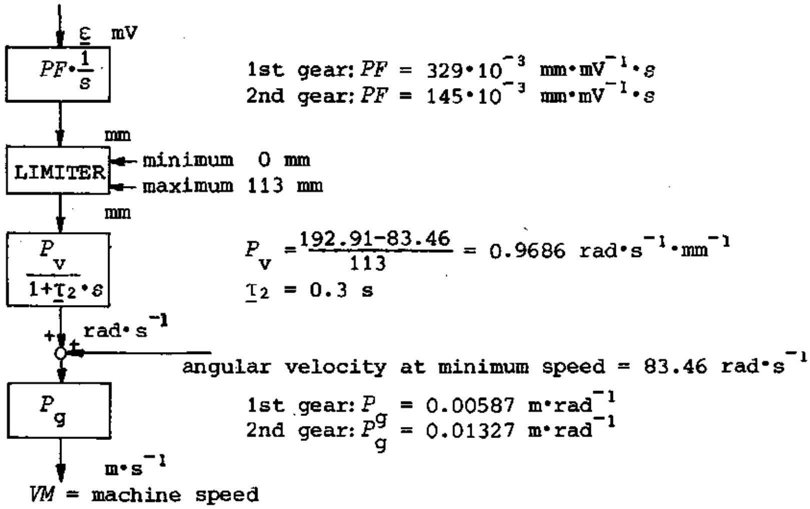



Fig. 2.4.1.2. Scheme of the model of the driving speed transmission of machine A

### 2.4.2. *Transmission in machine B*

Machine B is driven by a hydraulic drive designed to work as follows: the engine drives a variable pump, which generates an oil flow that drives a fixed hydraulic engine to which the wheels are connected by means of a gearbox.

The variable pump can be adjusted by two servo cylinders from which the position can be controlled by a valve connected to a control handle.

For an automated combine harvester, both the control valve and the control handle have to be adapted. This can be done in many ways. The simplest way is to replace the control valve by one which passes a (maximized) oil flow proportionally to the input signal.

By analogy with 2.4.1 the displacement of the cylinder is made proportional to the value for the variable $P_c/\tau_i$ in which $\tau_i$ = 1.67 s, derived from an assumed maximum piston displacement of 60 mm, while the adjustment time from minimum to maximum driving speed, found from field tests, is 1.0 s (this concerns the displacement of the piston over the above-mentioned 60 mm at maximum oil flow). After all, the real value of $P_c/\tau_i$ is unimportant so long as $P_c \cdot P_h \cdot P_g/\tau_i$ has a value that makes the control stable and the acceleration does not exceed the maximum value mechanically possible.

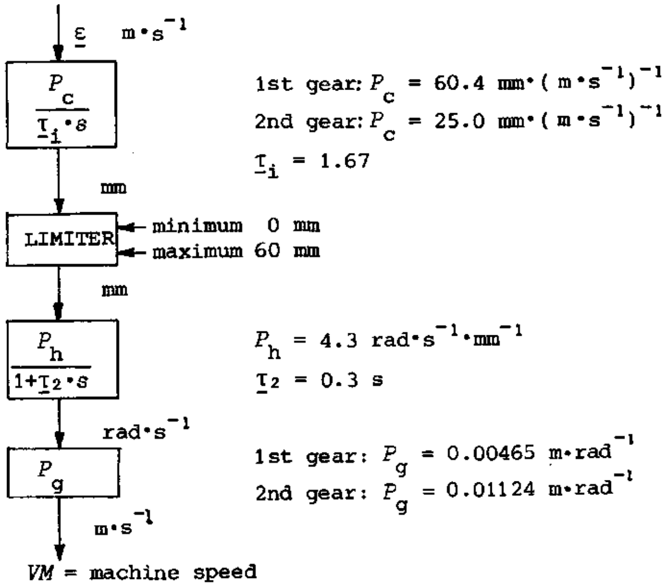



Fig. 2.4.2.1. Scheme of the model of the driving speed transmission of machine B

In order to make the model clear it is useful to show all its components. The gain of the hydraulic drive, $P_h$ is given the value 4.3 because the maximum number of rotations per minute of the hydraulic engine = 2463 rpm $= 41.05\ s^{-1} = 258\ rad\cdot s^{-1}$.

Since this is the case at the maximum 60 mm position of the cylinder, it follows that

$$P_h = \frac{258}{60} \approx 4.3\ (rad\cdot s^{-1})mm$$

The transfer between the piston position and the peripheral speed is *almost* linear. The maximum speeds of the machine during field measurements were: in 1st gear:

$$1.2\ m\cdot s^{-1} \rightarrow P_g = 0.00465\ m\cdot s^{-1}(rad^{-1}\cdot s^{-1})^{-1}$$

in 2nd gear:

$$2.9\ m\cdot s^{-1} \rightarrow P_g = 0.01124\ m\cdot s^{-1}(rad^{-1}\cdot s^{-1})^{-1}$$

During the simulations 2nd gear values were always used.

In the dynamic transfer of the hydraulic drive there is also a certain inertness which, based on field measurements, has been *approached* by a 1st order process in which $\tau_2 = 0.3$. An interaction with the engine has been neglected for both variators because of the low value of $P_c$. A recapitulation is given in figure 2.4.2.1.

### 2.4.3. *Threshing cylinder varidrive*

The engine and the threshing cylinder are directly connected to one another by a V-belt variator. The transfer ratio of the variator determines the rotational speed as well as the torque. Since the required power at the threshing cylinder varies because of feed rate variations, the inertia of the threshing cylinder, engine and other parts of the machine have also to be taken into consideration as a dynamic circuit.

Figure 2.4.3.1 shows the composition of the circuit.

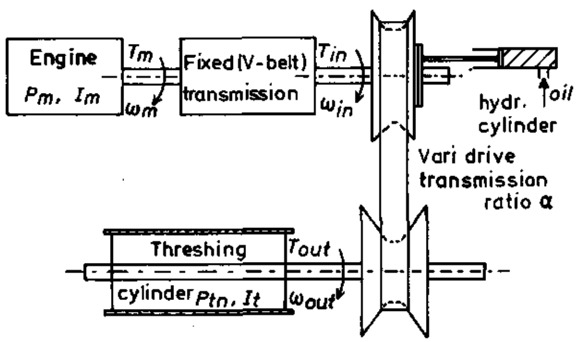



Figure 2.4.3.1. Scheme of engine, transmission and threshing cylinder
Symbols: $I$ = moment of inertia; $P$ = power, $T$ = torque on shaft,
$\underline{\omega}$ = angular velocity of shaft.
Subscripts: in = in variator, out = out variator, m = out engine shaft,
t = threshing cylinder, n = needed

From the threshing-cylinder side (out of variator), the following equation can be made:

Power needed for threshing = power from shaft of variator + power from inertia of threshing cylinder.

When $P$ stands for power, $T$ for torque, $I$ for inertia and $\underline{\omega}$ for angular velocity we have

$$P = T \cdot \underline{\omega} \tag{2.34}$$

$$T = I \cdot \frac{d\omega}{dt} \tag{2.35}$$

Then we can write the equation

$$P_{tn} = T_{out} \cdot \underline{\omega}_{out} \cdot I_t \cdot \frac{-d\underline{\omega}_{out}}{dt} \qquad (2.36)$$

The sign of $d\underline{\omega}_{out}$ is negative because power becomes available (positive) when $d\underline{\omega}$ is negative.

At the engine side (into variator) we have the equation: power available from power shaft = power from the engine + power from the inertia of the engine and the parts of the machine connected to the engine.
The formula reads as

$$T_m \cdot \underline{\omega}_m = P_m + \underline{\omega}_m \cdot I_m \cdot \frac{-d\omega}{dt} \qquad (2.37)$$

Since $T$ and $\underline{\omega}$ determine one another at the engine as well as at the threshing cylinder, there must be agreement about their causal dependence. For the simulation we must choose just one direction of the calculations. We preferred the direction as indicated in figure 2.4.3.2. Hence $\underline{\omega}_m$ can be calculated from $T_m$, and $T_{out}$ from $\underline{\omega}_{out}$. Equation (2.37) is therefore rewritten as

$$\frac{d\underline{\omega}_m}{dt} = \frac{1}{I_m} \cdot \left(\frac{P_m}{\underline{\omega}_m} - T_m\right) \qquad (2.38)$$

In the simulation, $\underline{\omega}_m$ is calculated by integrating the right hand part of the equation from the values of $P_m/\underline{\omega}_m$ and $T_m$ of the previous simulation step. In the same way equation (2.36) is rewritten to give

$$T_{out} = \frac{P_{tn}}{\underline{\omega}_{out}} + I_t \cdot \frac{d\underline{\omega}_{out}}{dt} = T_{tn} + T_{in} \qquad (2.39)$$

$T_{out}$ is thus calculated by differentiation of $\underline{\omega}_{out}$ (see also figure 2.4.3.7).
The following values are also needed in this equation.

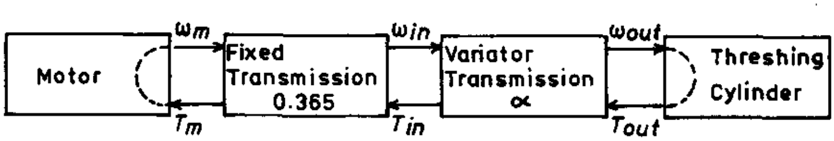



Figure 2.4.3.2. Direction of calculations of related variables
$T$ = torque, $\underline{\omega}$ = angular velocity

*The value of* $P_m$

$P_m$ is the power available for threshing, for which calculation the following *assumptions* are made: Normally the engine is loaded to about 85% of its maximum power, roughly 30% of which is used for threshing. The remainder of the engine power, that is 100-85=15%, is available for acceleration of the threshing cylinder if needed.

The maximum power of the engine of machine B is 131 kW. Consequently the available power for threshing is (0.3•0.85 + 0.15)•131 = 53 kW. However, only the necessary amount of power is delivered in accordance with the power-speed curve (see figure 2.4.3.3).

If the engine is not overloaded, section BC can be applied. Here B is the maximum power of 131 kW and C is 131-53=78 kW. The slope of line BC = 18 kW•(rad•s$^{-1}$)$^{-1}$. Therefore, in the model, the engine capacity depends on the rotational speed. Thus the available power is

$$P_m = (\underline{\omega}_{max} - \underline{\omega}_m) \cdot 18 \text{ kW} \qquad (2.40)$$

that is limited to

52.92 kW at $\underline{\omega}_m = \underline{\omega}_{top}$ = 264.20 rad•s$^{-1}$, because

$\underline{\omega}_{max}$ = 267.14 rad•s$^{-1}$

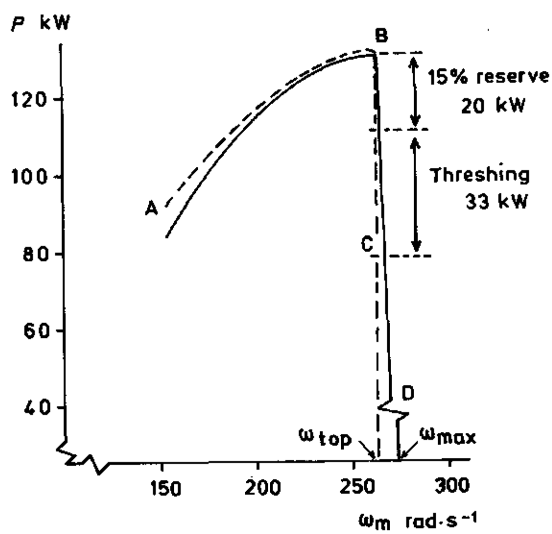



Figure 2.4.3.3. Engine power related to angular velocity of motor shaft

If $\underline{\omega}_m$ were to become smaller than 264.20 rad•s$^{-1}$ the available power would decrease like the dotted line of section BA. In the model this relation is estimated by the drawn line that is given by the equation

$$P_m = 52920 - 4 \cdot (264.20 - \underline{\omega}_m)^2 \qquad W \qquad (2.41)$$

*The value of* $I_m$ (moment of rotational inertia)

This value was unknown, in part because the other driven machine parts have to be included in the calculations. By means of simulation, values of 1 - 16 kg•m$^2$ have been researched. The effect is small at values of $I_m$ > 4 kg•m$^2$. Based on the results of figure 2.4.3.4 and simulation tests a choice for $I_m$ = 6 kg•m$^2$ has been made. At $I_m$ = 4 kg•m$^2$ a certain high-frequency variation of 0.2 rad•s$^{-1}$ still occurs and causes extreme oscillations in some simulation tests. For $I_m$ = 5 oscillations were also registered, but never for $I_m$ = 6.

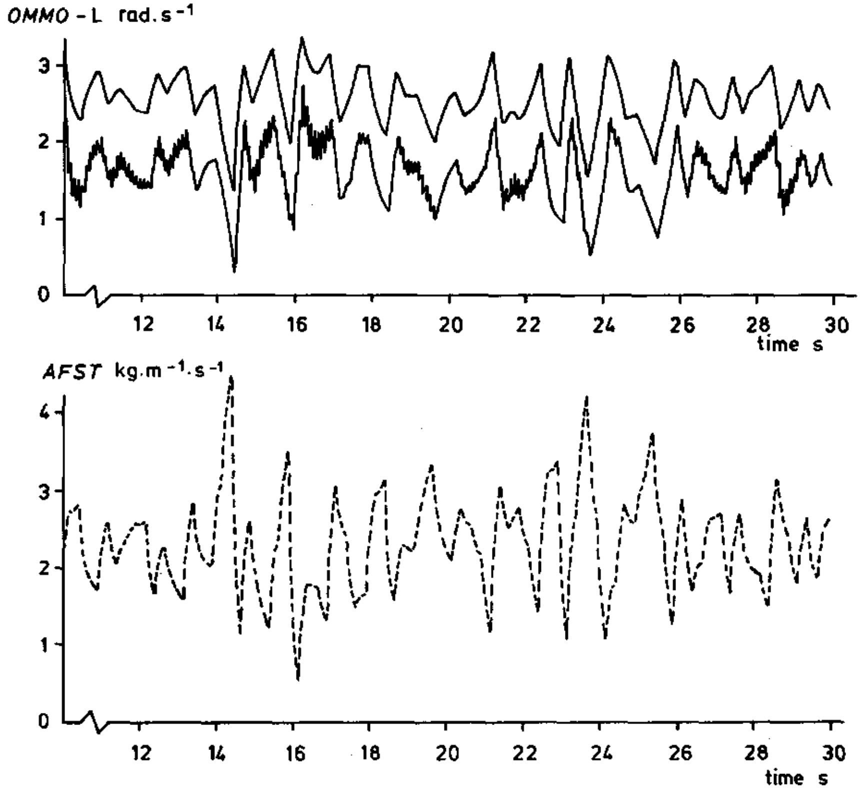



Figure 2.4.3.4. Rotational speed of engine (*OMMO*) as a function of specific straw feed rate at the threshing cylinder (*AFST*) for two different moments of inertia of motor and machine ($I$). Upper line $I$ = 6 kg•m$^2$ ($L$ = 263 rad•s$^{-1}$); lower line $I$ = 4 kg•m$^2$ ($L$ = 264 rad•s$^{-1}$)

*The value of $T_m$*

This value is calculated from $T_{out}$, so that $T_m = 0.365 \cdot T_{in}$ and $T_{in} = RT \cdot T_{out}$

hence $T_m = 0.365 \cdot RT \cdot T_{out}$ (2.42)

while *RT* depends on the control (see below).

Equation (2.39) applies to the calculation of $T_{out}$ but requires the value of $P_{tn}$ for the purpose.

*The value of $P_{tn}$*

During field measurements in 1969 (Oosten, 1970) and laboratory measurements, both with winter wheat, the power consumption was as indicated in figure 2.4.3.5. Through the measurement points of 1969 a regression line has been calculated as

$$P_{tn} = 2691 + 6737 \cdot FS \quad (r = 0.79) \qquad (2.43)$$

Though the tests relate to machine A, they can also be applied on machine B, because the required power is not dependent on the width of the threshing cylinder. Similar feed rates will have the same power demands for threshing with a small as well as a wider threshing cylinder. However, the zero-load power is higher for a wider threshing cylinder (*assume* 10%) so that the relation given below is used

$$P_{tn} = 2960 + 6737 \cdot FST \qquad (2.44)$$

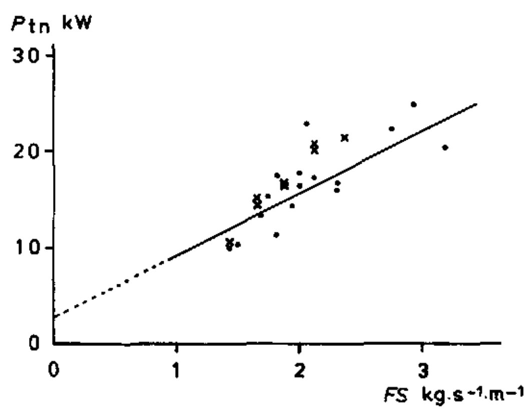



Figure 2.4.3.5. Threshing power ($P_{tn}$) related to straw feed rate for machine A (*FS*)
• = field tests for winter wheat (*MCS* = 10-13%) and fitted line
$P_{tn} = 2.691 + 6.737 \cdot FS$ (r = 0.79) for these tests; × = laboratory tests (*MCS*≈15%)

*The value of $I_t$*

According to the manufacturer this value is 7.85 kg•m$^2$.

*The value of $\underline{\omega}_{out}$*

According to the data given earlier

$$\underline{\omega}_{out} = 0.365 \cdot RT \cdot \underline{\omega}_m \qquad (2.45)$$

*The value of $\underline{\omega}_m$*

This is $\underline{\omega}_m$ as calculated.

*The value of RT*

This value is determined from the position of the variator discs, which are mechanically controlled in existing combine harvesters. When this type of control is replaced by a hydraulic cylinder, then the relation between the position of the variator disc (and also the cylinder position *DV*) and the transfer ratio *RT* (as well as the speed of the threshing cylinder *VT*) will be as indicated in figure 2.4.3.6. The derivation of this can be found in the appendix.

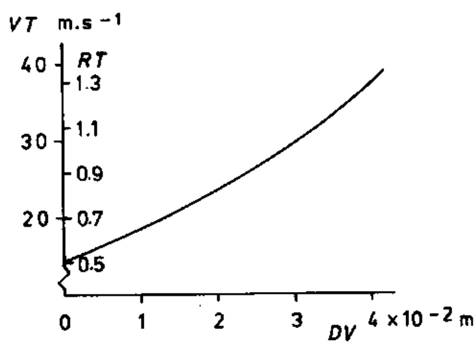



Figure 2.4.3.6. Relation displacement cylinder variator (*DV*) and threshing cylinder speed (*VT*) actuated by the speed ratio of the variator (*RT*)

Since the variator adjustment does not result directly in a change of speed, because of the elasticity and inertness of the V-belt, a transfer of a first-order process in which $\underline{\tau} = 0.3$ s has been used to represent this in the simulation. For this transfer a ratio *RT*, a linear relation likewise, could have been applied, but this idea has been rejected since the working diameter of the variator has to be known in any case to be able to react when the tension in the V-belt gets too high. This can

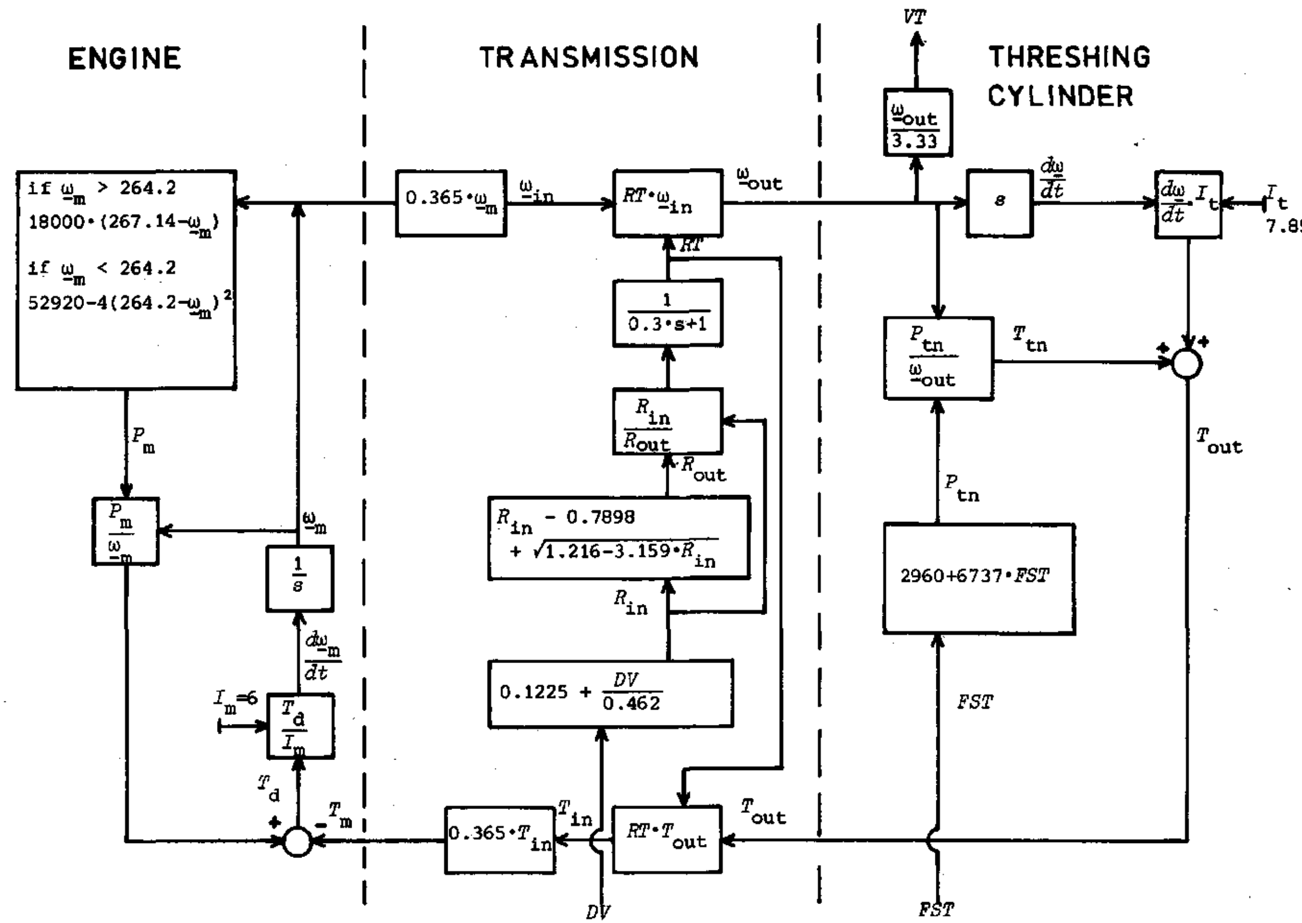



Figure 2.4.3.7. Scheme of motor, variator and threshing cylinder dynamics

happen when the mass inertia of the engine and the threshing cylinder counteract, causing the variator to transfer more power than the engine can generate. In reality this induces slip. It is *assumed* that this will occur when more than 55 kW has to be transferred at a threshing cylinder speed of 80 rad$\cdot$s$^{-1}$. In this case the tension in the V-belt is about 3200 N.

In the model, the slip is simulated by a momentary fixation of *RT* and is achieved by stopping the adjustment in the control. To prevent wear in reality this should also be built into the control. The desired *RT* is adjusted by control of *DV*. Although this is not yet feasible, the simplest way to do this is by means of a hydraulic cylinder with a displacement of 42 mm. This displacement is activated by an I-control as described in chapter 5.

The coherent actions of engine variator and threshing cylinder are shown in figure 2.4.3.7.

# 3. Measuring systems

In the various controls of the present study it is *assumed* that the grain and straw feed rate, the threshing separation efficiency, the walker loss and speeds of machine and threshing cylinder can be reasonably measured. The more accurately the real values of these variables are measured, the better the optimum values of threshing speed and machine speed can be calculated. In chapter 5 this will be explained, but it has to be stated here that, as most control systems are feedback systems in our case, the delay in the measurement of a variable should be as short as possible.

There will be measurement noise. The disturbances, including the signal-noise ratio of the measurements, will be discussed in chapter 4. In this chapter attention will be paid to

- the possibility of carrying out the measurement in practice,
- the accuracy of the measurements and
- the way the measurement devices are modelled.

## 3.1. FEED RATE MEASUREMENT DEVICES

In literature several possibilities are mentioned regarding the way in which parameters related to the feed rate can be measured. In our study some of thém have been researched, too. The possibilities referred to are given below.

*Measurement of crop density in front of the combine harvester*

Since variation of the crop density is one of the biggest disturbances of the process, measurement of it would be really beneficial to control considerations. However, the crop density measurement technology is not yet available.

*The power or forces for the cutter bar drive*

The measurement could be interesting, because it involves no delay to the entrance of the crop into the machine. It was expected that the greater the crop presented to the cutter bar, the more stems would have to be cut, and thus the greater the power that would be needed for cutting.

Eimer (1966) has measured the torque required to move the cutter bar and reported on it. In own research (Huisman, 1974) the forces have been measured in the rod in front of the tilting mechanism that drives the cutter bar.

The conclusion reached in both researches was that these signals are unsuitable, as

1) the signal-noise ratio is very low,
2) the influence on the signal of factors not directly related to the feed rate, such as the amount of weeds, wear, greasing and cutting height is just as high as the influence of the straw feed rate on the signal.

*The feed auger*

Depending on the construction of the feed auger in the header, one or other of the feed rate parameters can be measured. It can be the displacement when the feed auger is mounted in such a way that it can move up and down, making the vertical position of the auger dependent on the feed rate. The driving power or torque depends on the feed rate as well. The relationship between feed rate and auger torque is linear when the bearings are not movably fixed to the header. According to Eimer (1966 and 1973) this relation is not linear. Own research (see 3.1.1) has shown that this relation is linear if straw feed rate is higher than 1 $kg \cdot s^{-1}$.

*The straw elevator*

The lower axle of the wheels carrying the elevator chains is movable in the vertical direction. The position of this axle depends on the quantity of straw beneath it. According to Eimer (1966 and 1973) and our own research (see 3.1.2) the relation between displacement and feed rate straw is also linear above a minimum feed rate level of about 1 $kg \cdot s^{-1}$.

The relation between the straw feed rate and the torque for driving the upper elevator shaft has also been measured (Eimer, 1966, 1973; Huisman, 1973). This signal is measured later than the displacement of the elevator or an auger signal. Moreover, correlation with the feed rate is poor, as the measured value originates from friction, depending on the moisture content of the straw. It is therefore unsuitable for measurement of the feed rate.

The layer thickness of the straw under the middle of the elevator has also been measured (Eimer, 1966, 1973). This signal is not linear with feed rate, but depends on the chain tension and is measured later than the displacement of the lower axle, so that it is less attractive than axle displacement to measurement of feed rate.

*Threshing cylinder*

The relation between driving power and the feed rate has been investigated by many researchers (see A 1.2). Though this relation is good, it is not so attractive in a control system, as it is measured later than other, also useful signals referred to earlier.

*Engine power*

Only part of the power required for running the combine harvester (about 50-80%) is related to feed rate, so that in comparison to threshing power, the engine-power signal is less useful still.

In all cases a relation to quantity of straw and not to quantity of grain + straw has been considered. This can be explained by the fact that the measured parameter is related primarily to the volume of the material and not to the mass. The volume, in turn, depends mainly on the quantity of straw, expressed in terms of mass, i.e. dry matter mass.

The most suitable feed rate parameters, auger torque and elevator displacement will be described in detail in the following sections.

### 3.1.1. *Torque of the auger as feed rate sensor*

The straw feed rate and several other feed rate parameters have been measured during the field measurements from 1969 ... 1976. In figure 3.1.1.1 an example has been given of the experimental data of 1970 for the measurements of the auger torque. The results from the other years are given in the appendix.

It is found that the relation between feed rate levels which exceed

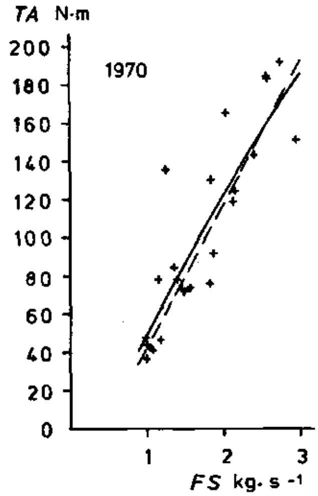



Figure 3.1.1.1. Relation auger torque to straw feed rate of field tests of 30-m stretches with oats (Astor), *MCS* = 38.3-58.7% (----) $TA = -31.5+74.9 \cdot FS$ (r=0.93), (——) $TA = -54.8+102.8 \cdot FS-7.57 \cdot (FS)^2$ (r=0.93)

1 $kg \cdot s^{-1}$ and the auger torque can be accurately approximated by a linear relation. From data of the year 1970 it has been found that a linear and a squared model had similar correlation values, r = 0.93 (see fig. 3.1.1.1) (Huisman, 1974a). This was based on the averages of 24 measurements each covering a stretch of 30 metres. This 30 metre stretch consisted of 5 separate stretches of 6 metres. The linear model provided a correlation value of 0.90 for these 120 values. The linear and the squared model were also equal in 1971 (r = 0.82) (see the figures in the appendix). The models and correlations are stated with the figures.

There are only slight differences between the various years and crops. Only the results of 1972 are extraordinary, probably because of a damaged (i.e, curved) auger. The scatter of points is not only a result of measurement errors, but also of the influence of the moisture content and ripeness of the straw which varied widely during the tests. The scatter is much less when the measurements apply to almost the same crop which can be achieved with short intervals between the individual tests, as in 1976.

A variation of the slope does not give rise to problems in practice. This is because the feed rate signal is used in a loss control at which the relation between the feed rate signal and loss has to be estimated in any case, and where it is not important what the transfer ratios are.

The relation will not be linear at feed rates below 1 kg•s$^{-1}$ and will tend to zero because zero load value is already subtracted in the given data.

When the auger torque is used as a feed rate parameter this can cause problems in the case of crops with little a straw. In such cases the auger has to be differently adjusted,so that a shorter distance to the bottom is realised.

When the signal is studied as to its dynamic aspects, it can be deduced from the power density spectrum of the torque signal measured by strain gauges on the shaft, that peaks occur at 50, 100, 150 and 200 rad•s$^{-1}$ (see figure 3.1.1.2). These are the frequencies and the higher harmonics coherent with the rotational speed of the auger and with the penetration into the straw by the pins in the centre of the auger. These pins are in 4 rows at 90$^{\circ}$ to one another.

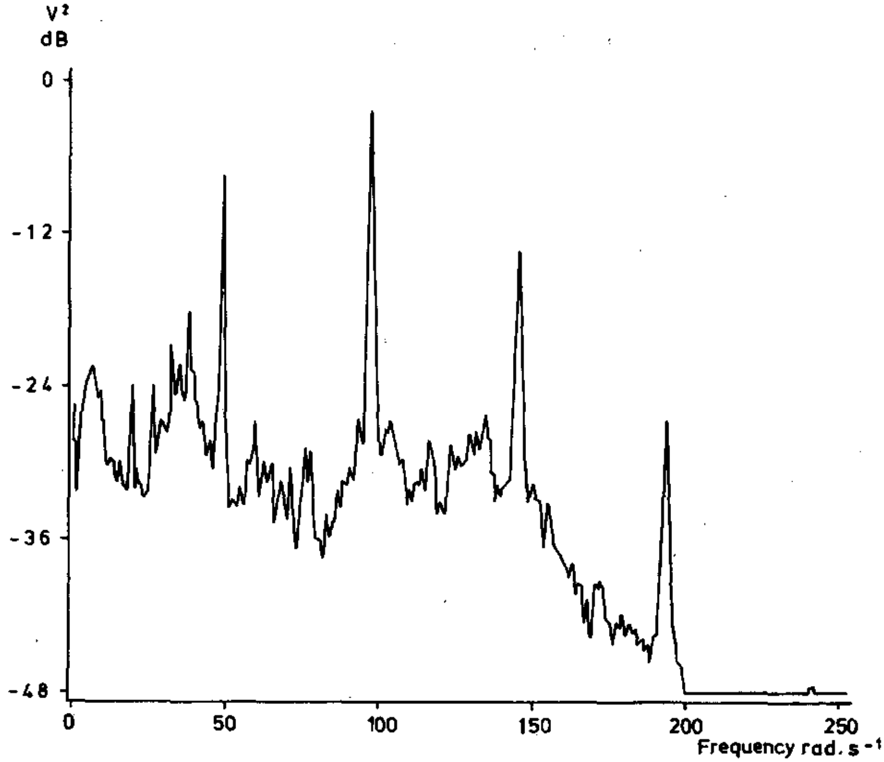



Figure 3.1.1.2. Power spectrum of the signal of the auger torque measured by strain gauges at the driving shaft

From this it can be concluded that a large part of the required torque can be explained by the penetration of the pins into the crop. Therefore the movement of the straw mass along the auger pins and between the tops of the pins and the bottom sheet will exert a torque on the shaft.

In addition the movement of crop in front of and under the auger windings will also require power, though to a lesser extent, as the quantity of crop is smaller (except in the event of jamming). Apart from these peaks, the power spectrum gives the impression of typical first-order noise, with some extra power in the lower frequencies.

It is not possible to be traced whether there is any relation between the torque and the feed rate for frequencies above about 0.3 $rad \cdot s^{-1}$, because the shortest stretch in which the crop has been collected and weighed is 5 metres. At a driving speed of 1 $m \cdot s^{-1}$ this represents a period of 5 seconds, resulting in a first-order low-pass filter action with a breakpoint frequency of $2\pi/(4 \cdot 5)=0.31$ $rad \cdot s^{-1}$. It was *assumed* that the same relationship holds for frequencies above 0.3 $rad \cdot s^{-1}$. For the machine speed control this assumption is without risk, as the feed rate signal used as input for the control, passes a low-pass filter with a bandwidth of 0.4 $rad \cdot s^{-1}$. Higher frequencies are still important for the threshing speed control.

To deal with the uncertainty of this assumption, noise was added to the calculated torque as measurement noise in the simulations. The introduction of noise into the measurements is also essential at the lower frequencies, as we must conclude from the scatter of the experimental data given in the figures that there can be considerable variation in the measured signal for the same straw feed rate. Without noise the control system would not work realistic in the simulation.

In the model, the measurement of the feed rate by the auger torque is represented by a linear equation.

- When the apparent straw density was calculated out of auger torque measurements on machine A, the equation

$$FS = 0.42 + 0.0193 \cdot TA \qquad (3.1)$$

  was used. This relation is the continuous line in fig. 3.1.1.3.
- When the same was done for machine B, the relations drawn in fig. 3.1.1.4 were used.

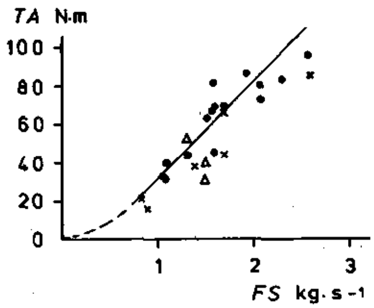



Figure 3.1.1.3. Relation auger torque to straw feed rate in field tests of 15-m stretches at machine A of the IJ.D.A. in 1975. × = wheat, ● = oats, Δ = barley ($MCS$ = 12.5–49.4%)
—— calculated relation:
$FS = 0.42 + 0.0193 \cdot TA$ (r=0.89)
---- probable extrapolation

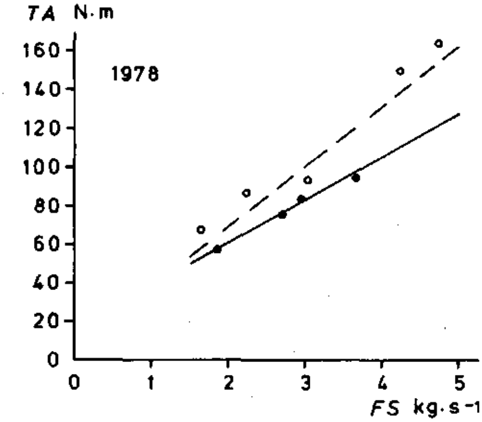



Figure 3.1.1.4. Relation auger torque - straw feed rate in field tests of 15-m stretches in 1978 at machine B of IJ.D.A. with winter wheat: nautica (●); $TA = 16.2 + 22.0 \cdot FS$ and anouska (o), $TA = 8.1 + 30.6 \cdot FS$

- In the simulation model, measurement of feed rate in the control requires the addition of noise to the calculated feed rate. So

$$FSM = FSA + \text{noise} \qquad (3.2)$$

The dimension of $FSM$ remains as $kg \cdot s^{-1}$. The noise is white noise created by a random generator of CSMP and varies around $0 \pm 0.2 \cdot FS$ average and is then coloured by passing a high-pass filter with a breakpoint frequency of 0.1 $rad \cdot s^{-1}$.

### 3.1.2. *Straw elevator displacement*

The mass transportated by the elevator is roughly the same as presented at the pins of the auger, there is no redistribution. The relation elevator displacement to feed rate is as given in figure 3.1.2.1. It shows that the signal has an upper boundary, since the displacement is mechanically limited at about 55 mm. Moreover, a certain feed rate of 1 $kg \cdot s^{-1}$ is necessary before displacement occurs.

The measurement points obtained are shown and the calculated regression lines drawn in figure 3.1.2.2 and in the appendix. The presented values

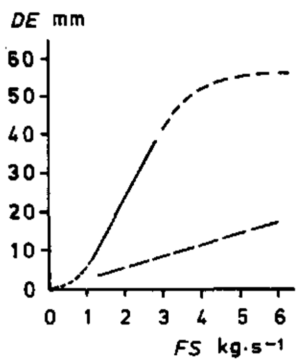



Figure 3.1.2.1. Relation elevator displacement to straw feed rate
—— for measurements in 1969...1973
----- probable extrapolation
— — measurements in 1974

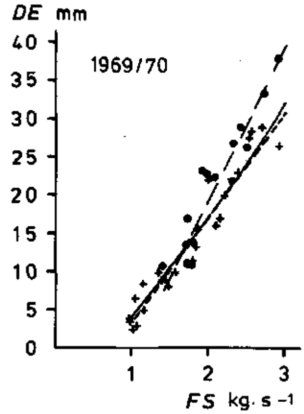



Figure 3.1.2.2. Relation elevator displacement to straw feed rate in field tests of 30-m stretches with winter wheat, Manella (o) in 1969, *MCS* = 10.3-13.6%, (— —): $DE = -20.8+19.9 \cdot FS$ (r=0.94) and with oats (+) under conditions given in figure 3.1.1.1, (------): $DE = -10.3+13.7 \cdot FS$ (r=0.96) an (——): $DE = -8.14+11.1 \cdot FS + 0.753 \cdot (FS)^2$ (r=0.96)

of the elevator position (*DE*) give the distances above the lowest position of the axle. There is already a small gap (± 2 mm) then between the elevator chains and the bottom of the elevator housing.

The results obtained in the years 1969-1973 show that the curves were about the same in these years and the measurement values 40 mm maximum. In 1974 the values were much lower at higher feed rates. Presumably the spring tension was adjusted higher. An other possible reason is that the crop properties differed, because it was found that the measured auger torques were also low in that season (see A 3.1.2).

This shows that the relation is comparable with the torque of the auger (above zero load) and is certainly so when only the higher feed rates are considered. Furthermore, there is no difference in correlation between linear and exponential regression lines.

Consequently the upper boundary was not reached at very high feed rates. Were this to happen, it could be corrected by increasing the tension of the elevator chain springs.

It is clear that no relevant feed rate signal can be measured at very low feed rate levels. This difficulty can be met by an altered chain

construction and possibly using weaker springs, but it remains a disadvantage.
The dynamic behaviour of the elevator displacement will differ from that of auger torque, for the following reasons:
- the elevator chain has a high mass,
- the elevator chain encounters a Coulomb friction and spring force when it is moving,
- the straw has elasticity.

The transfer of the elevator displacement is simplified by a first-order process with $\underline{\tau}$ = 0.3 s. This value has been chosen on the basis of visual comparisons of the measured and simulated signal plots. Figure 3.1.2.3 shows recorded signals of auger torque and elevator displacement in the same field test (Klein Hesselink, 1971). Figure 3.1.2.4 shows simulated signals of feed rates calculated on the basis of apparent straw density input (1978). The *DE* line has been shifted upwards in the plot by 2 $kg \cdot s^{-1}$.

In the simulation the elevator displacement can be used as a control input to represent feed rate measurement. In that case it is the calculated *FSE* value that has passed the first-order process, after which noise is added as was done in the model of the auger torque measurement. So that:

$$FSEM = FSE \cdot \left(\frac{1}{1+0.3 \cdot s}\right) + \text{NOISE} \qquad (3.3)$$

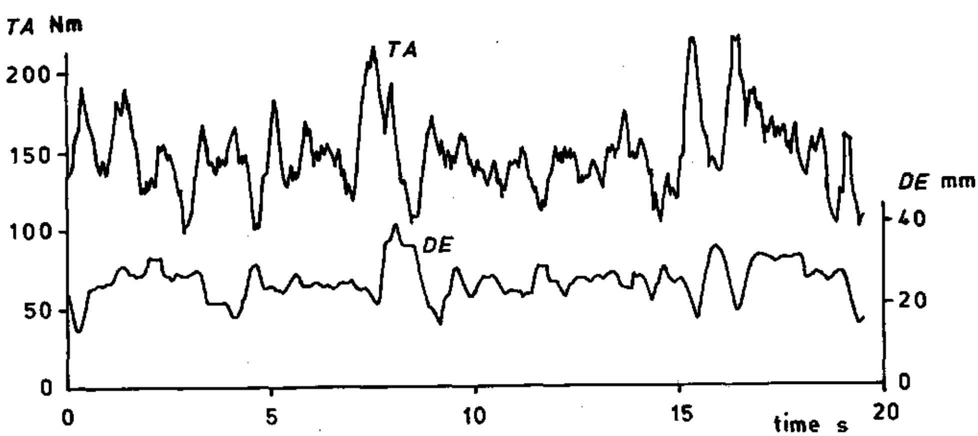



Figure 3.1.2.3. Signals of auger torque and displacement elevator for the same period of time in oats (1970)

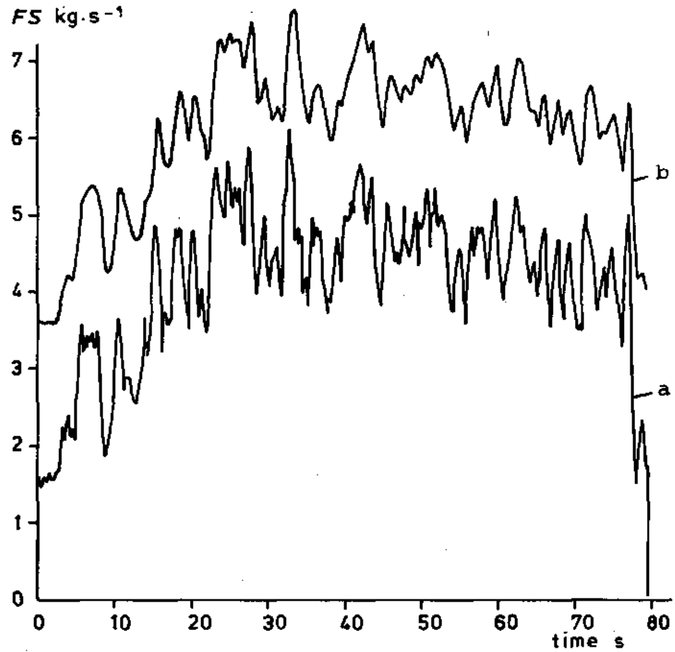



Figure 3.1.2.4. Signals of auger torque input (a) and calculated output through first-order process with $\tau$ = 0.3 (b) ( curve b was shifted 2 $kg \cdot s^{-1}$ upwards)

### 3.1.3. *Auger torque - elevator displacement relationship*

The results of two years of field tests have been studied in comparing the two feed rate signals. In 1970 (Klein Hesselink, 1971) the linear correlation was calculated between all variables mentioned in table 3.1.3.1. The data in the calculation were the average values of stretches of 5 m, in all 120 measurements in oats.

Table 3.1.3.1. Values of linear correlation coëfficients of the feed rate signals *DE* and *TA*

| | Straw feed rate | *DE* |
|---|---|---|
| Signal of elevator displacement: *DE* | 0.95 | - |
| Signal of auger torque : *TA* | 0.94 | 0.97 |

From table 3.1.3.1 it can be concluded that the correlation between both signals is of the same order or even a little higher than that between the signals and feed rate.

It can thus be concluded that the measurement faults in straw feed rate measurement are possibly greater than in the measurements carried out at the elevator and the auger. Another reason can be the redistribution of straw on the walkers.

From the 1973 wheat data (Teunissen, 1979) the correlation between both signals was established for values averaged for various periods (*AP*). The time lag between the two signals, established by cross correlations, was applied.

An increase in *AP* gives an increase in correlation coëfficient until it remains constant at values above 2 seconds (see A 3.1.3). For *AP* = 2 s, data of 14 tests, 204 s in duration, were correlated. Table 3.1.3.2 gives a summary of the results.

Table 3.1.3.2. Correlation coefficients (r) for the studied relations between displacement straw elevator (*DE*) and auger torque (*TA*)

| | r | | |
|---|---|---|---|
| | minimum | maximum | average |
| Linear relation<br>$DE = a + b \cdot TA$ | 0.53 | 0.93 | 0.80 |
| exponentional relation<br>$\ln(DE) = a + b \cdot TA$ | 0.51 | 0.93 | 0.78 |

From the above-mentioned results the following can be concluded: The relation between both signals is clearly present and improves for higher *AP* values. It shows that both signals have their specific properties and consequently show deviations from the real feed rate, which is especially noticeable in the higher frequencies.

When the auger torque and the displacement of the elevator chain for tests in wheat and oats over a period of 5 years are compared to one another as a measuring signal for the feed rate, then the following results are obtained:

*Coherence with the feed rate.* When the correlation coëfficient of linear models are compared to one another, the results shown in table 3.1.3.3 are obtained.

Table 3.1.3.3. Correlation coefficients between feed rate (*FS*) and feed rate measuring parameters: auger torque (*TA*) and elevator displacement (*DE*)
ww = winter wheat
wwe = winter wheat at early ripeness stage
wwl = winter wheat at late ripeness stage
sw = spring wheat

| Year | | 1970 | 1971 | 1972 | | 1973 | | 1974 | |
|---|---|---|---|---|---|---|---|---|---|
| Crop | | oats | ww | ww | sw | wwe | wwl | ww | sw |
| Correlation | *TA* | 0.93 | 0.82 | 0.79 | 0.86 | 0.98 | 0.98 | 0.98 | 0.93 |
| Coëfficient | *DE* | 0.96 | 0.78 | 0.73 | 0.86 | 0.99 | 0.98 | 0.94 | 0.94 |

The differences are minimal and not relevant to a qualitative statement. Also, they have the same dependence on differences in crop properties (see the figures in A 3.1.3).

*Measurement delay.* Depending on the place at the auger where the forces for transport of the straw are caused, the signal of the displacement of the elevator chain is measured 0.3-0.6 seconds later than auger torque. If it were possible to control high-frequency variations in feed rate, it might be important to use the feed rate measurement with the minimum delay.

*Technical possibilities for measurements.* The position of the lower axle of the elevator chain can be easily measured mechanically and transformed into an analog or digital signal. The measurement of the auger torque is more difficult and more expensive, but still feasible.

*Conclusion*: There is a preference for the application of the auger torque as a feed rate measurement parameter, because the time delay is less and there is no difference in quality between the measurement systems. The difference in total harvest costs due to the delay will be established by simulations.

## 3.2. MEASUREMENT OF GRAIN FEED RATE

Knowledge of the grain feed rate is essential when the processes in the combine harvester are to be examined. When walker loss measurement is done with the help of acoustic sensors (see 3.3.2) the calculated output has to be converted into the unit $kg \cdot s^{-1}$. When the concave separation is measured in this way (see 3.4) the threshing separation efficiency has to be calculated as a fraction.

Measurement of a grain flow is possible in terms of weight and volume. Both systems are at present being developed.

The system based on weight is merchandised as a "Discharge Meter" that can be attached to the discharge auger of a combine harvester. In trials, the responses of the meter in the case of wheat were scattered with a coefficient of variation of 4.6% and barley with 6.4% (Hooper, 1979).

Schueller (1982) reports on tests with a simular grain-flow meter mounted under the discharge auger in the grain tank. The performance was found to be poorer at lower feed rates. The reading was inaccurate when harvesting soy beans with a heavy concentration of wet weeds. Apparently the system has to be adapted to lower feed rates and to use in practice.

Volume measurement is easier, but needs a calibration to weight. This can easily be done by the operator and the result can be put into the microprocessor on the machine. No test results are known.

The model of the grain feed rate measurement for the simulation is based on the following reasoning. The grain flow is *assumed* to be measured when the grain leaves the conveyer at the bottom of the grain pan under the sieves. It takes *roughly* 5 seconds from the time of separation at the threshing cylinder and rotary separator to reach the conveyer through the sieves. A small part of the grain is separated from the straw at the walkers and reaches the conveyer at least another 5 seconds later.

In the simulation model, the grain feed rate is *assumed* to be known, for the purposes of the calculation of the threshing separation efficiency *TSE*, needed as input in one of the controls (see 3.4). The value of *TSE* is only known after a delay of 9 seconds. The measurement faults are introduced into the model as noise and added to the calculated threshing separation efficiency.

## 3.3. MEASUREMENT OF WALKER LOSS

The walker loss is the main loss occurring with combine harvesters in Western Europe, because of its exponential character. It is an input variable in all control systems considered in this study. It is an important cost factor, not only because of its own financial value, but also because it affects the speed of the combine harvester set by the cost minimisation output of the control. Therefore it is very important to measure the loss accurately.

The loss unit in the cost criterion ($VWL$) is $fl \cdot ha^{-1}$, while in the real process it is $kg \cdot s^{-1}$ ($WL$). The transfer from the second to the first is easily obtained by multiplication by the value of the grain in $fl \cdot kg^{-1}$ ($V_2$) and division by the area harvested per time unit ($VW$) $m^2 \cdot s^{-1}$ or better ($VW/10000$) $ha \cdot s^{-1}$

$$VWL = WL \cdot V_2 \cdot 10000/VW \quad fl \cdot ha^{-1} \tag{3.4}$$

This is also the most interesting information for the farmer, so knowledge of $VW(= VM \cdot CL)$ is necessary for the calculation of loss.

The loss fraction of total grain feed rate or of grain feed rate to the walkers is more instructive when the quality of the process is observed. In this case the grain feed rate has to be known also. The way loss measurements are done nowadays will be discussed in 3.3.1. As we shall see, this method is inaccurate, hence a suggestion for a better principle has been introduced in 3.3.2.

### 3.3.1. *Grain-loss monitor*

Nowadays so-called grain-loss monitors based on the principle of acoustic sensors, can be bought for use on combine harvesters. The principle was introduced by Feiffer (1967) and Reed (1968) and consists of a sounding-board with microphone, attached to an extension at the end of the walkers (or sieves) and some electronic devices.

Seeds and bits of straw will drop on the sounding board and generate an output signal that will be processed, so that grain impacts are discriminated from noise and other material striking the sounding-board. Grain impacts are converted into uniform square-wave pulses that can be converted into an analog voltage, made visible on a meter.

The sounding-boards vary in design. The electronics can discriminate the different kinds of seeds from straw. Some systems take the machine speed into consideration in converting the meter output in losses per area. The meter output has to be calibrated to real losses, because the ratio of seeds striking the sounding-board to total losses has to be established.

The relation of measured loss to real loss is fairly good and linear under nearly constant harvest conditions. Pulse saturation occurs when more and more seeds fall on the boards at nearly the same time. In figure 3.3.1.1 results of field tests done in 1974 are shown. This figure shows the pattern just described.

However, when the harvest conditions change considerably, as was the case in the field tests of 1971, the results are like those shown in figure 3.3.1.2. This result is found because the ratio between seeds falling on the acoustic sensor and the real loss changes during the day or season as described below.

When walker separation decreases, losses increase and the fraction separated above the sounding board decreases as well, with the result that meter output increases less than the real losses do. An output of about 5 pulses per second in figure 3.3.1.2 can sometimes indicate a loss of 0.05 $kg \cdot s^{-1}$ and 0.20 $kg \cdot s^{-1}$ at others. This can be regarded as 0.1 $kg \cdot s^{-1} \pm 100\%$.

More results are given in the appendix and lead to the same conclusion as can be drawn when all literature on this subject is studied. The meter output gives no indication of real loss when calibration for various conditions is omitted.

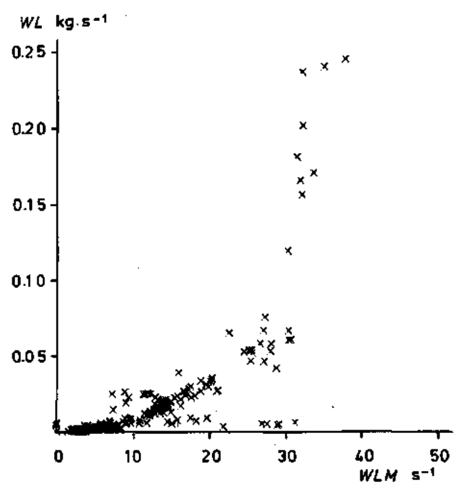



Figure 3.3.1.1. Relation walker loss measured by grain loss monitor (*WLM*) to loss measured by means of loss measuring machine (*WL*) over stretches of 30 m in field tests of 1974

behind the point where the correct exponential separation starts ($kg \cdot s^{-1}$),

$G_o$ = quantity of grain in the straw at $x = 0$ ($kg \cdot s^{-1}$), and

$WE$ = walker efficiency $m^{-1}$.

The grain separation at $x$, ($S_w$) is then the derivate to $x$ of $G_w$, so that

$$d(G_w)/dx = S_w = - WE \cdot G_o \exp(- WE \cdot x) \qquad (3.6)$$

According to Glaser (1976) who worked this out for a shaking grain separation conveyer instead of walkers, the walker loss $G_w$ for $x = \ell$ = end of walkers, can be calculated from (3.5) when $WE$ and $G_o$ are estimated by measurements of the grain separation $S_w$ for two different values of $x$.

We *assume* that this principle, shown in figure 3.3.2.1, also will work for straw walkers. The grain separation can be measured by monitors at various points under the walkers as described in the previous chapter. With these monitor signals the walker loss can be calculated as explained below.

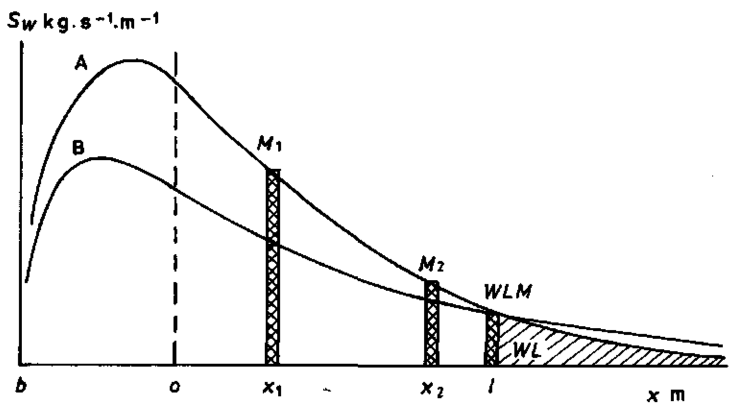



Figure 3.3.2.1. Walker separation ($S_w$) as a function of the distance from the front (b) of the walkers ($x$) for two (A and B) different crop property situations. $M1$ and $M2$ = separation measured by monitors at $x_1$ and $x_2$. $WLM$ = separation measured at the end of the walkers ($\ell$) o = the place where the theoretically correct exponential separation starts late

Two possible separation curves A and B are shown in figure 3.3.2.1. The separation process becomes correctly exponential at *0* after a starting process from *b* to *0*. The end of the walkers is at $\ell$, so that the hatched area at the right side of $\ell$ represents the walker loss. The losses can be calculated by using two monitor outputs from well chosen places under the walkers for instance $x_1$ and $x_2$. In A 3.3.2 the formulas and results

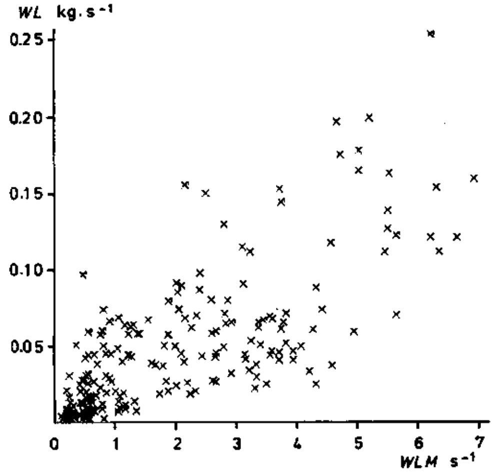



Figure 3.3.1.2. Relation walker loss measured by grain loss monitor (*WLM*) to walker loss measured by rethreshing the straw, gathered on sheets of 6 m in field tests of 1971 (*WL*)

Calibration is omitted in general practice or not applied frequently enough, because it is not simple and needs either a second man to do it, or includes machine stops. Farmers use the system to check for sudden changes in losses, but they do not refer the meter output to real losses in terms of $kg \cdot ha^{-1}$ (Dongen, 1981a).

The conclusion to be drawn from these results is that such monitors cannot be used for automatic control. They can only be used for manual control if calibrated at least every hour, especially when harvest conditions change.

### 3.3.2. *Principle of an improved loss monitor system*

A mathematical model of grain separation at straw walkers was worked out in 2.3.4 and A 2.3.4-b. In this model an assumption was made about the constancy of separation efficiency behind the curtain. The separation, as a function of distance from the curtain decreases exponentially in a way that can be derived from the model, so that

$$G_w = G_o \exp(- WE \cdot x) \qquad (3.5)$$

Note that

$G_w$ = quantity of grain in the straw passing over the walkers at $x$ m of some laboratory tests are given. These tests show that the estimation of loss is much better than with just one monitor at the end of the walkers. Field tests will have to show the practical use, so that further research is necessary.

Some remarks on this measuring technique are be made below.

1) The time delay between the output of the two monitors has to be taken into consideration.
2) A redistribution of grain in the area between the two monitors will give rise to measuring errors.
3) The measuring signals show much measuring noise, so a long averaging period will be necessary for loss calculation.
4) The dimensions of the monitors have to be chosen so that no pulse saturation will occur.
5) The monitors need to be calibrated often to check their proper functioning, but also to obtain information on the transfer from monitor output (pulses per second) to $kg \cdot s^{-1}$. Both actions could be done by calculation of the total separation through the walkers from *0* to $\ell$ as well as from *b* to *0* and through the concave grates of threshing cylinder and rotary separator by additional monitors and comparing the calculated separation in the unit pulses per second to a measured grain flow in $kg \cdot s^{-1}$ to obtain the ratio. It will be clear that a microprocessor is needed for these calculations.
6) Having a number of monitors in the combine harvester offers the possibility of supervising the processes in the machine. This will be an important advantage of this complex measuring technique.

To avoid misunderstanding it has to be explained that the use of one monitor for loss measurement is principally different from the use of two or more monitors.

If a monitor, connected at the end of the walker, measures the grain separation *WLM*, indicated by the cross-hatched column at $\ell$ in figure 3.3.2.1 the walker loss is not uniquely defined. For instance, if we consider curves A and B, the loss is represented by a different surface below the curve at the right-hand side of $\ell$, but both curves show the same separation *WLM* at $\ell$.

If two monitors are used, for instance at $x_1$ and $\ell$ curve A is defined by $M_1$ and *WLM* and the assumption of exponential separation. If the separation is also measured ($M_2$) at a third point the assumption can be verified and corrected.

The model of the measurement of walker loss for the simulation is easily represented by the value of the walker loss calculated in the process model. In this case also coloured noise is added in same way as in the measurement of feed rate.

## 3.4. MEASUREMENT OF THRESHING SEPARATION EFFICIENCY

In one of the control systems studied the threshing separation efficiency will be used as an input variable. As threshing separation efficiency cannot be measured by any known system the intention is to put one forward in the following paragraphs.

The measurement system can be based upon measurement of concave separation by acoustic sensors, mentioned in paragraph 3.3. The sensors have to be very small to avoid pulse saturation. The design of the electronic device can perhaps be adapted to the large amount of kernels passing the concave.

Several sounding-board sensors have to be placed under the concave. The separation pattern is nonlinear so that at least three sensors, situated in the direction of rotation, are required for a good estimate.

A check of the concave adjustment is possible too then, as the correct adjustment has to show a pattern of decreasing separation towards the end of the concave. More sensors are also required in the transverse direction for good estimation of total concave separation.

From preliminary laboratory tests it was concluded that such a measurement system could estimate the separation satisfactorily. It has also become clear that a microprocessor will be needed to perform the calculations and calibrations to the unit $kg \cdot s^{-1}$. More research will be needed.

The threshing separation efficiency, the ratio of concave separation to total grain feed rate, can only be calculated if both values are known in the same unit. If the rotary separator and walker separation and walker loss are also estimated by the use of acoustic sensors (see 3.3) the total separation can be calculated, too. The walker separation and walker loss can only be calculated after a delay of about 8.0 s and some time for averaging.

In the simulation model, the value of the threshing separation efficiency is taken from the threshing model but delayed by 9.0 s. The expected measurement errors are brought into the model by adding noise from a white noise generator passing a high-pass filter with adjustable breakpoint frequency. The noise default level is maximal $\pm$ 3% around 0.

## 3.5. MEASUREMENT OF SPEEDS

All the control systems studied need correct information on the actual speeds of the threshing cylinder and the machine.

The speed of the threshing cylinder can be measured very simply and accurately by all kinds of rotational speed sensors available commercially. No special attention is therefore paid to this subject in the model. It has been *assumed* that the measurement is done accurately.

The speed of the machine can be measured from the rotational speed of the wheels. The driving wheels, however, will be subject to slip, depending on the soil properties and the weight of the machine. As this weight is influenced by the amount of grain in the tank, the slip will vary. The measuring error will thus vary roughly from 1% to 5%.

Measuring the rotational speed of the steering wheels at the end of the machine will give rise to a smaller error due to slip but also to an extra error depending on steering activity. The expected total error is estimated to be 1%.

The measurement of speed can be done more accurately but more expensively by ultrasonic reflection. No special features were therefore introduced in the model.

In the optimisation criterion it is in fact the product of machine speed and cutting width which is used, so that the cutting width has to be known, too. The cutting width is generally constant, but in special circumstances the operator does not use the full width or does not steer accurately, so that the width will vary. It could be significant therefore to develop a system to measure the actual width of the cutter bar when a control system needs that information.

In our model it was *assumed* that the cutting width is always constant.

# 4. Disturbances

## 4.1. INTRODUCTION

In control systems design, study of the way in which process disturbances occur is necessary. The disturbances are one of the most common reasons why a controlled variable tends to deviate from its desired value and why feedback control is required. The disturbances in the processes of the combine harvester are mostly due to the natural variation in crop properties caused by growing and weather conditions. These conditions change as a function of place and time.

As combine harvesting is done with a locomotory machine taking crop from a certain area at a certain speed, the place variations also become time variations. The control system has to react to these variations.

Other disturbances are due to the measurement systems of the control. These disturbances are inevitable and the control system will react to them, so that account of this fact has to be taken when we develop a control.

Knowledge of the disturbances in the process of combine harvesting is necessary as

1) it is possible to develop an opinion about what can be expected from control.
2) The design of the control system is affected by the disturbances.
3) A realistic situation, including all important disturbances has to be considered for calculating the benefits of controls.

In some cases the disturbances themselves can be measured but in most cases it is only the results, the outputs of processes that can be measured. The disturbances of the process being considered are those affecting losses: straw density on the field, and process variables at threshing and separation.

The disturbances on the measured signals considered are feed rate, concave separation and walker loss. It is important to realize in advance that it is not only the high-frequency disturbances that have to be considered, but that the very-low-frequency disturbances, in fact, the mean level variations are of great importance, too. The following chapters will also discuss the way in which the disturbances are modelled for the simulations.

## 4.2. DISTURBANCES IN FEED RATE

As was stated in the previous chapters, the feed rate of straw ($kg \cdot s^{-1}$) or grain is obtained by multiplication of the momentary speed of the machine ($m \cdot s^{-1}$), the cutting width (m) and the yield of the straw or grain on the field in $kg \cdot m^{-2}$, the so-called straw or grain density.

When the speed of the machine and the cutting width are held steady, the density variation and the redistribution on the cutting table gives the feed rate variation.

The density of the straw and grain on the field has been investigated by many authors (see A 4.2.1a). They report on the variation in weight of straw and grain of fields of 0.5 $m^2$ up to 150 $m^2$ in area.

From these studies it can be concluded that the variation in straw yield, expressed in terms of coefficient of variation on fields with an uniform crop growth, shows figures between 5 and 30%. There is no evidence for concluding that these figures depend on the size of the area considered. For the grain yield the same conclusion can be drawn.

The quotient of the grain yield and the straw yield, the grain-straw ratio, however, gives a coefficient of variation that is about half the straw-density variation. This is because the grain production has a direct relation to the straw production. (In the simulation of the combine harvester process the feed rate grain is therefore directly calculated from the product of the feed rate straw and grain straw ratio.)

Figure 4.2.1 shows the variation in yield of successive 5-m-wide plots (the width of the cutter bar of a normal combine harvester) and 1.5-m-long, in fact the straw density offered to the combine harvester. The test was done in a drained field, so that the difference between fig. a, working direction perpendicular to that of the drainage, and fig. b parallel to the drainage, can be clearly seen.

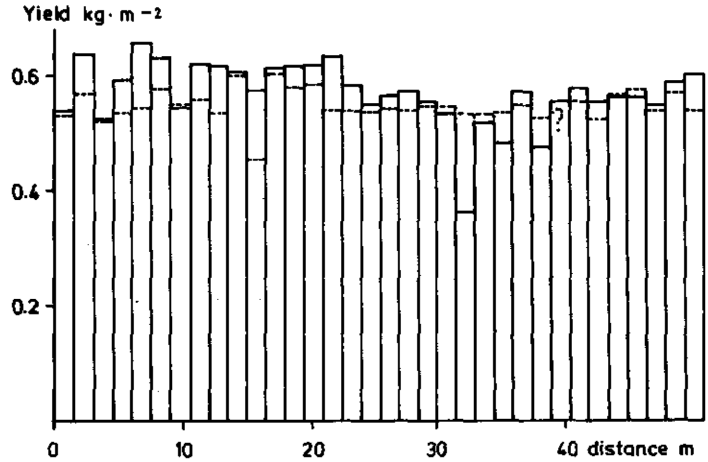



Figure 4.2.1.a. Yield of winter wheat of plots, 5-m-wide and 1.5-m-long, harvested in the direction, perpendicular to that of the drainage.

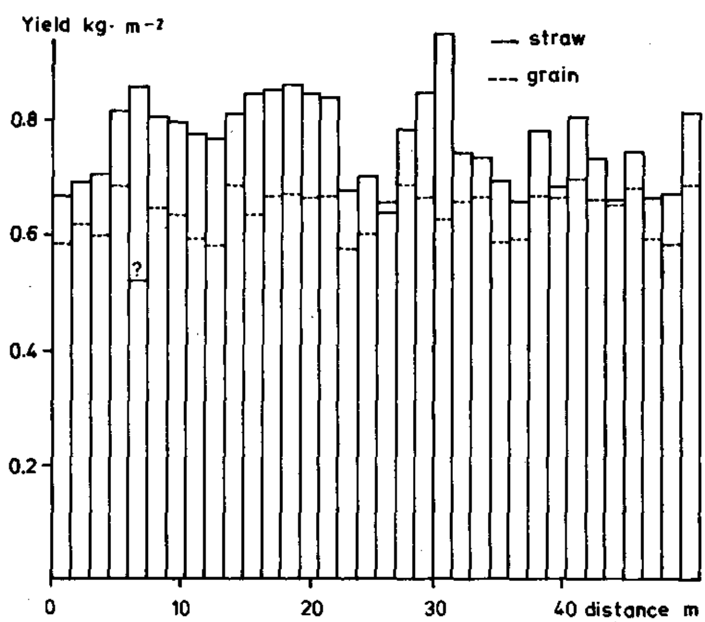



Figure 4.2.1.b. Same as fig.a,but direction parallel to the drainage.

When we consider areas larger than 150 $m^2$ we can compare the yields of different fields in various years so as to get an impression of the long-term variation in yield.

From agricultural practice and research it is known that this variation is considerable, too. For instance, in practice, at the IJsselmeerpolders Development Authority Grain Farm the coefficient of variation in grain yield of 19 fields of 30 ha (!) was calculated. In the year 1978 it was found to be 19.6% at a mean yield of 6280 $kg \cdot ha^{-1}$.

When we consider a combine harvester moving at a constant machine speed and constant cutting width along these fields, the crop density variation generates a feed rate variation as a function of time. The character of this variation will be taken to be white noise in the frequency band of 0 to 1 $rad \cdot s^{-1}$ with extra variation at 0 to be due to sudden steps in the mean level. This can be explained as follows. The coefficient of variation, as mentioned earlier, is defined (Cool, 1979) as $CV = \underline{\sigma}_x/\underline{\mu}_x$. Defined in discrete time the variance is

$$\underline{\sigma}^2_{x,d} = \sum_{i=1}^{n} (x_i - \underline{\mu}_x)^2/(n-1) \qquad (4.1)$$

and defined in continuous time it is

$$\underline{\sigma}^2_{x,c} = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} (x(t) - \underline{\mu}_x)^2 \, dt \qquad (4.2)$$

If we want to transform the discrete variance of straw density into the continuous variance of feed rate it can be done by assuming a constant machine speed and cutting width. Let us take the cutting width as 5 m and a realistic average machine speed of 1 $m \cdot s^{-1}$ so that straw density variations of 7.5 $m^2$ plots, for instance from fig. 4.2.1, become feed rate variations per averaged 1.5 s. In this case the variations within the 1.5 s are unknown, hence information on frequencies above $2\pi/4 \cdot 1.5 \approx 1.0$ $rad \cdot s^{-1}$ is lost because averaging acts as a first-order low-pass filter with that breakpoint frequency (Verbruggen, 1977). For a length of 5 m this is roughly 0.3 $rad \cdot s^{-1}$.

The variance is also affected by the total area taken into consideration at the field tests. If at these field tests, yields are measured which are comparable with, let us say, 200 m traversed distance of the combine harvester, only information was available on the mean level $\underline{\mu}_x$ for a period of 200 s. This means that frequencies smaller than about $2\pi/200 \approx 0.03$ $rad \cdot s^{-1}$

could not influence the value of $\underline{\sigma}_x$. When an impression of the power spectrum of the feed rate variations is to be obtained from the value of $\underline{\sigma}_{x,d}$ we can use the definition

$$\underline{\sigma}_{x,d} \approx \underline{\sigma}^2{}_{x,c} = \frac{1}{\pi} \int_0^{\infty} S_x(\underline{\omega})\ d\underline{\omega}$$

in which

$$S_x(\underline{\omega}) = \lim_{\Delta\underline{\omega}\to 0} \pi \cdot \frac{\underline{\sigma}^2{}_{x,c}(\underline{\omega}, \Delta\underline{\omega})}{\Delta\underline{\omega}} \tag{4.3}$$

is the power for a given frequency band. In our example, however, the integral has to be calculated for a smaller band, e.g.

$$\underline{\sigma}_{x,d} = \frac{1}{\pi} \int_{0.03}^{1} S_x(\underline{\omega})\, d\underline{\omega}$$

The various coefficients of variation mentioned in literature and calculated in our research, concern values of greatly differing situations, making it difficult to translate these figures into power spectra. There are, however, no special reasons to expect more power in special frequency bands, except in situations where a systematic variation due, for instance, to drainage or a repeating soil variation occurs.

Close to zero there has to be much variation due to the mean level variations that occur every time the combine harvester starts in an other field, with another crop or variety or under other soil fertility conditions. Continued research is desirable, but for our purpose the conclusion as stated earlier will suffice.

The signals of the measured auger torque representing the feed rate signal were studied for the frequencies greater than 1 rad$\cdot$s$^{-1}$. The measurement disturbances are then included. Figure 4.2.2 shows an example of such a signal as measured in 1978. In figure 4.2.3 an autospectrum of a signal period of 150 seconds is shown at double logarithmic scale.

From this spectrum and others (see appendix) showing the same characteristics it can be concluded that there is relatively much power (hence variation) in the frequencies lower than 0.6 rad$\cdot$s$^{-1}$ and peaks in the frequencies of 18 and 36 rad$\cdot$s$^{-1}$. These peaks are caused by the rotation of the auger (3.2 s$^{-1}$) and the 4 rows of auger pins penetrating the crop for transport. The peak at 3.1 rad$\cdot$s$^{-1}$ is also found at each spectrum. A possible explanation is the conveying action of the reel.

From the plot of the autocovariance function in figure 4.2.4 can be concluded that the autocorrelation decreases very rapidly with time lag, so

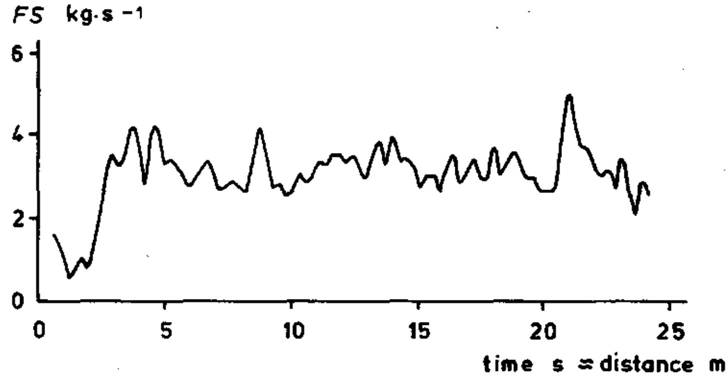



Figure 4.2.2. Variation in straw feed rate at constant machine speed of 1 $m \cdot s^{-1}$ in winter wheat (anouska) at Flevopolders in 1978

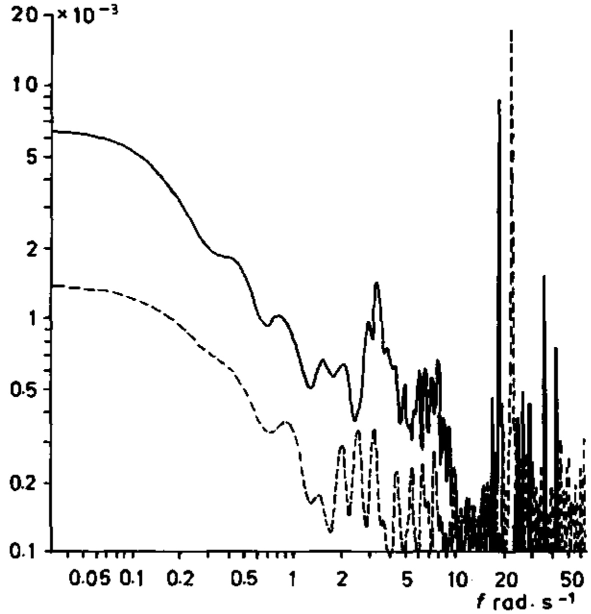



Figure 4.2.3. Autospectra of measured walker loss (----) and measured auger torque (———) for data averaged per 0.05 s and for a period of 180 s Barlett window 10% (see appendix)

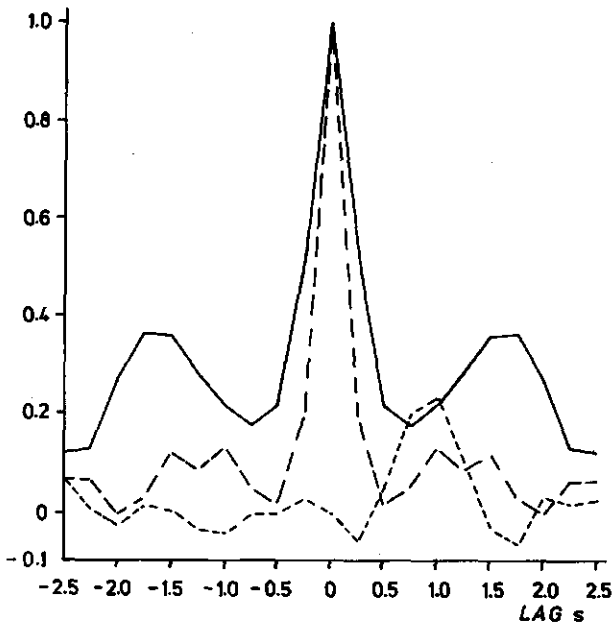



Figure 4.2.4. Autocorrelation function of straw feed rate (——) and walker loss (— — —) signals as well as crosscorrelation Data averaged per the delay is corrected up to the difference of 1 s.a averaged per 0.25 m for a total stretch of 187.5 m (see A 4.2.)

that after about 0.4 s the level has dropped to 1/e, so that the prediction of feed rate based on a instantaneous measurement is poor.

The following conclusions can be drawn.

1. The high-frequency variations in measured feed rate include a large deal of measurement disturbance caused by the design of the auger and redistribution at the auger, which makes prediction of high-frequency variations of feed rate based on the measurement of auger torque difficult.
2. It can be expected, on the basis of the results given in paragraph 3.1, that the accuracy of the relation of auger torque to straw feed rate will increase with the length of the averaging period of the signal, with the result that it is the low frequency variations, which are best estimated.
3. The most important feed rate variations are the low frequency variations and change in mean level between various fields.

The feed rate is one of the disturbances in the process that has to be controlled. Various control systems will be compared in this study, so that the calculations have to deal with the same kind of feed rate disturbances for each control system. One can use randomly generated disturbances for this purpose but, as was stated earlier the character of the disturbances has not been intensively studied, so that the composition of the disturbances would be difficult to establish and empirical disturbances could be used to better purpose.

For this reason data files of apparent straw density were made from field measurements obtained with a combine harvester (type B) of the IJsselmeer-polders Development Authority large-scale grain farm. The details are explained in A 4.2.1.c. The mean values of the apparent straw density are calculated for each 0.25 m traversed in 8 field tests of 187.5 m.

The machine operator had been instructed to work in the way he would have done if there were no registration of data, so that the information on a realistic manual-control situation was also obtained. Table 4.2.1 gives some information on the data files created of apparent straw density in the sequence used in the simulations.

Table 4.2.1. Average data of the field experiments, used to calculate the input file of apparent straw density and manual-control situation *FSAV* = average feed rate, *VMAV* = average machine speed, *SDAV* = average apparent straw density, *WLAV* = average walker loss.

| Nr. | Variety | *SDAV* | *FSAV* | *VMAV* | *WLAV* |
|---|---|---|---|---|---|
| | | $kg \cdot m^{-2}$ | $kg \cdot s^{-1}$ | $m \cdot s^{-1}$ | $kg \cdot s^{-1}$ |
| 61 | Anouska | 0.49 | 2.81 | 0.96 | 0.007 |
| 39 | Nautica | 0.62 | 3.29 | 0.90 | 0.007 |
| 12 | Nautica | 0.66 | 3.81 | 0.99 | 0.016 |
| 55 | Anouska | 0.42 | 2.29 | 0.94 | 0.017 |
| 57 | Anouska | 0.45 | 2.53 | 0.95 | 0.030 |
| 52 | Anouska | 0.52 | 3.10 | 1.02 | 0.026 |
| 37 | Nautica | 0.49 | 2.89 | 0.98 | 0.050 |
| 33 | Nautica | 0.60 | 3.50 | 0.99 | 0.110 |

The simulations were done with CSMP III with a calculation interval of 0.1 s. The straw density values required for each step, were calculated by a function generator using linear interpolation technique to avoid negative values that are liable to be created by interpolation techniques of higher order at values near to 0.

Using the values of apparent straw density averaged over 0.25 m, means that variations with frequencies above about 6 $rad \cdot s^{-1}$ are reduced, assuming machine speeds of 1 $m \cdot s^{-1}$. It was concluded in A 4.2.1.b that the power, hence the amplitude in feed rate variations of frequencies above 6.0 $rad \cdot s^{-1}$ are reduced very rapidly.

*Model of the feed rate measurement*

In the model of the combine harvester, the momentaneous machine speed, the constant cutting width of 5.9 m and the straw density generated by the function generator of CSMP simulation language create the instantaneous feed rate at the cutter bar. After a delay of 0.4 s the straw reaches the auger and generates a "measured feed rate". The measurement errors were introduced into the model by white noise added to this feed rate with a default level of 20% on the average value mentioned in table 4.2.1, based on resemblance to registered signals alone.

To avoid disturbances in the mean level the noise was coloured by filtering by first-order high-pass filter with default breakpoint frequency of 0.1 $rad \cdot s^{-1}$. The same noise was put into the elevator displacement output, when this was used as measured feed rate.

## 4.3. DISTURBANCES IN THRESHING SEPARATION EFFICIENCY

From paragraph 2.3.2 we know that the threshing separation efficiency is dependent on several factors. These factors can be split up into three groups:

a) machine design and adjustment variables,

b) feed rate of straw and

c) process variables affected by crop properties.

In this research the machine design and adjustment variables, except threshing speed, are kept constant. The threshing speed will in some cases be the control output.

The effect of straw feed rate has been discussed in paragraph 2.3.2 and the variations in feed rate in paragraph 4.2. The disturbances in the process variables will be considered in the present chapter. The process variables in the model of threshing are *NU*, *RPS* and *BETA*. The concave adjustment and kind of crop is not varied in this study, so that *NU* and *RPSI* are dependent just on feed rate. In fact, the crop properties also will affect *NU* and *RPSI*, but there was not enough information available from field tests on walker separation itself to estimate more than one parameter.

The threshing coefficient *BETA* is most suitable for consideration, as this factor affects the rate of change of separation due not only to crop properties but also to threshing speed.

The variation in threshing separation efficiency can be due to a number of causes, for instance

1) grain properties affecting the forces binding grains to the ear. Important variables here are the kind of crop, variety, ripeness, moisture content of grain, changes in temperature and moisture content for several days before the harvest. The later the grains are dislodged from the ears in the threshing cylinder the less chance they have of being separated from the straw and passing through the concave.

2) The straw properties affecting the separation. Some important variables here are the kind of crop, variety, ripeness, moisture content of grain.

3) The straw feed rate has been discussed in paragraph 2.3.

4) The amount of weeds in the straw which affects the separation.

5) The position of the ears in the straw layer.

6) The direction of the stem of the ears in relation to the direction in which the ear is accelerated by the threshing bars.

7) The distribution of the straw and ears over the width of the concave.

8) The speed of straw intake and that of the crop in the space between the threshing cylinder bars and the concave.

9) Concave stoppage due to wet conditions and a large amount of weeds in the crop.

10) Noncontrolled variation in threshing cylinder speed due to engine-speed variation.

The variation in separation efficiency can be subdivided into high-frequency disturbances due to random processes mentioned under items 5 to 10 above and low-frequency disturbances or even change in mean level, owing to change in crop properties, to which points 1 to 4 above refer.

The high-frequency disturbances are not yet quantified, because they do not affect the mean level of separation calculated over several seconds, the period over which the separation will be averaged.

The low-frequency disturbances are quantified by parameter estimation over each 187.5 m test run in the simulation (see chapter 6). The values are listed in table A 4.2.1.3. The effect of these values on losses are shown in 4.6, but it should be borne in mind that the effect of *BETA* on walker loss is important. For instance, if the threshing separation efficiency drops from 0.9 to 0.8, the amount of grain delivered to the rotary separator and straw walkers is doubled, so that walker loss will be doubled, as well.

The variation in low-frequency disturbances can occur within a few seconds, when the soil properties or moisture properties suddenly change, causing crop properties to do likewise. In this study they are simulated by connecting the data files on the various crop properties to each other, *BETA* and *WEP* changing within a few seconds (see ch. 6). This is so simulated because in general, the disturbances can be regarded as low-frequency variations and sudden changes in mean level. This signifies that, for control purposes, the threshing separation itself, or the resulting walker loss, can be measured with an averaging period of about 2-10 s, so that the control can be quasi steady state.

The measurement of threshing separation is based on a theoretical system, the accuracy of which is not yet known. The measuring error is assumed to be random, with white noise characteristics, whose maximum amplitude is 0.06 around a separation efficiency of about 0.85. The noise is coloured by filtering by means of a high-pass, first-order filter which has a breakpoint frequency of 0.1 $rad \cdot s^{-1}$.

## 4.4. DISTURBANCES IN ROTARY-SEPARATOR EFFICIENCY

Not much information is available on the variation of the separation of the rotary separator. The only data that can be used are those plotted in figure 2.3.3.1. It can be concluded from these data that crop properties will affect the relation of feed rate to separation efficiency, so that low-frequency disturbances or mean-value drift of these parameters will occur.

Change in the kind of crop or variety will give other parameter values, but in this study only wheat is taken into consideration, so that the mean level will not change much.

High-frequency disturbances will occur for the same reasons as mentioned in paragraph 4.3. For the purposes of the present study the relation of feed rate to separation efficiency is assumed to be constant.

The disturbances that occur in the practical situation are simplified for the simulation model to variations in *BETA* in the threshing process and *WEP* in the walker separation process.

## 4.5. DISTURBANCES IN WALKER SEPARATION EFFICIENCY

Walker separation, like threshing separation, is dependent on the three following groups of factors:

a) machine design and adjustment,

b) straw feed rate,

c) process factors affected by crop properties.

The design and adjustment of the machine are not variable in our study. The straw feed rate is a variable as has already been explained. The process parameters affected by crop properties and other variable conditions will be considered in this chapter.

The walker separation is the only dynamically to be modelled process in the combine harvester as is shown in chapter 2. These process dynamics are modelled by a first-order transfer in the straw feed rate and by the delay of straw on the walkers.

The time constant of the first-order transfer was estimated to be 0.8 s. Not enough details of the dynamic process transfer are available to enable us to discuss a variation of this constant. Further research has to be done on this subject.

More information is available on the variation of the time delay. From A 2.3.2.4.d and A 4.2.1.c it is seen that the delay varies considerably owing to the stoppage of the straw at the curtain in front of the walkers. The speed of the straw at the walkers also varies. In field observations a mean speed of 0.5 $m \cdot s^{-1}$ was registered.

In laboratory research by Gubsch (1969) the speed was found to be dependent on straw feed rate and the slope of the straw walkers. At a straw feed rate level of 1.6 $kg \cdot s^{-1} \cdot m^{-1}$ the speed varied from 0.35 to 0.66 $m \cdot s^{-1}$. At a straw feed rate level of 4.7 $kg \cdot s^{-1} \cdot m^{-1}$ the speed varied from 0.64 to 0.77 $m \cdot s^{-1}$. When the slope was changed, the speed changed too. Under Dutch harvest conditions the slope is always about 0, so that this is not of any importance.

The time the straw remains in the machine was studied in some of our field tests (Wevers, 1972) by measuring the displacement of coloured straw to the ground. In machine A, with winter wheat, a variation between 7.0 and 13.0 s was measured around the mean value of about 9.75 s. This variation can be explained by both the stoppage at the curtain and the speed of the straw on the walkers, because the speeds elsewhere in the machine are roughly constant.

This effect is very important because it impedes the measurement of the relation of loss-to-straw feed rate. For this purpose an averaging time of loss and feed rate of at least 8 s would be necessary to calculate a stable loss-feed rate relation (see A 4.2.1). In 4.7 a number of results on loss-to-feed rate estimation will be given.

The disturbances in walker separation will have the same character as threshing separation and rotary separation. Not only high-frequency random disturbances, but also low-frequency variations and changes in mean level of the separation occur.

The random variations are mainly caused by the redistribution of the straw on the walkers in the longitudinal and transversal directions. The low-frequency variations are due to properties of the grains as well as those of the straw.

These properties are dependent on the kind and variety of grain, ripeness and moisture content, surface moisture from dew and rain and weathering of the straw. The crop properties can be established from various physical properties, such as friction, strength, straw length distribution and so on, but it proved to be very difficult to explain walker losses by the values of these properties (Huisman, 1978). The grain-straw separation process on walkers is very complex and not predictable on the basis of the known physical properties.

## 4.6. VARIATION IN WALKER LOSS

The variation in walker loss is the result of the disturbances, drift and sudden change of mean level in the parameters dealt with in the previous sections. The processes of grain separation at the threshing cylinder, rotary separator and straw walkers all depend closely on the straw feed rate. The extent to which straw feed rate affects each of these separation processes, will differ a great deal, hence the extent to which they affect walker loss varies, but an increase in feed rate will always result in increase of loss.

The impact on walker loss by the threshing cylinder is very important because about 70-99% of the grain flow is separated here from the straw flow. This is very often forgotten. The walker separation is responsible for high losses, especially under wet conditions and under those in which the straw is shortened or split by the threshing action in such a way that separation becomes difficult. Mostly an increase in moisture content has the effect of increasing the loss, but in some cases the reverse relation is measured. Surface moisture of the straw, either from dew or short periods of rainfall is more important than the average moisture content in which the moisture is an element of ripeness.

Figures 4.6.1 and 4.6.2 show good examples of these phenomena based on results of field tests obtained with machine A in winter wheat (Snel, 1977). At these tests the machine speed was constant and the same in each test, so that feed rate was maintained at a fairly constant rate of about 2.5 $kg \cdot s^{-1}$. The walker loss, the straw moisture content and the air humidity in the crop at 0.5 m above the soil are measured during one evening and the following evening and night.

On the first night (figure 4.6.1) the moisture content did not change much, but air humidity increased. In this case the surface moisture affected straw properties so as to reduce loss.

In figure 4.6.2 there is more scatter in the data but the general effect was that losses increased at the end of the night and then fell rapidly when the air humidity and crop moisture decreased thanks to the sunshine. These differences are also found in the course of the day.

Fedosejev (1969) also presents figures of that kind.

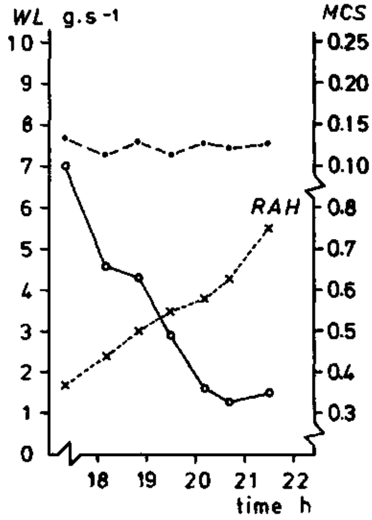



Figure 4.6.1. Walker loss (*WL*, o—) related to straw moisture content (*MCS*, •---) and relative air humidity (*RAH*, ×----) as they changed during the tests in winter wheat in 1976 at the same forward speed

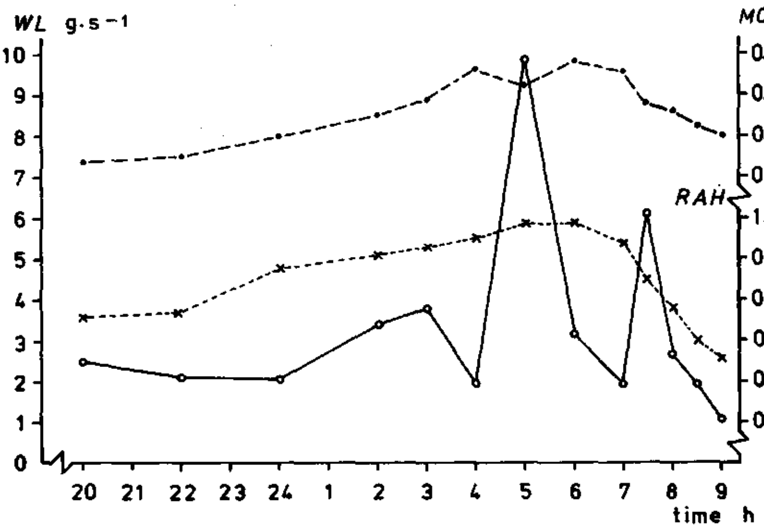



Figure 4.6.2. See figure 4.6.1 but for tests during an other night in 1976, however

The data of field tests with machine A in the years 1970 ... 1976 were investigated in search of relations between crop properties and walker loss (Huisman, 1974b). Finding the real relations proved to be too complex a task. In the present study, it is only important to learn the extent of the variation of the loss, to see the total effect of separation processes in the combine.

The tests were carried out each year throughout the harvest seasons, to discover how the crop properties varied in practice. The feed rate was also varied from low to the highest level that could be achieved. In figure 4.6.3 the results are shown of loss as a function of straw feed rate on the same scale so that the differences between the years and the crops becomes very clear.

Measurements were also carried out with combine harvesters of farmers and contractors and showed the same variation. A table is given in A 4.6.4, showing walker loss measured in 1980 which varied from 0.75 to 232.0 $kg \cdot ha^{-1}$, while straw feed rate per metre width of threshing cylinder varied from 0.5 to 1.9 $kg \cdot s^{-1} \cdot m^{-1}$ (Dongen, 1981a).

In 1972 the sieve and walker losses were summed up (Jansen, 1972). The total amount varied from 3.3 to 418.0 $kg \cdot ha^{-1}$ of which the walker loss contributed the greater part to the total in each case. The details of this research are also given in A 4.6.4.

Figures of this kind are also found in literature (Anonymus, 1969; Brown, 1967; Klinner, 1979). It can be concluded from such research that the losses vary very much in practice, not only because of the varying circumstances, but also because the farmer does not check upon his loss intensively. In most cases the farmer does not even know what loss level he should try not to exceed. This can be understood when we consider that loss measurement is very difficult. Farmers, who own a grain loss monitor, are better aware of the loss level they intend to work with.

The loss-to-feed rate relation is a very important thing to know as regards speed control, be it manual or automatic. Knowing this relation, in fact, means that the separation parameters are estimated, and can therefore be adapted to the disturbance of these parameters.

It is generally claimed in literature and confirmed by our research, this relation being exponential (Huisman, 1974b). (See also the general shape of the scatter of the measured values in figure 4.6.3.)

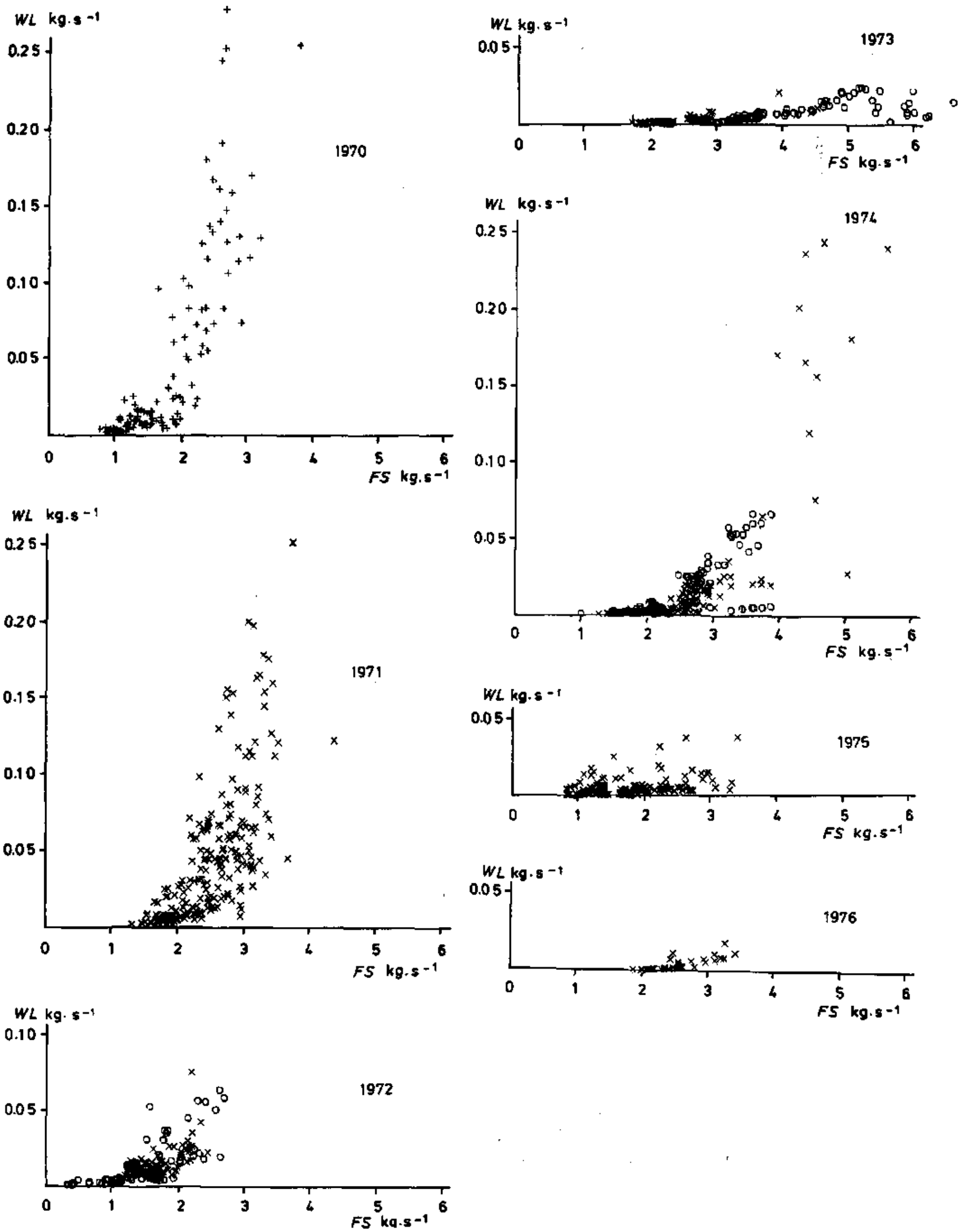



Figure 4.6.3. Walker loss (*WL*) related to straw feed rate (*FS*) for machine A in different crops (+ = oats, × = winter wheat, o = spring wheat in the years indicated.
In 1970-1972 the stretches considered were 5 m in length,
in 1973,1974 the stretches considered were 40 m in length
and in 1975,1976 the stretches considered were 30 m in length.

Nyborg, 1968, found the best fit for the:percent loss = a(feed rate)$^{b}$ equation by linear regression analysis of a large amount of experimental data from literature. Under western European conditions these conclusions are also drawn but the equation: loss = a•exp(b•$FS$) fits well, too (Goss, 1958; Baader, 1966; Anonymus, 1967; Lint, 1968; Kroeze, 1970; Eimer, 1974b; Claesson, 1972; Anonymus, 1976). When the unit of loss is kg•s$^{-1}$ or kg•ha$^{-1}$ the same equations can be used as well.

If the feed-rate range is small a linear relation will also serve, being a small part of the experimental relation. These conclusions are in conformity with the model of the combine harvester as will be shown in chapter 6.

For simulation of the disturbances of the separation parameters for the model, realistic data are needed. The parameters should be chosen so that the variation in loss curves are in conformity with a wide loss range arising from a realistic range of crop properties.

The range of losses incurred in the field experiments shown in figure 4.6.3 was held to be realistic. Eight test runs were selected on this basis from the available runs of the field tests of 1978. The details of the method of calculation are given in A 4.2.2.

The loss curves of the selected test runs are drawn in figure 4.6.4. There are loss curves showing small losses as well as large ones roughly in the same ratio as measured loss occurred. They can be compared to the measured data given in figure 4.6.3.

These curves are of exponential shape: $WL = \exp(D_0+D_1 \cdot FS)$. The values of $D_0$ and $D_1$ are given in table A 4.2.1.3. They represent values calculated by linear regression of the values of loss and feed rate averaged over 8 m. This averaging distance was required in order to filter out the stochastic variation in losses due to the random disturbances in the separation processes. Averaging distances of more than 8 m did not change the curves much, but when shorter distances were used, the correlations deteriorated and curves deviated as a result.

If the loss-to-feed rate curve has to be estimated by the control system on the combine harvester, special techniques have to be developed. Further research in this subject is necessary.

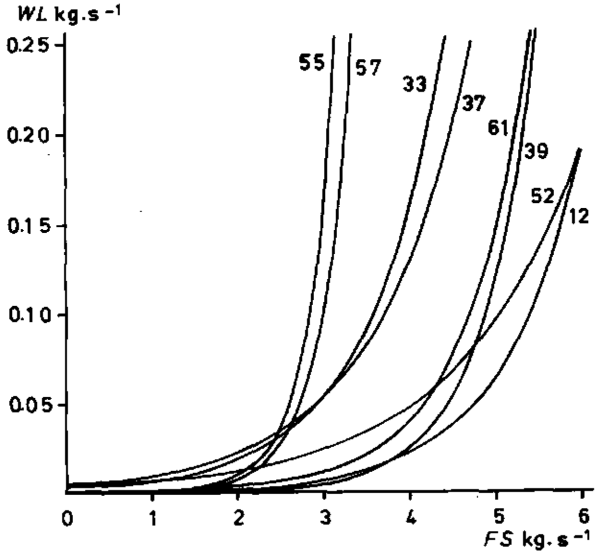



Figure 4.6.4. Curves of walker loss (*WL*) related to straw feed rate (*FS*) calculated by linear regression of the equation $\ln Wl = D0 + D1 \cdot FS$ of of the selected test runs (see number) used for the simulation

## 4.7. CONCLUSIONS

The most frequently occurring type of disturbance in the processes of separation in the combine harvester is low-frequency disturbance and sudden changes in the mean level in those cases in which the harvest is to be started in another field or on another day. There is a high degree of measurement disturbance in frequencies, that are high compared to those in the above-mentioned process disturbances. This means that, for good measurement, filter action with a large time constant is needed. More field research is needed to establish the optimal filter techniques.

For simulation of the control systems deterministic disturbances are calculated. On comparison with the variability measured over a number of years, they seem to be realistic.

# 5. Control systems

## 5.1. INTRODUCTION

### 5.1.1. *General*

The aim of the control system is stated in chapter 1 as the minimisation of the cereal harvest costs by control of the machine speed and the threshing cylinder speed. The financial benefit of automatic control compared to a manually controlled system, depends on how correctly the optimum speed level can be calculated and on how capable the system is of realizing a relatively small deviation between the calculated optimum level and the actual speed. The correct choice of the level depends in particular on the correctness and extent of the used information, that is the control inputs. The correctness depends on:

1) the cost information of the cereal harvest parameters,
2) the choice of the input variables,
3) the observability of the input variables. This refers to the accuracy and integration time of the measurements.

By the extent of the used information is meant the number of measured or calculated process parameters taken into consideration.

The differences between calculated optimum speed and actual speed will be minimised by speed feedback control systems. The extent to which the system really works at minimum costs is determined by its controllability. For the combine harvester there are some unfavourable conditions, such as:

a) The time delays are quite large in the process; 0.4 s for the straw feed rate and 10 s for the grain losses after the intake. Moreover these are not constant.
b) The observability is low because of the low signal/noise ratio.

For these reasons the speed can only be controlled for low-frequency disturbances, so that a quasi steady state approach can be established for calculation of optimum speed.

### 5.1.2. *Models for control system design*

#### 5.1.2.1. *Models*

The models of the relevant processes in the combine harvester, considered in chapters 2 and 4 are presented briefly together with the disturbances in figure 5.1.2.1. From this it is clear that both the machine speed *VM* and the threshing cylinder speed *VT* affect the walker loss *WL*. The sieve, threshing and breakage losses are left out of further consideration as they are relatively small compared to the walker loss in general. In conditions of relatively high sieve loss the total of sieve and walker loss can be taken as input. The remaining adjustable parameters, such as the concave adjustment and the walker frequency are not variable in this study.

It has to be realized that the transfers of the processes are nonlinear, so that the disturbances have nonlinear effects on loss.

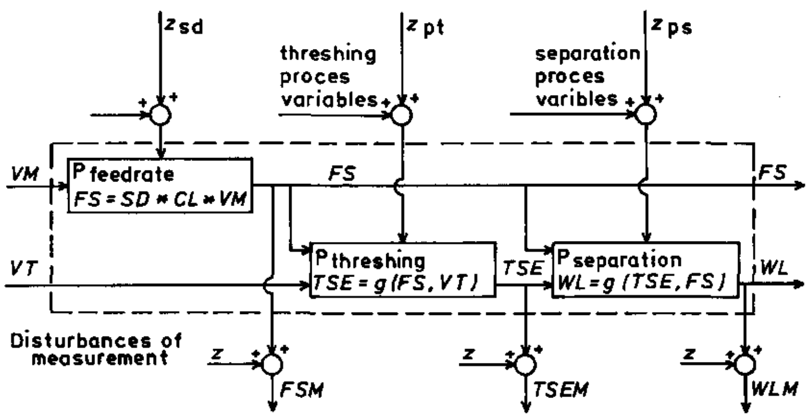



Figure 5.1.2.1. Simplified scheme of process (*P*), disturbances (Z) and measurement of variables (*FSM, TSEM, WLM*), *g* = nonlinear functions

The control input factors are: the straw feed rate *FSM*, the concave separation *TSEM*, and the walker losses *WLM*. The *M* is added to indicate the added measurement noise.

When the input variables, the cost factors of machine and crop and the cost criterion mentioned in chapter 1 are combined in a cost-minimisation calculation, this should result in optimum values for the driving speed $VM_o$ and the threshing cylinder speed $VT_o$. Two feedback speed controls will ensure that the actual speeds $VM_a$ and $VT_a$ will follow the optimum speeds. The subsequent models of the control systems will systematically use more input variables or control more output variables in the following way.

*System 1*, the loss control system, is obtained when the measured loss *WLM* is used as the input signal and $VM_o$ becomes the output of the optimum speed calculation (see figure 5.1.2.2). The $VM_a$ is the actual machine speed, that is the output of the control which is also used as input for the cost minimisation.

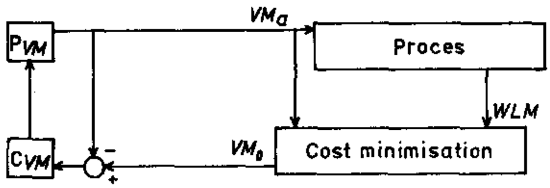



Figure 5.1.2.2. Loss control (system 1)
P = process, C = control, $VM_o$ = optimum machine speed, $VM_a$ = actual machine speed

*System 2*, the loss feed rate control also controls just machine speed but, for reasons of observability and controllability, uses the measured feed rate *FSM* as input in addition to *WLM* and *VM* (see figure 5.1.2.3).

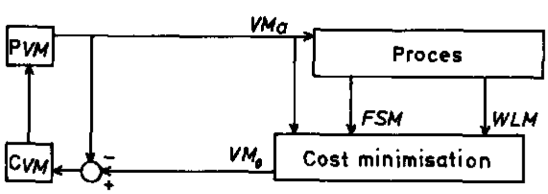



Figure 5.1.2.3. Loss feed rate control (system 2)

In the previous systems the threshing cylinder speed *VT* is fixed. If this speed is also controlled on the basis of the input variable measured feed rate, *FSM*, then *system 3* is obtained, that is the loss feed rate cylinder speed control (see figure 5.1.2.4).

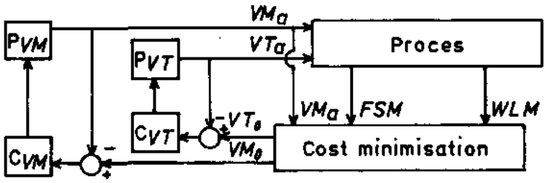



Figure 5.1.2.4. Loss feed rate cylinder speed control (system 3)
$VT_o$ = optimum threshing speed, $VT_a$ = actual threshing speed

If, in addition to this, the threshing separation efficiency *TSEM* is used as input in the cost minimisation criterion then *system 4* is the result, that is the so called loss feed rate threshing separation control (see figure 5.1.2.5).

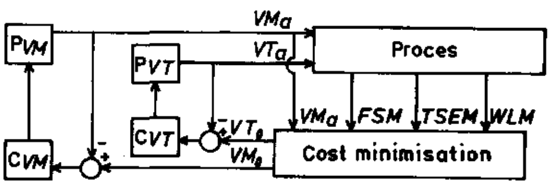



Figure 5.1.2.5. Loss feed rate threshing separation control (system 4)

### 5.1.2.2. *Observability and controllability of the control output variables*

Various parameters have to be measured in order to control the systems mentioned above. From previous chapters the following review can be given below, together with the conclusions as to controllability:

*VT*. The measurement of the threshing cylinder speed can be performed rather accurately.

*VM*. The value of the machine speed will be used in the optimisation calculation, multiplied by the cutting width. The product can have a steady state deviation of at most 5%. This is because of slip which depends on the soil properties and the mass in the grain tank and because of the *assumed* constant working width.

*FSA*. There is an unknown measurement noise component in the straw feed rate measured by auger torque. An estimation has been made of the correlation between straw feed rate and auger torque, varying between 0.6 and 0.9 for frequencies below 0.63 rad·s$^{-1}$ (see 3.1.2). The measurement of the feed rate by auger torque is delayed 0.4 s compared to the intake moment of the feed rate. The covariance function shows a time constant also of about 0.4 s. Hence prediction of the feed rate is bad. The combination of delay and measurement noise makes it difficult to control the high-frequency disturbances. Only the low-frequency disturbances can be controlled sufficiently.

*TSE*. In measuring the threshing separation efficiency, measurement noise can be expected as well as variation caused by the varying grain-to-straw ratio (see 3.4). The measurement is expected to be only reliable for the low-frequency part with an *estimated* error of 0.03 at the level of about 0.85. This measurement also has a time delay of about 10 s.

*WL*. The variation of the time delay of the straw on the walkers is responsible for a considerable amount of measurement noise on walker loss. The measurement technique also introduces a considerable amount of noise in the high frequencies. Only the variations of the frequencies less than about 0.2 rad·s$^{-1}$ can be measured reliably. The variations in walker loss as a consequence of disturbances in the separation processes $Z_s$ and $Z_b$ are also of low frequency. Generally these variations occur in the frequency range below roughly 0.2 rad·s$^{-1}$ (see 4.6).

The influence of straw feed rate on walker loss is noticeable in the frequency below the estimated level of 1.25 rad·s$^{-1}$ (first-order process with $\underline{\tau}$ = 0.8). The variations in straw feed rate, in frequencies between 0.15 and 1.25 rad·s$^{-1}$ are, despite the disturbances, more or less measurable by auger torque. Moreover, the measurement of the auger torque takes place 10.1 s before measurement of the corresponding loss.

From the point of view of measurability and controllability it is attractive for these reasons to predict walker loss based on auger torque and estimates of the parameters of the transfers of the separation processes. The following equation, based on field measurements mentioned in chapter 4 has been chosen for this.

$$WL(t) = a \cdot \exp\{b \cdot FS(t-10.1)\} \qquad (5.1)$$

An estimate of a and b can be made after filtering the high-frequency noise out of the measurements of loss and feed rate. These values can then be used in the cost minimisation criterion, resulting in a better estimation of the slope of the loss curve and consequently in an improved optimum machine speed.

## 5.2. COST MINIMISATION

The main disturbances are low-frequency ones. They can be controlled by adjusting the machine and threshing speeds to levels calculated in a cost-minimisation algorithm. The principles of this algorithm are worked out in this chapter as required for the simulations. If these algorithms are used in practical control systems, the calculation techniques must be adapted for use with microprocessors.

The calculation of optimum machine speed is not the same in systems 1 and 2. The principle and procedure is most clearly demonstrated in system 2, so that it should be dealt with first.

### 5.2.1. *Optimum machine speed calculation for system 2*

The point of minimum costs of the optimisation criterion can be derived from the shape of the total cost curves of the machine and loss costs (see figures 1.4.1.2 and 3). At an increasing harvested area *VW* the cost curve of the *machine costs* descends in cost situations 5 and 6, in accordance with the equations derived from 2.2, giving total machine costs (*CM*) as the sum of *MVC*, *HVC* and *MFC*, so that

$$CM = MVC + (NE \cdot 0.36 + 1/VW) \cdot K_1 \qquad (5.2)$$

in which

$$K_1 = \frac{WA}{0.36} + \frac{AFC \cdot VMN \cdot CL}{AAN \cdot (NE \cdot VMN \cdot CL \cdot 0.36 + 1)} \qquad (5.3)$$

The cost curve of *walker loss* ascends in accordance with

$$VWL = K_2 \cdot a \cdot \exp(b \cdot FS)/VW \qquad (5.4)$$

in which $K_2 = 10000 \cdot V_1$ (5.5)

The total of both factors gives the total costs

$$TC = CM + VWL \qquad (5.6)$$

The minimum cost point occurs for that value of *VW* at which

$$d(TC)/d(VW) = 0 \qquad (5.7)$$

so that

$$d(CM)/d(VW) + d(VWL)/d(VW) = 0 \qquad (5.8)$$

It can be derived from (5.2) that

$$d(CM)/d(VW) = -K_1/VW^2 \qquad (5.9)$$

It should be realized in the calculation of $d(VWL)/d(VW)$ that $FS$ is a function of $VW$, namely

$$FS = SD \cdot VW \qquad (5.10)$$

so that with (5.4) we get

$$d(VWL)/d(VW) = d(K_2 \cdot a \cdot \exp\{b \cdot VW \cdot SD\})/d(VW) = \qquad (5.11a)$$

or $$d(VWL)/d(VW) = K_2 \cdot a \cdot \exp(b \cdot VW \cdot SD) \cdot (b \cdot VW \cdot SD - 1)/VW^2 \qquad (5.11b)$$

hence $$d(VWL)/d(VW) = K_2 \cdot a \cdot \exp(b \cdot FS) \cdot (b \cdot FS - 1)/VW^2 \qquad (5.12)$$

Inserting both derivatives to $VW$, (5.9) and (5.12) in (5.8) gives

$$-K_1/VW^2 + K_2 \cdot a \cdot \exp(b \cdot FS) \cdot (b \cdot FS - 1)/VW^2 = 0 \qquad (5.13)$$

or $$K_1 = K_2 \cdot a \cdot \exp(b \cdot FS) \cdot (b \cdot FS - 1) \qquad (5.14)$$

The derivative to $FS$ of the right hand part of this function is

$$K_2 \cdot b \cdot FS \cdot a \cdot \exp(b \cdot FS) \qquad (5.15)$$

This derivate is always positive as $a \cdot \exp(b \cdot FS) = WL$ and, since a negative loss is impossible, $a$ will always be positive. Moreover, the loss is expected to increase, so that $b$ is positive, too.

This means that the right hand part of the equation always increases with increasing $FS$, starting from a negative value at $FS = 0$. Therefore there is always one solution for $FS$ from this equation. This is the optimum feed rate level appropriate to that situation from which an optimum $VW$ follows for every $SD$.

$$FS_{opt.} = SD \cdot VW_{opt.} \rightarrow VW_{opt.} = \frac{FS_{opt.}}{SD} \qquad (5.16)$$

It has been calculated for the situation given in figure 1.4.1.2 for the loss curve of the field tests of the Anouska winter wheat variety, that $FS_{opt.} = 3.14\ kg \cdot s^{-1}$ from which it follows for $WL(2)$ in that curve, that $VW_{opt.} = 7.85\ m^2 \cdot s^{-1}$ and for $VWL(e)$ that $VW_{opt.} = 6.28\ m^2 \cdot s^{-1}$

The necessary value of $SD$ in equation (5.16) can be calculated from the measured values of straw feed rate $FSM$ and harvested area $VWM$, namely that

$$SDM = FSM/VWM \qquad (5.17)$$

A complication occurs, because there is a time delay between $FSM$ and $VWM$. Actually it applies that

$$SDM(t) = FSM(t+\underline{\tau})/VWM(t), \text{ etc.} \qquad (5.18)$$

The influence of this phenomenon is neglected because it is small since $\underline{\tau} = 0.4$ and only the low-frequency variations are of importance.

The cost function is a little bit more complicated for the cost situations in which the costs of timeliness losses *CTI* occur (situations 1 ... 4). The costs of these timeliness losses have to be added to the total machine costs of which the fixed costs component *MFC* is not dependent on *VW*. In that case

$$d(CM)/d(VW) = WA/(0.36 \cdot VW^2) \qquad (5.19)$$

*CTI* is not known as a function but from a function table, so that $d(CTI)/d(VW)$ can also be derived from a table as a function of *VW*. This function was called *DTI*. In the same way equation (5.8) holds.

$$d(CTI)/d(VW) + d(CM)/d(VW) + d(VWL)/d(VW) = 0 \qquad (5.20)$$

so with $d(CTI)/d(VW) = DTI$ and both (5.12) and (5.19) we find

$$DTI \cdot VW^2 + WA/0.36 = K_2 \cdot a \cdot \exp(b \cdot SD \cdot VW) \cdot (b \cdot SD \cdot VW-1) \qquad (5.21)$$

So here also, for every "measured" *SD* value, one optimum *VW* applies.

### 5.2.2. *Optimum machine speed calculation for system 1*

If a system using exclusively the information about driving speed and loss were developed, then the calculation of the optimum speed would be different. Then the relation between straw feed rate *FS* and walker loss *WL* is not known, so that the direct relation between the harvested area *VW* and walker loss *WL* has to be used. This is difficult to ascertain because *VW* doesn't vary much whereas the variations in straw density do cause variations in the walker loss.

Therefore it is not possible to obtain a good estimate of the shape of the curve describing the relation between *VW* and *WL*. For this a greater range of *VW* should be processed; the operator should perform special curve calibration runs which should be regularly repeated. This is very important since the minimum cost system is established by the slope of the loss.

If this has to be dispensed with, then the known level of the loss and the known general shape of the curve can be combined to a one-parameter loss model, e.g.

$$WL = c \cdot \exp(q \cdot VW) \qquad (5.22)$$

$c$ doesn't have to be estimated in this model, but is adjusted at a low but realistic value to let the curve almost pass through 0 at a low *VW*. Then

$$VWL = K_2 \cdot c \cdot \exp(q \cdot VW)/VW \qquad (5.23)$$

so that

$$d(VWL)/d(VW) = K_2 \cdot \{c \cdot \exp(q \cdot VW) \cdot (q \cdot VW-1)\}/VW^2 \qquad (5.24)$$

Now (5.24) has to be inserted in (5.8) and (5.20) in order to calculate the optimum *VW* for system 1. It is evident that the choice of *c* has a great influence on the calculation of the optimum value of *VW* calculated according to the minimum cost procedure, as in paragraph 5.2.1. In fact, *c* is estimated in the case that a curve calibration run is made.

### 5.2.3. *Optimum threshing speed calculation for control system 3*

As indicated in 1.4.1 there is an optimum speed of the threshing cylinder when minimum costs are pursued (see figures 1.4.1.4 and 1.4.1.5). The optimum speed can be ascertained for each feed rate level.

The shape of the curve is influenced by the crop properties and the concave adjustment, that is the distance between the rasp bars of the cylinder and the concave grate. Under given conditions (concave adjustment and crop properties) there will be a relationship between the straw feed rate and the threshing speed at which the losses, hence the loss costs, are minimum. Eimer (1977) has worked this out for a number of different crop properties.

Figure 5.2.3.1 shows lines of constant threshing separation deficiency, this being the ratio of non-separated grain to grain feed. The walker losses closely cohere with this deficiency as was shown in 2.3. Here it concerns wheat with straw moisture contents of 12% and a grain moisture content of 14%, a grain-straw ratio of 1:1.75 and a concave adjustment of 16 mm at the front and 8 mm at the rear. In figure 5.2.3.2, curves have been drawn of the threshing loss for the same crop. Figure 5.2.3.3 shows the appropriate curves for damaged seed.

When these loss percentages are embodied in the contribution to the loss costs, this results in curves of similar loss percentages as those indicated by (-------) in figure 5.2.3.4. The threshing loss is completely incorporated, while the broken grain is incorporated to the extent of a 0.4th part as not all broken grain is worthless. The grain that is not separated by the concave is passed on at a percentage representing the not by the walkers separated grain which depends on the feed rate level.

The most favourable combinations of feed rate and threshing speed are indicated by the hatched field A in fig. 5.2.3.4. Hatched areas B and C originate in the same way for just ripe harvested wheat (*MCS* = 18%, *MCG* = 18%, *GS* = 0.8) and wheat moistened after storage (*MCS* = 26%, *MCG* = 22%, *GS* = 0.7), respectively. The short curves in the hatched area indicate the lines or the same total loss percentages.

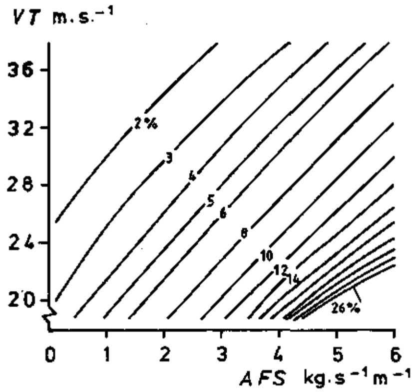



Figure 5.2.3.1.

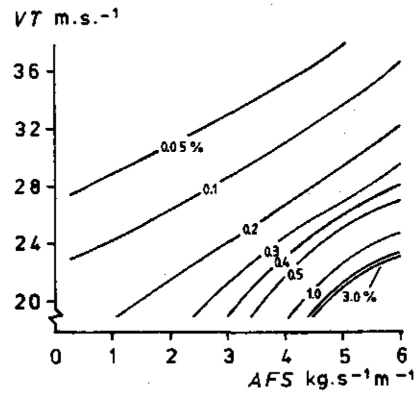



Figure 5.2.3.2.

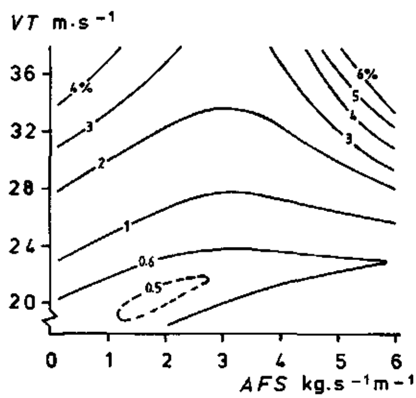



Figure 5.2.3.3.

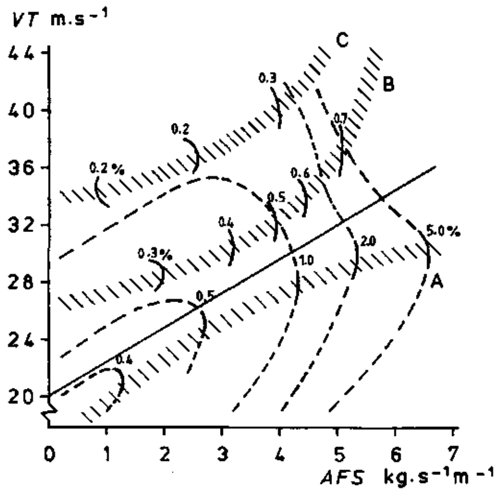



Figure 5.2.3.4.

Figure 5.2.3.1. Curves of constant concave separation deficiency (1-*TSE*) of wheat A related to threshing speed (*VT*) and specific feed rate (*AFS*) *MCS* = 12%; *MCG* = 14%; *GS* = 0.6, concave adjustment: 16/8 mm

Figure 5.2.3.2. Curves of constant threshing loss of wheat A related to threshing speed (*VT*) and specific feed rate (*AFS*)

Figure 5.2.3.3. Curves of constant grain breakage of wheat A

Figure 5.2.3.4. Total corrected loss percentages of wheat A (----) and wheat B and C ( ⁄‾ ), hatched area shows optimum combinations (least loss) of *VT* and *FS*. Wheat A: *MCS*= 12%, *MCG* = 14%, *GS* = 0.6; wheat B: *MCS* = 18%, *MCG*= 18%, *GS* = 0.8; wheat B: *MCS* = 26%, *MCG* = 22%, *GS* = 0.7
Line (——) is *VT* = 20 + 2.4 *AFS*

Observation of the hatched areas at feed rates between 2 and 5 $kg{\cdot}s^{-1}$ brings to attention that they have to some extent an equal slope as the lines of a constant, concave separation deficiency. This is logical because the threshing loss and the concave separation deficiency have this slope, the quantity of broken seed is small and is only important at a high feed rate.

A line fitting these data fairly is $VT = \ell + 2.4{\cdot}AFS$. This line is drawn in figure 5.2.3.4 for $\ell = 20$ and is less steep when compared to the concave separation deficiency lines. Such a line is $VT=9+4.0{\cdot}AFS$ for a concave separation of 10% of the crop belonging to the hatched area A.

The influence of threshing speed control on the feed rate can be clearly shown by assuming a threshing speed $VT$ of 24 $m{\cdot}s^{-1}$ at $AFS = 2.0\ kg{\cdot}s^{-1}{\cdot}m^{-1}$. Then the loss at crop A would amount to about 0.45%. If $FS$ increases to 4 $kg{\cdot}s^{-1}{\cdot}m^{-1}$, the loss would rise to 1% at the same $VT$. However, the loss will decrease to 0.9% by increasing $VT$ to 30 $m{\cdot}s^{-1}$. The advantage is greater when the slope of the equal loss lines differs considerably from that of the optimum threshing speed-to-feed rate relationship.

The benefit of such a system has two sources. In the first place, control of the mean level of threshing speed in order to optimise in accordance with the low frequency disturbances and mean level variations in crop properties affecting the threshing process.

In the second place, control of the actual threshing speed in order to adapt to the variations in feed rate as measured in the machine. These are the variations whose frequencies are above the bandwidth of the feed rate control and at which a feed forward threshing cylinder speed control can in fact react. The drive system of the threshing cylinder tolerates rather fast changes in speed and the measurement of the auger torque takes place $\pm$ 0.9 seconds before the crop enters the threshing cylinder.

The benefit is very dependent on the accuracy of the measurement of the feed rate. As accuracy is better at the lower frequency variations than at the higher ones, the benefits have to be expected from control of the lower frequency variations.

The concave clearance also affects the concave separation and the threshing loss. A continuous automatically controlled adjustment of the clearance, however, is not yet worthwhile because the influence is very small, according to Arnold (1964) and Caspers (1973), and not obvious since, at a greater adjusted distance starting from 4/2 mm, the concave separation first increases and then decreases. Moreover, the position of the optimum settings depends on the type of crop, threshing cylinder speed, crop intake speed, etc. If all effects of threshing could be measured like grain breakage, threshing loss, threshing separation efficiency and straw damage, the adjustment could be automated. Much research has to be done to develop such system.

The conclusion of this chapter will be that a threshing cylinder speed control can make a contribution to minimizing the loss costs and that the optimum speed $VT_o$ is determined by the straw feed rate and crop properties. To this the function which applies is $VT_o = VFL + VFS \cdot AFS$, in which *VFL* has to be chosen on the basis of the crop properties.
$VFS = 2.4\ m^2 \cdot kg^{-1}$ applies to all the crop dealt with in the research by Eimer (1973) and $VFL = 24\ m \cdot s^{-1}$ applies to wheat B (just ripe). A threshing cylinder speed control can be based on this equation.

Eimer (1973, 1974a, 1974b) applied this in practice (see also A 1.2). Presumably the above mentioned equation has been applied in this system, although it has not been explicitly stated. This equation will be used for the simulation of control system 3.

### 5.2.4. *Method for calculation of the optimum threshing cylinder speed for system 4*

Crop property variations will have the effect that the relationship between optimum threshing speed and feed rate derived in paragraph 5.2.3 will not be optimal in all cases. For optimisation of the mean threshing speed this equation has to be adapted to the change in crop properties. The equation is largely determined by the concave separation deficiency so this information could be used for adaption of the desired equation. Other factors like straw breakage affecting walker and sieve loss should also be considered, but this is a very complex matter. First optimisation will be researched using the concave separation.

It can be deduced from figures 5.2.3.1 and 5.2.3.4 that the deficiency curves are not completely parallel to the relation $18 + 2.4 \cdot AFS$, which would be chosen for crop A. However, when the threshing loss and the walker deficiency are unknown, the correct relation cannot be calculated either. From the way in which the hatched (optimum) area has been chosen for crop A, it is apparent that the area has no precise boundary, so that the curve of about 8% deficiency in figure 5.2.3.1 comes rather close to it.

On consideration of the deficiency curves of the crop with which Caspers (1973) performed his research, it can be concluded that these curves correspond better to the optimum curve of Eimer (1977) as far as the slope is concerned. Figure 5.2.4.1 shows this curve (curve 1, ------) and the optimum areas A, B and C as well as the 10% (curve 2, —— - ——) and the 20% (curve 3 ——.—— ) deficiency curves of Eimer. At the same time the figure shows the calculated points of 10% and 20% deficiency from the model of Caspers, for *BETA* = 1.8. These points are calculated for 3 different concave clearances. For 20% deficiency 8/4 (+), 12/6 (o) and 16/8 (□) are drawn. A well fitting line (——— ) for these points is

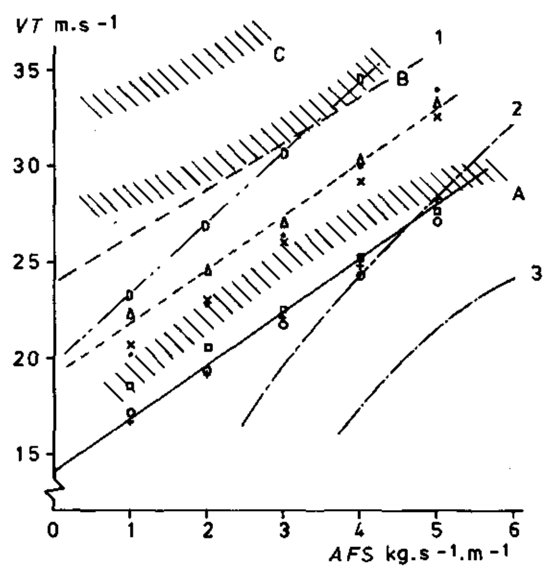



Figure 5.2.4.1. Threshing speed related to specific straw feed rate. Threshing deficiency curves: Eimer (1977): 20% (—·—·— ), 10% (—-——); Caspers (1973) for *BETA* = 1.8 20% (———), 10% (----) and for *BETA* = 1.7 (-- ——— -- ——). Threshing deficiency points for different concave clearances (mm/mm) Caspers (1973) for *BETA* = 1.8: 20%, 8/4(+), 12/6(o), 16/8(□); 10% 8/4(●), 12/6(×), 16/8(△); for *BETA* = 1.7: 10% 12/6(D) Optimum threshing speed area for crop: A, B, C (see figure 5.2.3.4). Relation used for optimum threshing speed in model 3: (———)

$VT = 14 + 2.75 \cdot AFS$. For 10% deficiency 8/4 (•), 12/6 (×) and 16/8 (▲) are drawn with the appropriate line (--------): $VT = 19 + 2.75 \cdot AFS$.

The line (--••--) and points (◘) apply to $BETA = 1.7$, concave clearance 12/6 and a deficiency of 10%. From this it is apparent that *BETA* in particular has impact on the slope and that the separation deficit determines the level of the equation in particular.

Therefore a control system adjusting the optimum threshing cylinder speed-to-feed rate equation should operate on the basis of: 1) an adjusted level *VFL*, based on the desired concave separation and on knowledge about the influence of crop types on it; 2) an adjustment of the slope *VFS* depending on the difference between the desired and measured concave separation.

The unit of the measured concave separation has to be the fraction of the grain feed rate, that is the threshing separation efficiency *TSE*, because its value has to be a process parameter that can vary with the crop properties but not with the momentary grain feed rate.

Thus the grain feed rate has to be known and its measurement has to be as accurate as possible. For that reason a delay of 10 s has to be taken into consideration in the measurement of the threshing separation efficiency (see also 3.4).

## 5.3. SPEED CONTROL

Cost minimisation calculation results an optimum machine speed and an optimum threshing speed. These speeds have to be adjusted by means of feedback speed controls, in our case a machine speed control and a threshing speed control.

### 5.3.1. *Machine speed control*

The task of this control is to reduce the difference between the calculated optimum area, $VW_o$ and the actual area $VW_a$ as much as possible. The relation $VW = VM \cdot CL$ is applied in this. The cutting width *CL* is assumed to be constant so that for our situation it applies that $CL = 5.9$ and $VM = VW/5.9$.

In the case that *CL* deviates strongly from this in practice then the fact should be reported to the control via a switchboard. Measurement systems are under development for this parameter.

The diagram in figure 5.3.1.1 describes the control and indicates the transfers of chapters 2 and 3.

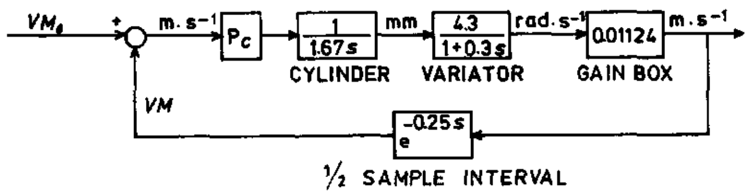



Figure 5.3.1.1. Machine speed control

It is also evident from the figures that an integrating control has been chosen. The integration action is realized by a hydraulic cylinder. An initial value of 45 has been calculated for $P_c$, based on the Nyquist plot in figure 5.3.1.2. The step response of $VW_o$ was studied in the simulation.

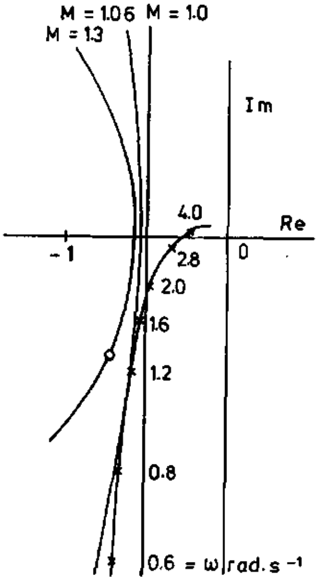



Figure 5.3.1.2. Nyquist diagram of machine speed control for $P_c$ = 45

From figure 5.3.1.3 it becomes clear that unnecessary wear of the driving system is best prevented by taking the value of $P_c = 15$, but $P_c = 25$ can also be used.

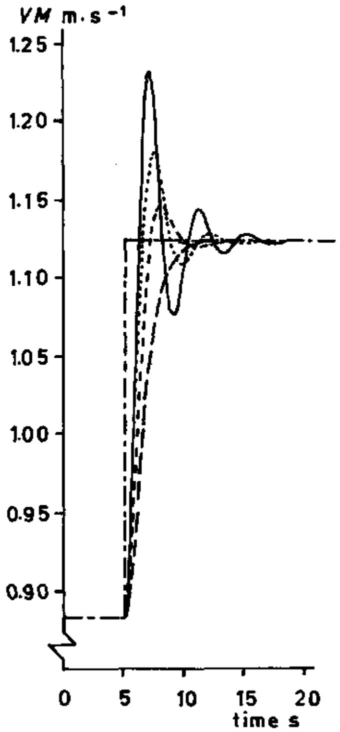



Figure 5.3.1.3. Response of machine speed (*VM*) to a step function in the optimum machine speed input from 0.883 to 1.125 $m{\cdot}s^{-1}$ (—·—·) for different values of $P_c$ of the machine speed control. *VM* lines — — for $P_c = 15$, ——·— for $P_c = 25$, ----- for $P_c = 35$, ——— for $P_c = 45$

## 5.3.2. *Threshing speed control*

The task of this control is to reduce the difference between optimum threshing speed and the actual speed $VT_o - VT_a$ as much as possible. The speed is adjusted by a hydraulic cylinder, so that integrating action is already present and is adequate for this control loop, shown in figure 5.3.2.1. Since we are concerned here with a peripheral speed, *VT* can be transformed via a constant transformation factor to *OMOUT*, the angular velocity in $rad{\cdot}s^{-1}$.

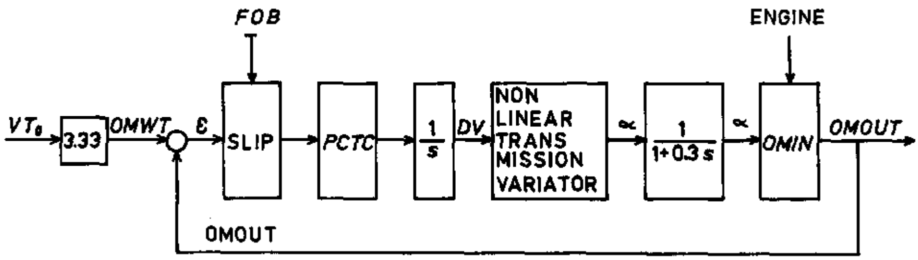



Figure 5.3.2.1. Threshing speed control

In order to prevent slip, there is a block in the loop preventing *OMOUT* from increasing too much when the force in the variator V-belt exceeds a certain value, in this case 3200 N. In the simulation this has been realized in the control system by making the first following time step $\underline{\varepsilon} = 0$.

The value 3200 N corresponds to a transformed power (depending on *OMOUT*) of about 55 kW.

Simulations have been performed with a sinusoidal signal on the control input at frequencies between 0.5 and 6 rad•s$^{-1}$ in order to ascertain the value of *PCTC*. By this means the amplitude corresponded to variations in the straw feed rate (*AFS*) of 0.6 kg•s$^{-1}$ around an average *AFS* of 2.5 kg•s$^{-1}$. $VT_o$ was then calculated via the threshing speed-to-feed rate equation $VT_o = 19 + 2.75\ AFS$. Figure 5.3.2.2 shows the Nyquist diagram of the control with $PCTC = 8 \times 10^{-4}$. Although a *PCTC* value of $10 \cdot 10^{-4}$ also gives a stable system, the value $8 \cdot 10^{-4}$ has been preferred because at this value the phase shift between the actual feed rate and $VT_a$ for $\underline{\omega} = 0.5 - 3$ rad•s$^{-1}$ is about 0.80, which corresponds exactly to the time delay between auger torque measurement and threshing cylinder (at $10 \times 10^{-4}$ this was $\pm$ 0.65).

There is no measurement time included in the measurement loop, because it is assumed that this control works fast. A sample interval of 0.5 s for instance will be too slow compared to the delay of 0.8 s.

Figure 5.3.2.3 shows the step response of *OMOUT* for a step of *AFS* from 2.5 kg•s$^{-1}$ to 2.1 kg•s$^{-1}$. There is a little overshoot. A high overshoot causes excessive wear of the V-belt drive.

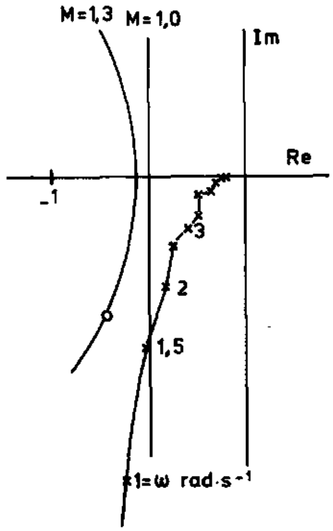



Figure 5.3.2.2. Nyquist plot of threshing speed control for *PCTC* = $8 \cdot 10^{-4}$

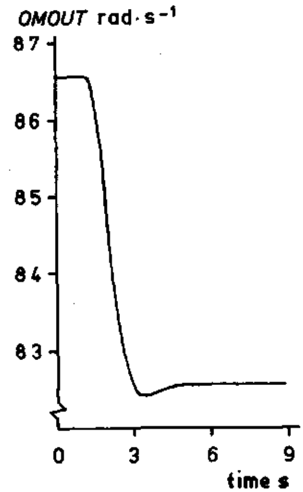



Figure 5.3.2.3. Step response of angul[ar] speed of the threshing cylinder (*OMOUT*) to a step function in specific feed ra[te] (*AFS*) from 2.5 to 2.1 kg·$s^{-1}$ for a *PCT*[C] value of $8 \cdot 10^{-4}$

## 5.4. CONTROL SYSTEMS

As was stated in 5.1.2, four different control systems will be studied. They will be discussed in detail in the following chapters as far as the implementation for the simulation is concerned. The simulation will be dealt with in paragraph 6. However, some results will already be discussed in the next chapter to show the effects of control adjustment.

### 5.4.1. *Loss control system*

This control system comprises the machine speed control and the cost minimisation calculation using the measured walker loss and the measured machine speed and estimating the momentary optimum machine speed (see figure 5.4.1.1). Owing to the time delay of 10.5 s in the process only low frequency variations in walker loss can be controlled. These variations are caused by the disturbances in the process variables and straw density levels. The higher frequencies in loss measurement have to be filtered out.

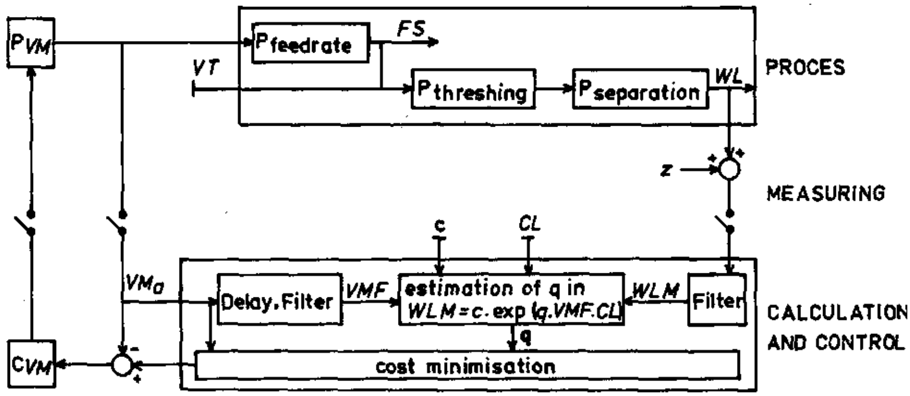



Figure 5.4.1.1. Loss control system

The low-pass filter used was an exponential smoothing filter, that is a discrete time filter acting as a first-order low-pass filter (Verbruggen, 1975).

The measured machine speed has to be in phase with the measured walker loss so that the measured value of the speed is delayed 10.5 s.

The value of $q$ was then calculated from the equation $\overline{WL} = c \cdot \exp(q \cdot VW)$ in which $c = 3.4 \cdot 10^{-4}$. This value is chosen because it is near the estimated $D_o$ values of the model $WL = \exp(D_o + D_1 \cdot FS)$ (see table A 4.2.1.3).

The necessary adjustment of the filter is examined by simulation of the system in two ways. The response to a 25% step in straw density level of 0.6 $kg \cdot m^{-2}$ was studied in the output of machine speed, feed rate, walker loss, and calculated $q$. The value of $q$ shows the input of the cost minimisation criterion. Figure 5.4.1.2 shows the response for a breakpoint frequency of the filters of 0.2 $rad \cdot s^{-1}$. The response to initial values can be seen at the beginning of the curves. The step in straw density can be seen at t = 11 in the straw feed rate at the cutter bar. Its effect on walker loss 10.5 s later, the response of $q$ and the machine speed is recognised at t = 22. As a result of that, again 10.5 s later, the walker loss decreases (at t ≈ 33) so that $q$ also reacts. This will cause a slight resonance, which is a reason of decreasing the breakpoint frequency of the filter.

This effect can also be seen in figure 5.4.1.3 in which the behaviour of controlled machine speed is shown in a process simulation based on the input of apparent straw density values obtained in test nr. 61. The three

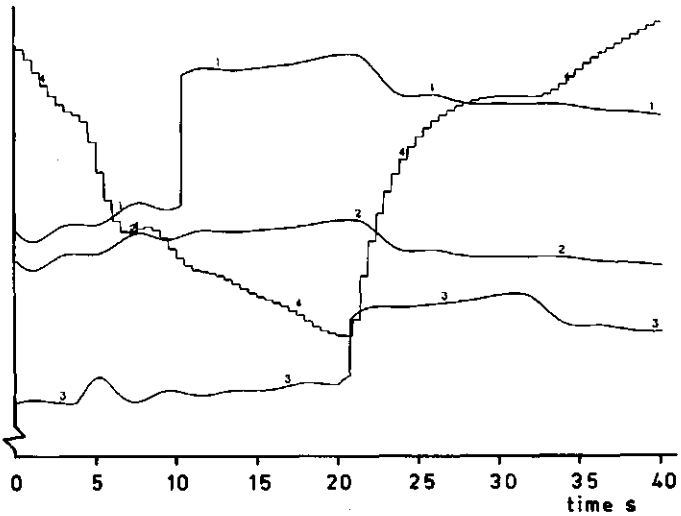



Figure 5.4.1.2. Responses for the loss control system of process variables to a step function on straw density at t = 11. Line 1 represents straw feed rate, measured at the cutter bar. Line 2 represents machine speed. Line 3 represents walker loss and line 4 the input of the cost minimisation criterion i.e. the value $q$ of the equation $WL = c \cdot \exp(q \cdot VW)$

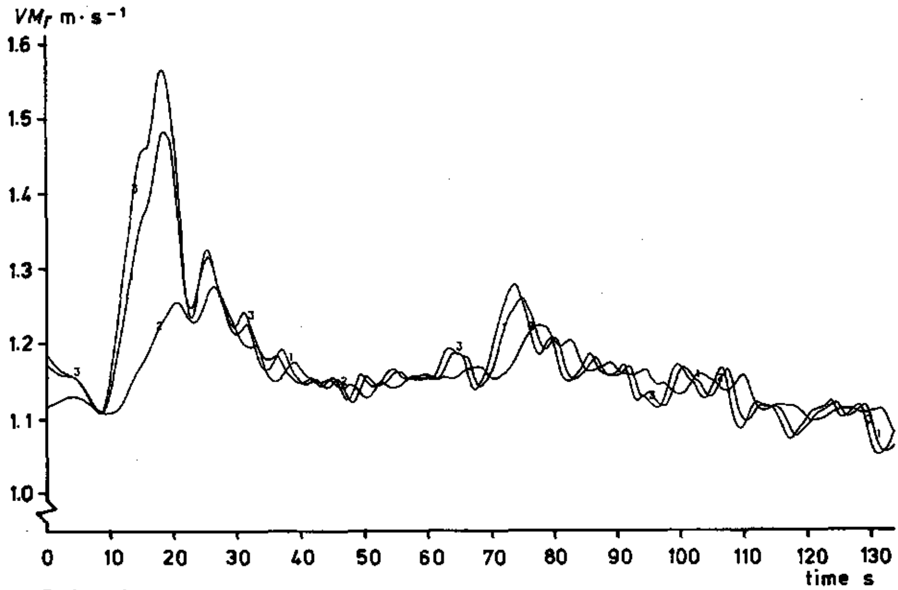



Figure 5.4.1.3. Simulated actual machine speed ($VM_a$). Output of the loss control system for different values of the breakpoint frequency ($f_b$) of the low-pass filter in the control system. Line 3: $f_b$ = 0.40, line 1: $f_b$ = 0.32, line 2: $f_b$ = 0.16 rad·s$^{-1}$. Input of the simulation is the apparent straw density data file

breakpoint frequencies of the filters were 0.40, 0.32 and 0.16 $rad \cdot s^{-1}$. The last named evinces reasonably stable behaviour, for which reason this breakpoint frequency was used in the first simulations.

### 5.4.2. *Loss-feed rate control system*

The inputs of this control system are walker loss, feed rate and actual machine speed. The output is the momentary optimum machine speed. In fact this optimum speed has to be calculated as shown in figure 5.4.2.1.

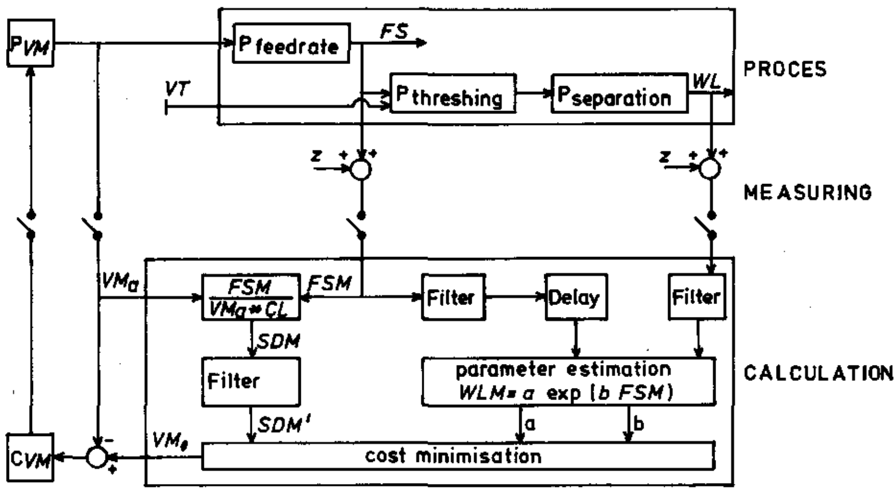



Figure 5.4.2.1. Loss feed rate control system

The values of a and b have to be calculated in an on line parameter-estimation procedure, using the measured value of the walker loss (*WLM*) and the delayed measured value of the feed rate (*FSM*). In this estimation procedure, filtering is needed to be sure that the values of a and b are good estimates. Preliminary research showed that the used data of measured auger torque and walker loss have to be taken from an estimated period of about 30 to 50 s. Only long-term variations in crop conditions will thereby be taken into consideration. The optimum technique for this parameter estimation still has to be worked out in further research. It has to be some kind of recursive technique with a forgetting factor. In the simulations dealt with in the next chapter, values $a$ and $b$ are used that are calculated off line over a period of about 150 s. They are then held constant during that time. (In 4.6 and A 4.2.1.c $a$ and $b$ were called exp ($D0$) and $D1$, respectively.)

This is a simplification needed for the simulation but it deviates from the real situation where only on-line estimation can be used. Estimated values of $a$ and $b$ will change more rapidly then (see also 5.5 and chapter 6)

The behaviour of controlled machine and threshing speeds in the higher frequencies is affected by the variations in straw density, delay and accuracy of the measurement. The straw density is estimated from the feed rate and the actual machine speed. The estimated value of the straw density has to be filtered to be sure of quiet behaviour on the part of the control.

This is tested by simulation of the response to a step of 0.15 $kg \cdot m^{-2}$ in the apparent straw density input with a mean level of 0.66 $kg \cdot m^{-2}$ and inspection of the control behaviour of the output of the control, that is the realized machine speed. Figure 5.4.2.2 shows the responses at the breakpoint frequencies of the filters of 0.33, 0.4 and 0.5 $rad \cdot s^{-1}$. The behaviour of 0.4 $rad \cdot s^{-1}$ was preferred as it was quiet enough. The effect on costs of other levels will also be tested and dealt with in chapter 6. In figure 5.4.2.2 the acceleration values of the simulation with breakpoint frequency of 0.4 $rad \cdot s^{-1}$ are also plotted. An additional constraint for this control, namely is the comfort of the operator, who has to bear the continuous acceleration and deceleration of the machine.

Former research with a feed rate control system (Huisman, 1974; Van Loo, 1977) has shown that the controller has to be less stringently adjusted than was necessary for stability reasons (see also 6.2.2). The values of the acceleration and deceleration then measured in the field were maximum 0.4 $m \cdot s^{-2}$. There are no standards of acceptable levels of acceleration and deceleration for these situations. Only little information about standards governing passenger trains is available on this subject (Rookmaker, 1967).

For normal acceleration and deceleration, limiting levels between 0.7 and 1.5 $m \cdot s^{-2}$ are mentioned. For an operator on a combine harvester the speed of which is continuously changing, the limiting levels have to be lower, for which reason we adopt the level of 0.4 $m \cdot s^{-2}$ (see also 6.2.2).

An acceleration limitation element could be introduced in the control system but the simulations with the step functions and data files showed that this would not be necessary at the used breakpoint frequencies of the filter. The maximum decelerations as a reaction to the feed rate step functions in figure 5.4.2.2 for the breakpoint frequencies of the filter, that is 0.33, 0.4, 0.5 $rad \cdot s^{-1}$ were 0.04, 0.06 and 0.065 $m \cdot s^{-2}$.

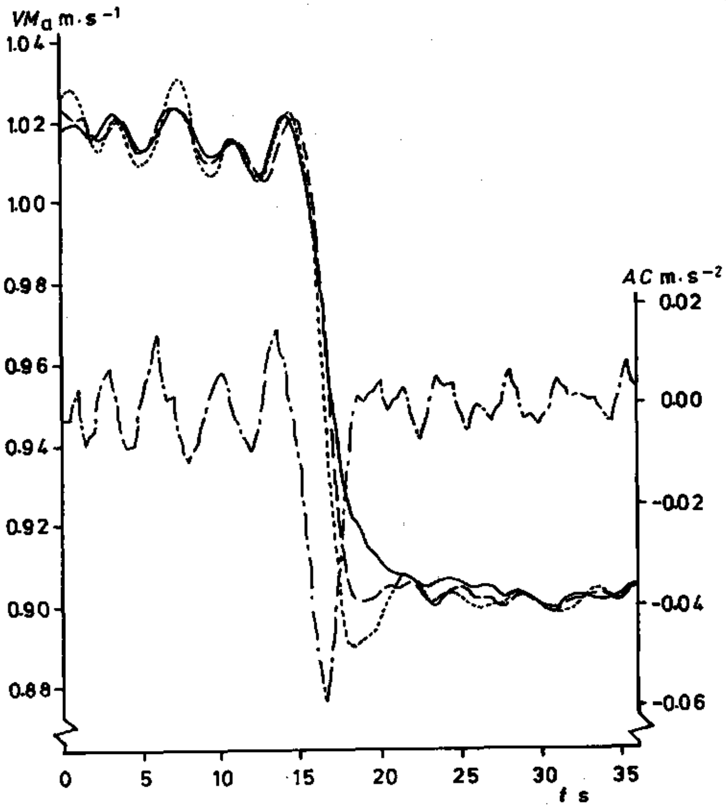



Figure 5.4.2.2. Simulated response of actual machine speed ($VM_a$) and acceleration ($AC$) to a step function in straw density for different values of the breakpoint frequency ($f_b$) of the low-pass filter in the loss feed rate control system. The measured feed rate includes measurement noise. $VM_a$ lines: ——— for $f_b$ = 0.33, — — for $f_b$ = 0.4, ---------- for $f_b$ = 0.5 rad·s$^{-1}$; $AC$ line —·— for $f_b$ = 0.4 rad·s$^{-1}$

### 5.4.3. *Loss-feed rate-threshing speed control system*

This control system comprises the loss-feed rate control and an additional threshing speed control (see figure 5.4.3.1). This means in fact that the loss-feed rate control reacts to the low-frequency part of the disturbances of the calculated straw density and to the process disturbances of threshing and separation measured by the variation in $a$ and $b$ of the loss feed rate relation.

The threshing speed control reacts to the variations in the measured feed rate as is explained in 5.2.3. The sources of these variations are:

- variations in the calculated straw density of frequencies which the loss feed rate control could not deal with because of delay in the header;

- feed rate variations introduced because of redistribution in the header;
- variation on the part of the estimated parameters in the loss feed rate relation giving rise to other feed rate levels because such other feed rate levels mean other threshing speeds.

The response in total machine losses to a straw density step and threshing efficiency parameter will be shown in 5.5.

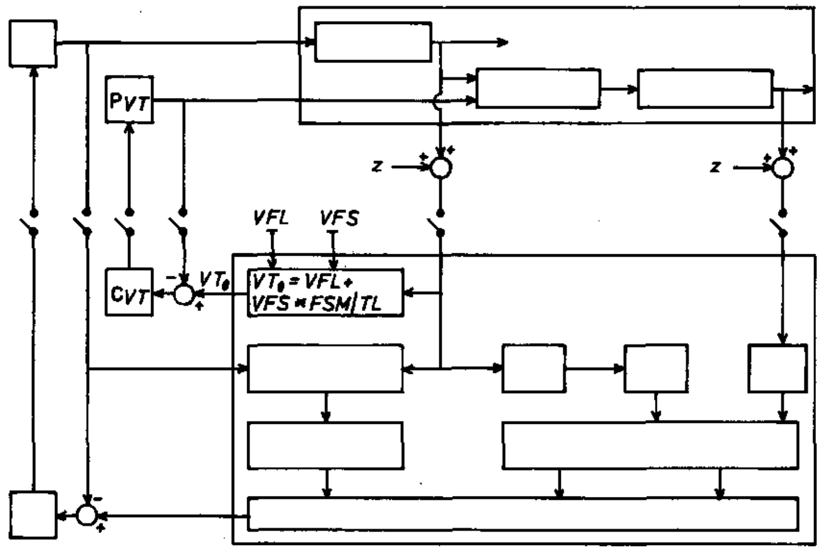



Figure 5.4.3.1. Loss feed rate threshing speed control system

### 5.4.4. *Loss-feed rate-threshing separation control system*

This control system can be regarded as the loss feed rate threshing speed control in which the feed rate to optimum threshing speed relationship is adapted to the threshing separation characteristics. These characteristics change very slowly due to differences in crop properties, so that the adaption can be done slowly, too (see figure 5.4.4.1).

It can then also be done more correctly, because we can filter the high-frequency disturbances during measurement of the threshing separation efficiency.

Ideally we should like to adapt both the level and the slope in the threshing speed-to-feed rate equation. For the purpose of this study it

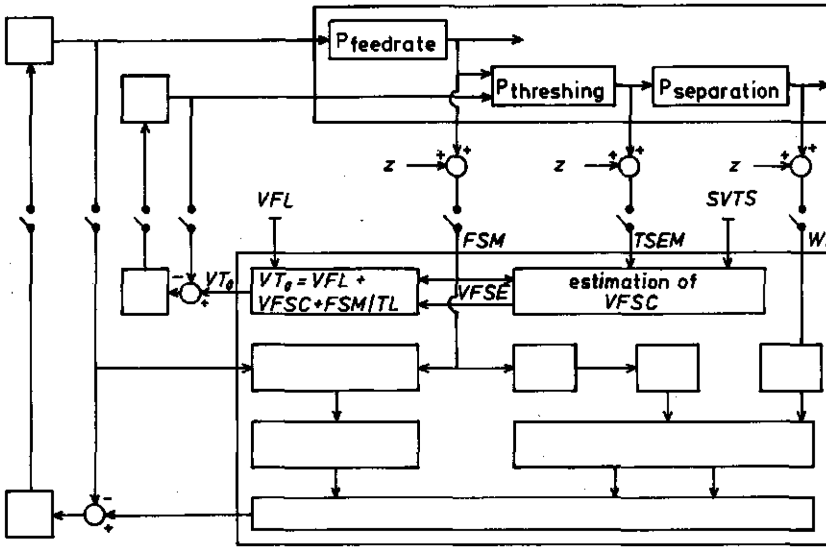



Figure 5.4.4.1. Loss-feed rate-threshing separation control system

*will do to adapt just one of these*, because it underlines the fact that we are never likely to know the real optimum relationship.

As is argued in paragraph 5.3, we will adapt the slope of the relation. For the calculation of the estimated slope (*VFSC*) we will use the steepest descent method as described by Eykhoff (1977).

The principle of this method is to minimize the difference between the output of the real process as it should be and the output of the process as influenced by the estimated relation (see figure 5.4.4.2). Let $N$ be the transfer of the real process and $\hat{P}$ the transfer as influenced by the estimation. Then $e = N \cdot FS - \hat{P} \cdot FS$. If we want to minimize the error function

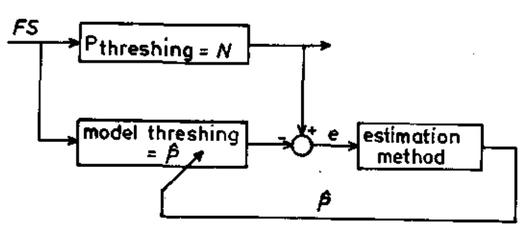



Figure 5.4.4.2. Method for parameter estimation in the threshing separation transfer

$E = e^2$ with monotonic convergence

then $\frac{d\hat{P}}{dt} = - v \cdot \frac{\partial E}{\partial \hat{P}}$

because

$$\frac{\partial E}{\partial \hat{P}} = 2e \cdot \frac{\partial e}{\partial \hat{P}} \quad \text{is} \quad \frac{d\hat{P}}{dt} = - 2v \cdot e \frac{\partial e}{\partial \hat{P}}$$

We know that

$$\frac{\partial e}{\partial \hat{P}} = - FS$$

and then

$$\frac{\partial \hat{P}}{\partial t} = 2v \cdot e \cdot FS$$

and

$$\hat{P} = \int 2v \cdot FS \cdot e \cdot dt$$

The real feed rate-to-separation relationship is not known in practice, but we only want to realize one specific separation, so that this level (*SVTS*) can also be used for the $N \cdot FS$ input. Hence the calculation of *VFSC* is done as shown in figure 5.4.4.3. The value of $2v$ can be low because of the slow action that is needed. The value of $2.5 \cdot 10^{-3}$ gives a small overshoot and is chosen by simulation of a step function. Figure 5.4.4.4 shows the responses of the threshing separation efficiency to a step in the value of *BETA* from 1.76 to 1.61 for three different values for $2v$, namely $1.0 \cdot 10^{-3}$, $2.5 \cdot 10^{-3}$ and $5.0 \cdot 10^{-3}$.

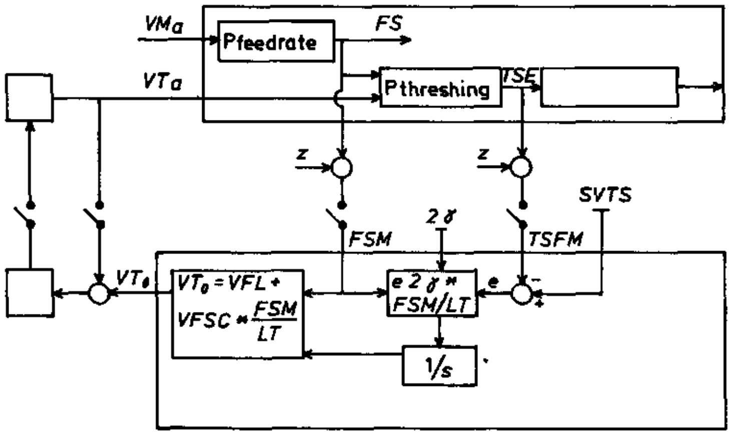



Figure 5.4.4.3. Estimation procedure for the slope in threshing speed to feed rate relation *VFSC* of control system 4

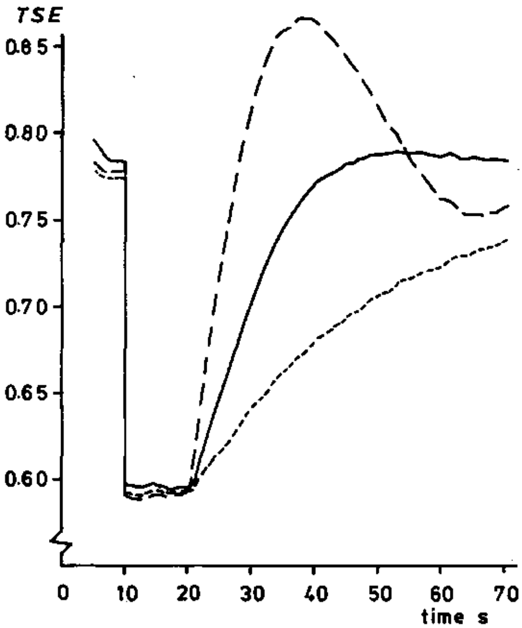



Figure 5.4.4.4. Response of threshing separation efficiency to a step function in *BETA*, from 1.76 to 1.61 for different values of the proportional factor $2v$ in the adaption procedure of the slope in the feed rate to threshing speed relation

## 5.5. DISCUSSION

The control systems described in the previous chapters are designed to minimize total harvest costs and to calculate the benefits.

The systems themselves are not optimized in the sense of finding the best control adjustments or the best estimation techniques, because much more field research has to be performed for that. The aim of the design was to obtain systems that could be simulated, on the basis of empirical disturbances to get an impression of the differences in the expected levels of benefit, so as to decide on the field research that has to be continued and the control systems which have to be improved.

The control systems and, in particular, the parameter estimating techniques are simplified at some places because the simulation would become too complicated and time-consuming. The following simplifications have been made:

- the value of c in the loss control system is not adapted to crop conditions;

- the estimate of parameters $a$ and $b$ of the loss feed rate control system was performed "off line" over the rather long distance of 178.5 m;
- the threshing speed optimisation criterion can be improved.

However, the differences between the four control systems are great enough to decide on the differences in the benefits to be expected.

The differences will be shown on the basis of figure 5.5.1. In this figure the responses of walker loss to two step functions are plotted. The first step is in straw density. It steps from 0.6 to 0.75 $kg \cdot s^{-1}$. The second step is 20 s later and *BETA* then steps from 1.76 to 1.61. Both steps affect walker loss and therefore machine speed. The abscissa has the travelled distance dimension, so that the second step does not occur at the same place, depending on the machine speed in the previous period.

The manually control(system o, line ...........) has a constant speed so that losses increase similarly to the steps in straw density and *BETA*. The machine speed was lower than in other cases, hence feed rate and the loss were lower. The simulation time was the same for the various controls with the result that the travelled road was shorter at manual control.

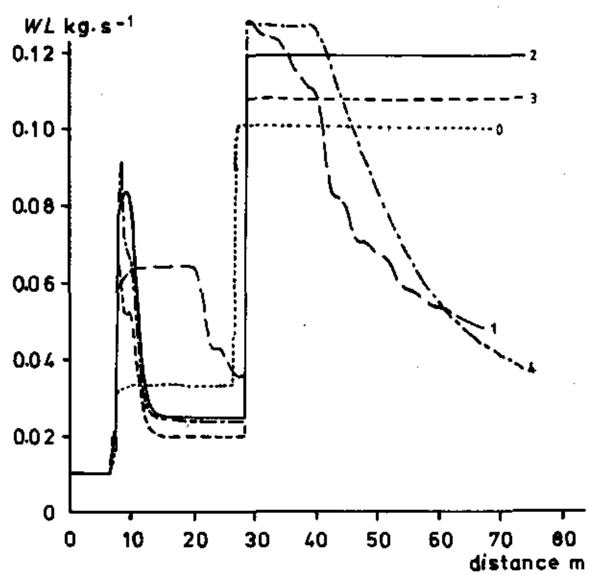



Figure 5.5.1. Simulated responses of walker loss ($WL$) to two step functions for the various control systems as a function of traversed distance. At t=0 (distance=0) the straw density increases from 0.6 to 0.75 $kg \cdot s^{-1}$ and 20 s later the value of *BETA* decreases from 1.76 to 1.61. The simulation time is the same for each system, indicated by 0 ... 4. See text.

In the response of the loss control system (system 1, line —— ——) a delay of 10.5 s can be recognized after both steps. The speed decreases after each step (with some resonance) resulting in a decrease in feed rate and loss.

The feed rate-loss control system (system 2, line ————) reacts more quickly to the straw density step than system 1 but does not react to the *BETA* step. This is because the loss is not measured in the simulation, but the values of the parameters in the loss to feed rate relationship are estimated in advance. In the simulations for cost calculation, *BETA* and said parameters undergo a similar change. In a control system on a combine harvester the estimation can, of course only be done after the loss occurs, but over shorter travelled distances than 178.5 m. When $a$ and $b$ then change, the speed changes accordingly. The same facts apply also to the next control, but in this case the threshing speed reacts to feed rate, so that loss is lower for the loss feed rate threshing speed control (system 3, line ----).

The loss feed rate separation control system (system 4, line —·—·—·—) adapts the threshing speed feed rate relation to the threshing separation efficiency. After the *BETA* step the separation decreased below the desired level so that threshing speed continuously increases after the delay of 10 s. Losses thus decrease accordingly.

The effect of these control actions on cost, will be discussed in the next chapter.

# 6. Simulations

## 6.1 . METHOD

### 6.1.1. *Introduction*

In the foregoing chapters the process and control-system models have been shown separately. In the present chapter they will be presented linked together in the simulation program. The simulation process will be explained in 6.1 and 6.2, in particular on discussion of the input. The stages in the simulation program, the parameter estimation and finally the comparison of simulation results with experimental results are explained in 6.2. The results of the simulations are dealt with in 6.3 on the basis of the researched variables of our problem and the conclusions as to the costs of the harvest will be given in section 4 of chapter 6.

### 6.1.2. *Simulation program CSMP*

The simulation has been carried out on the digital computer DEC10 of the Agricultural University, using the Continuous System Modelling Program CSMP III of the IBM Corporation. This program is thought to be suitable for our purposes. Only a short description of the program will be given in the appendix as the details of the language can be found in the Program Reference Manual (Anonymus 1975). The CSMP Function Blocks used in our program and the added ones will also be given in the appendix.

The accuracy of the simulations depends on the calculation time step, the integration method and interpolation techniques of the function generators chosen.

For the time step the value of 0.1 s was used because the smallest time constant in the process is 0.3 s. This also was tested by comparing the results of a small number of runs with time step values of 0.1 and 0.05 s, the results showing a very slight difference (see also 6.3.3.14).

The chosen integration method was the fixed step, first order Euler rectangular method because with this method and the chosen time step no stability problems were encountered that demanded more sophisticated methods.

The function generators will be discussed when they are introduced in the next chapters. Fig. 6.1.2.1 shows the main elements of the simulation program.

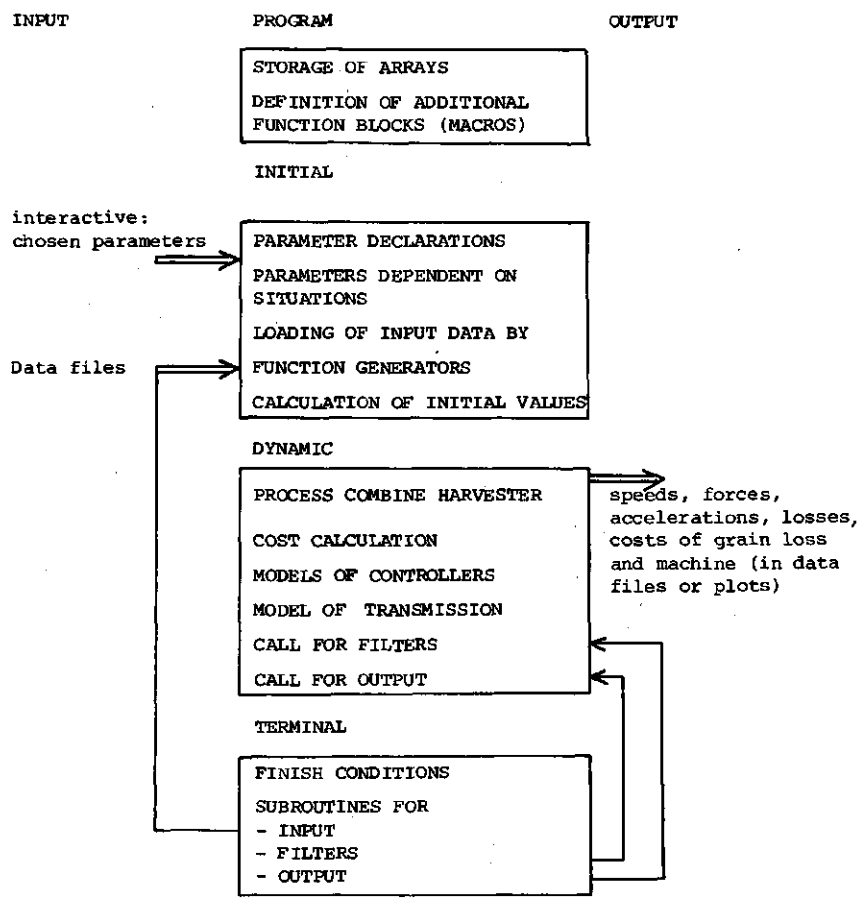



Figure 6.1.2.1. The main elements, inputs and outputs of the program

### 6.1.3. *Simulation input*

The input can be split up into three categories.
- Data on the variation of the crop properties;
- data on the choice of control system and variables of the controllers;
- data specifying the parameters in the cost criterion.

#### 6.1.3.1. *Data concerning crop properties*

The straw density input is simulated by connecting the data of 8 different data files of "apparent straw density" together. Each data file comprises data that represent the straw density values, averaged over 0.25 m of traversed distance and a cutting width of 5.9 m, calculated from field test data as explained in A 4.2. The data represent a total distance of 187.5 m that we will call a swath. The straw density data are stored in a function generator as a function of distance. The read-out data are calculated by linear interpolation, because higher order interpolation can give rise to negative, thus unrealistic, values if stored straw density data are close to zero.

These 8 swaths together represent a sample of the variation that a combine harvester is faced with when operating at the Flevopolders in Holland. The mean straw density differs from one swath to the other (see table 4.2.1).

A second class of input data are the crop properties affecting the grain separation in the process. In the simulation they are constant within each swath, but can differ from one swath to the other, resulting in different steady state conditions in the process.

These properties are:

| | |
|---|---|
| - threshing coefficient | *BETA* |
| - walker efficiency parameter | *WEP* |
| - grain-to-straw ratio | *GS* |
| - mean grain yield | *YIELD* |

These values are also stored in function generators as a function of distance and are read out by linear interpolation. The values used in the simulation have to be regarded as a sample of the wide variation of mean values encountered in the field. Their values are given in table A 4.1.2.3.

In the field, however, the values of these parameters will also vary within the swath but this variation is small compared to the differences between the swaths. In reality these mean levels usually remain nearly constant even for a period longer than the duration of the harvesting of a swath in the simulation. Thus the harvesting of a swath in the simulation could be repeated several times, but is not, in order to reduce the calculation time of the computer.

When another swath is started in the simulation the crop properties are really changed as they are taken to be affected by other crop conditions in the field, such as weather or crop variety. The control systems are expected to react to this sudden change. Since controller 1 reacts slowly and the effect of this controller is intended to be compared fairly with the others, this controller is offered the swath data three times in successsion before the next swath enters the simulation.

This procedure in the simulation is *assumed* to be close to the reality in the field, since the various control systems follow the small and slow changes in crop properties in the same way, but will react differently to the fast and large variations in crop properties. Such changes in properties are due to differences in soil conditions and to the start of another crop.

6.1.3.2. *Data concerning control systems*

For manually controlled runs (system 0) the machine speed is put in from the swath data, hence each swath has its own constant machine speed equal to that measured in practice.

For manual controlled runs as well as those of control systems 1 (loss control system) and 2 (loss-feed rate control system) the speed of the threshing cylinder is adjusted at a mean value of 30.0 $m \cdot s^{-1}$ by setting the position of the variator (*DV*) to 0.032 m (see 2.3.3). In this way the threshing cylinder speed varies dynamically with variation of straw feed as in reality. For control systems 3 and 4 the threshing cylinder speed is automatically controlled.

For the loss-feed rate control system (system 2) values are needed for the parameters in the loss-feed rate equation for the optimum machine speed calculation as is explained in 5.2.1 and 5.4.2. The parameter values are calculated for each swath based on data of the field tests as explained in 4.6 and A 4.2.1. In the simulation these values are also stored in function generators like the crop properties. When they are read out of the function generator, the output is first treated by a first order low-pass filter with time constant $\underline{\tau}$ = 10 s for the following reason. Used in practice the parameter values of the control system are *assumed* to be estimated by such a method that loss and feed rate data are averaged over about 50 s (see also 5.4.2 and 6.2.4.1). In addition, the loss is delayed by 11 s, so it takes about 60 s untill the change in crop property is completely incorporated in the parameter values. This behaviour can be *approximated* by a first-order low-pass filter with a time constant of roughly 30 s. Since the control system cannot adjust the machine speed at the optimum level as long as the parameters are not correctly estimated, the costs are also suboptimal for that time. If the parameter values in the simulation differ for two succeeding swaths, the costs are suboptimal for the period the parameter values change in the first part of the second swath. This period would be about 60 s with $\underline{\tau}$ = 30 s, a relatively long period compared to the simulation period of 187.5 s, when the machine speed is 1 $m \cdot s^{-1}$. Since each swath is simulated three times in succession for control system 1 and once for control systems 2, 3 and 4, control system 1 could be ahead as regards costs. For this reason the suboptimum period of control systems 2, 3 and 4 was decreased by a factor of 3. $\underline{\tau}$ was therefore taken as 10 s. In the cost minimisation criterion of the control systems, the parameter *YIELD*, that is the grain yield also, has to be considered as an estimated parameter so that the cost of timeliness loss can be calculated correctly. However, the timeliness loss fraction is calculated and used in the calculation as an expectation of the mean loss fraction over a certain number of years, so that this loss will not occur in the same way for the specific harvest situation in practice. In practice we do not know the real timeliness loss either. A value for *YIELD* that is an expectation of the mean grain yield, is therefore accurate enough. The mean yield of the two wheat varieties, that were used for the input data measured in the field, was used and also treated in the simulation as a crop property. The time constants of the integrating action and the break-point frequency of the filters (see 6.2) of the controllers are also input parameters concerning the control systems. The effects of the values of these parameters will be studied in 6.3.

### 6.1.3.3. *Data concerning cost calculation situations*

The costs of wheat combine harvesting using the different controls will be calculated for 6 different situations in which the controller is used. These situations are characterized by various cost-determining variables, affecting not only the cost calculation but also the cost minimisation algorithm of the control system because they influence the machine speed for minimum cost.

For the cost situations 1...4 (see table 6.1.3.3.1) different timeliness loss fraction lines are used (see fig. 1.4.1.3). These different lines are put into the simulation by function generators loaded from data files containing the fractions of timeliness loss per value of *VW*, that is the harvested area, increasing per 0.1 $m^2 \cdot s^{-1}$ from 0 to 10 $m^2 \cdot s^{-1}$. In the cost minimisation criterion the first derivates of these lines are used, so that function generators are loaded from other data files containing the slope values per 0.1 $m^2 \cdot s^{-1}$. The values used in the simulation are calculated by linear interpolations to the actual value of *VW*.

For situations 5 and 6, constant values of timeliness loss percentages are used because in these situations the machine cost lines determine the cost minimisation. The cost-determining variables are listed in table 6.1.3.3.1. For explanation see 2.2 and A 2.2.

Table 6.1.3.3.1. Cost-determining factors in the various cost situations

| Cost situation | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| User | Farmer | IJ.D.A. | Farmer | IJ.D.A. | Contractor | IJ.D.A. |
| Timeliness loss risk % | 25 | 25 | 16 2/3 | 16 2/3 | 25 | 25 |
| Timeliness loss % | f(*VW*) | f(*VW*) | f(*VW*) | f(*VW*) | 0.057 | 1.65 |
| *AAN* ha | 100 | 175 | 100 | 175 | 100 | 175 |
| *NE* $h \cdot ha^{-1}$ | 0.20 | 0.27 | 0.20 | 0.27 | 0.20 | 0.27 |
| *LO* $fl \cdot h^{-1}$ | 20.00 | 40.00 | 20.00 | 40.00 | 32.60 | 40.00 |
| *MVC* $fl \cdot ha^{-1}$ | 54.00 | 58.00 | 54.00 | 58.00 | 66.00 | 58.00 |
| *VMN* $m \cdot s^{-1}$ | - | - | - | - | 1.0 | 0.9 |
| *AFC* $fl \cdot yr^{-1}$ | 35280.00 | 20387.50 | 35280.00 | 20387.50 | 36350.00 | 20387.50 |
| $V_1$ $fl \cdot kg^{-1}$ | 0.534 | 0.505 | 0.534 | 0.505 | 0.534 | 0.505 |

6.1.4. *Simulation output*

The aim of the study was to calculate the expected financial benefits of the various control systems, hence the calculated costs of combine harvesting are stored in output files. Besides, it is informative to follow the simulated processes so losses, speeds, accelerations and forces are also stored in output files. The total costs of the various control systems have to be calculated in a way that enables them to be compared. The unit $fl \cdot ha^{-1}$ is the most informative for the farmer as well as for the contractor because the total costs are then clear, given the known area to be harvested. In the simulation the calculations are done per time interval, so that costs also will be computed per time interval but in fact refer to the area harvested in that time interval. The costs of each interval are added until the total area (8 swaths) is harvested. This is the case when the traversed distance is $8 \cdot 187.5 = 1500$ m or three times as much in the case of control system 1.

*Machine costs*

The calculation of machine costs is done as explained in 2.2.The sum of the calculated costs in $fl \cdot ha^{-1}$ per time interval is then multiplied by the area harvested in that interval, that is $VW$ in $ha \cdot s^{-1}$, so that we know the costs of that time interval in $fl \cdot s^{-1}$. These costs then are integrated.

*Costs of machine losses*

The cost of machine losses is found by integrating the values per time interval of the sum of the costs of breakage loss, walker loss, threshing loss and sieve loss calculated as explained in 2.3 by the model of the process.

*Costs of timeliness loss*

The costs of timeliness loss are in reality not known until the harvest is completed and the total harvest period is known. In our simulation we can only calculate the costs for our sample of 8 swaths. We therefore calculate the "expected" timeliness loss of each time interval on the basis of the loss that would occur, were the whole harvest done at the machine speed of that particular interval and at the same grain yield of the swath then harvested. We could have used the mean machine speed of our 8 swaths together but since the timeliness loss curve, as a function of machine speed (or *VW*) is not linear, the result would be too optimistic in the case of mean low machine speeds. This is because the timeliness losses occur mainly at the end of the season and are therefore considerable when the harvest season is long owing to low machine speeds. In this way the risk of high timeliness loss has become part of the cost calculation results. The timeliness loss is calculated from the integrated product of the grain feed rate (*FGTD*), the timeliness loss fraction (*TILF*) and the value of the grain ($V_1$). The value of *TILF* is found from the function generator as explained in 6.1.3.3.

*Costs of wear of threshing cylinder V-belts*

The costs of the wear of the V-belts driving the threshing cylinder are calculated as explained in 2.2, per time interval and then integrated.

*Total costs*

The above-mentioned cost factors are added together and then, depending on the desired dimension, divided either by the harvested area or harvest duration giving output data in $fl \cdot ha^{-1}$ or $fl \cdot s^{-1}$.

## 6.2. SIMULATION MODEL

Here the models dealt with in chapter 2, will be discussed as to the adaption to the simulation. In addition in some cases the sensitivity of various parameters will be analysed and the comparison with experimental data will be made. The parameter estimation technique for some important parameters will also be discussed.

### 6.2.1. *Threshing and separation*

Fig. 6.2.1.1 shows the processes of threshing and separation in a block diagram. The input parameters of the models, enclosed in a circle are variable and originate from function generators or controls. The other

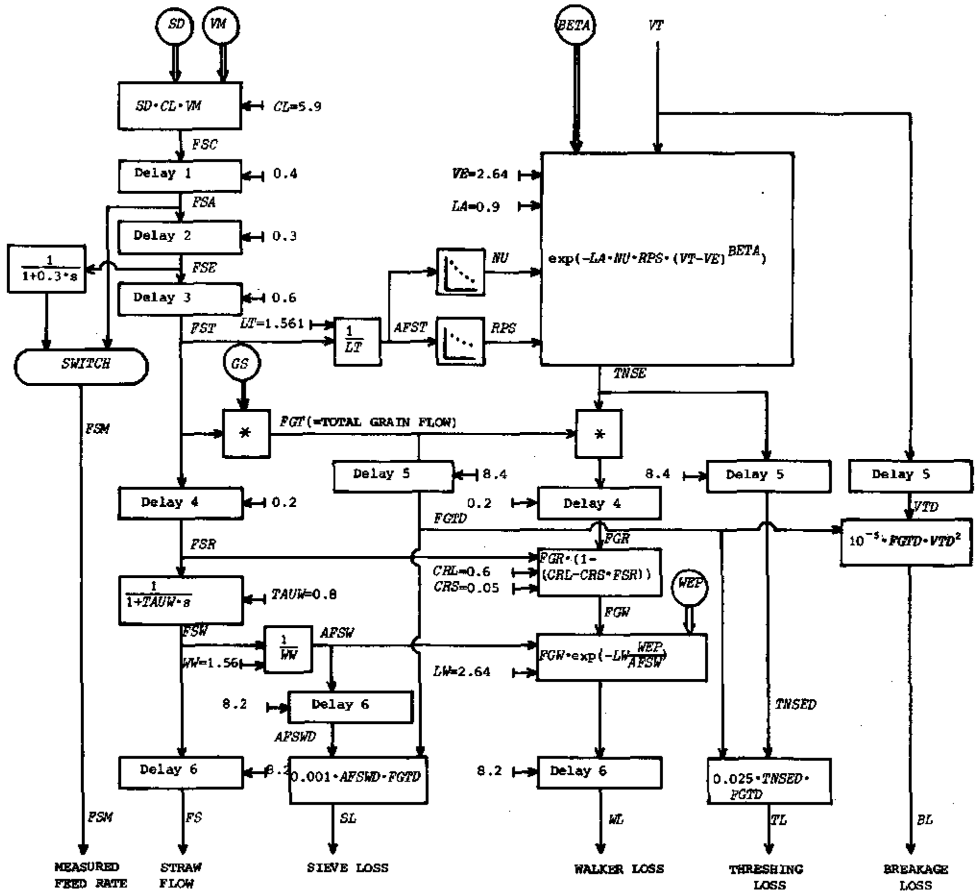



Figure 6.2.1.1. Flow chart of the simulated process of threshing and separation

input parameters are indicated at their default values.

The sensitivity of the various parameters affecting the walker loss will be studied first. These parameters are: threshing coefficient (*BETA*), walker separation parameter (*WEP*), and rotary separator parameter (*CRL*). Figures 6.2.1.2 ... 6.2.1.4 show how the various values of these parameters influence the walker loss-to-feed rate relation.

These plots show results of experiments as well as of simulations so that comparison is also possible. The points indicated by (▫) in these plots represent the values from field experiments as explained below. These are the 23 mean values of walker loss and straw feed rate calculated for

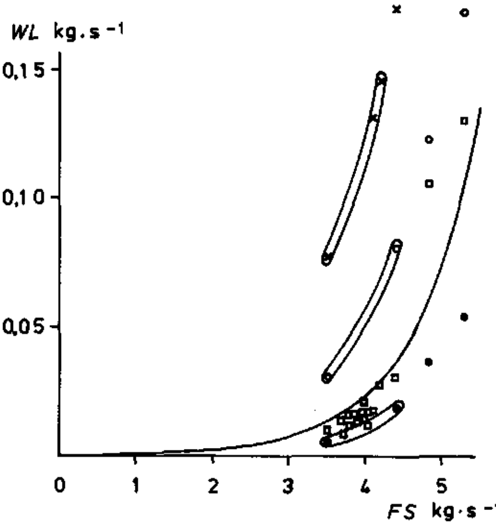



Figure 6.2.1.2. Data of field measurements and simulation of straw feed rate (*FS*) and walker loss (*WL*), averaged over 8 m traversed distance. Measured data of field test 31 (□) and least square best-fit curve of form $WL = a \cdot \exp(b \cdot FS)$ on these data (———). Simulated data for *BETA* = 1.4 (×), 1.6 (o) and 1.8 (●) (*WEP* = 1.8, *CRL* = 0.55). Where the simulated data are too close to each other for a clear plot,they are not plotted but shown by the enclosing line

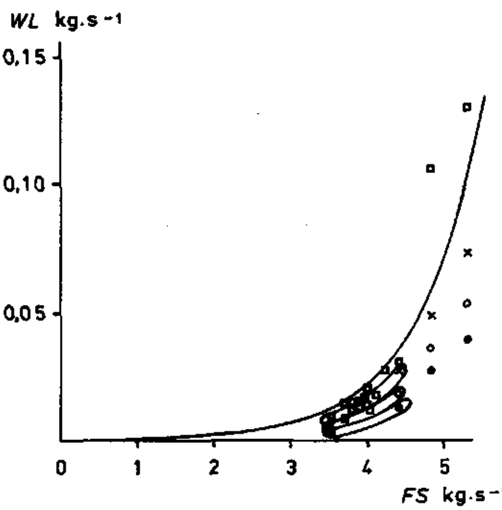



Figure 6.2.1.3. Same as for figure 6.2.1.2 but simulated data for *WEP* = 1.4 (×), 1.8 (o), 2.2 (●) (*BETA* = 1.8, *CRL* = 0.55)

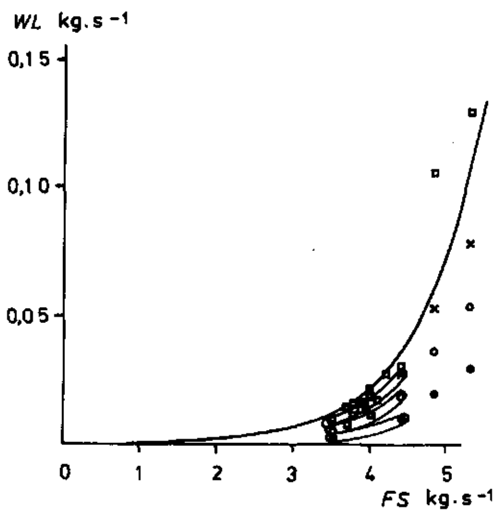



Figure 6.2.1.4. Same as for figure 6.2.1.2 but simulated data for *CRL* = 0.35 (×), 0.55 (o) and 0.75 (●) (*BETA* = 1.8, *WEP* = 1.8)

consecutive stretches of 8 m traversed by a combine harvester. The "apparent" straw density of the same field test was calculated per 0.25 m and stored in a data file in the way as described in A 4.2.1.c. This data file, representing data of a total distance of 187.5 m, was used as input of the simulation applying the process parameter values as given in the plots.

The machine speed was the same in the simulation and the field test and the simulated loss and feed rate were also averaged per 8 m simulated traversed distance. These values are represented in the figure by (×), (o) and (•).
The points are often so close together that, for the sake of clarity, it was decided to enclose the area of greatest density. Finally the plot also shows a line, representing the least square, best fit curve of shape $y = a \exp(b \cdot x)$ on the data (□) of the field experiment.

Each figure shows the same points and line of the data of the field experiment and different simulated points. In each figure just one parameter is varied, while the others are retained at the default values.

Figure 6.2.1.2 shows that the model is very sensitive to *BETA* and figures 6.2.1.3 and 6.2.1.4 demonstrate that the same effect on loss can be obtained by both *WEP* and *CRL*. It was therefore decided to keep *CRL* at a constant level of 0.6 for the simulations and to estimate the values for *BETA* and *WEP* for each swath by standard parameter estimation techniques, such that the walker loss in both simulation and experiments are similar.

A package of parameter estimation techniques was used containing various optimisation routines described by Himmelblau (1972). The error criterion of the routines was:

$$J = \int \{(\text{measured loss}) - (\text{calculated loss})\}^2$$

The tested routines were (Dongen, 1981):
- DFP, using the Davidon - Fletcher - Powell algorithm
- POWEL, using the Powel algorithm without derivates
- SIMPLX, using the simplex algorithm of Nelder and Mead.

As can be seen in figure 6.2.1.5 it was found during the optimisation that there are sometimes a number of combinations of *WEP* and *BETA* with the same low error criterion. The lowest values are always found in an oblong area Fig. 6.2.1.6, for an other field test, is an example of this. The routines DFP and POWEL do not always find the absolute minimum of $J$ because they

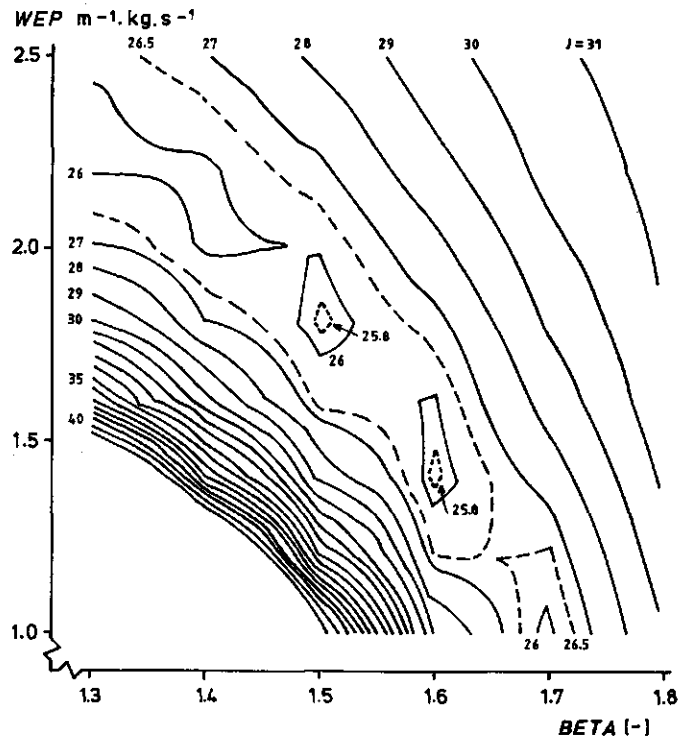



Figure 6.2.1.5. Lines of constant values of the error criterion $J = \int \{(\text{measured loss}) - (\text{calculated loss})\}^2$ of the SIMPLX parameter estimation algorithm for the threshing coefficient (*BETA*) and walker efficiency parameter (*WEP*) for data of field test 55

use hill-climbing methods, whereas SIMPLX is a direct search method with restart algorithms, so also optimum combinations of *BETA* and *WEP* are found that are more close to the expected values. Values of *BETA* and *WEP* are calculated in this way for each "swath" with the SIMPLX method. These values are listed in table A 4.2.1.3 in the colums *BETA 1* and *WEP*.

The mean walker loss, as a result of simulations with these values, deviated from the mean losses measured in the experiments owing to the quadratic error criterion. This is undesirable because the simulated losses of the runs at the same speed as in practice will be used as the loss level of the manually controlled practical situation, hence these simulated losses have to be at the same level as in practice. New values of *BETA* have therefore been found by a hand-operated optimisation calculation until the simulated loss deviated from the measured one by less than 0.1%. These values are given in table A 4.2.1.3 in column *BETA 2*. The parameter *WEP*

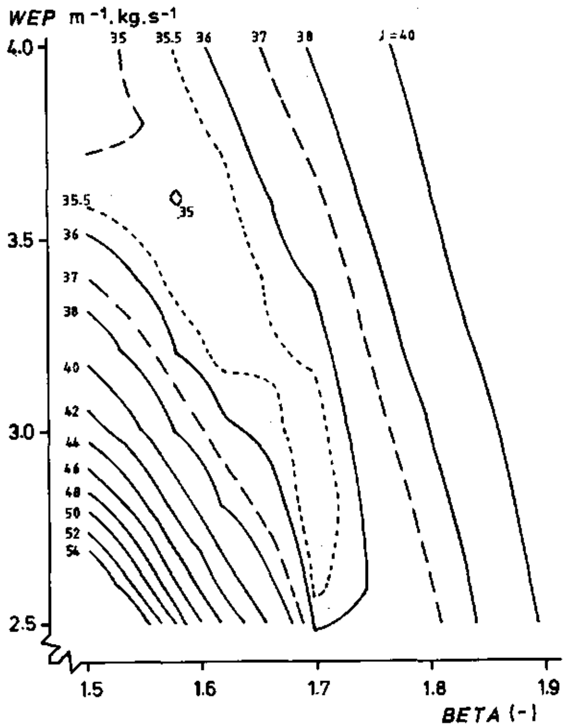



Figure 6.2.1.6. Same as figure 6.2.1.5 but in this case for data of field test 31, that also was used for figure 6.2.1.2 ... 6.2.1.4

was kept unchanged.

The dynamic behaviour of the simulated walker loss can be studied and compared to the loss measured in the field experiments in figure 6.2.1.7. The dotted line in the figure shows the loss in the simulation in which the apparent straw density input of nearly a complete swath (nr. 12) was used. The line connects the loss values averaged over 0.25 m. The full line connects the loss values averaged over 0.25 m as they were measured in the field by means of an acoustic sensor.

At first sight the lines are not too close to one another. In particular the peaks are not at the same place. This can be explained by the variation in the delay of the loss in the real machine caused by the irregular straw accumulation at the baffle curtain and by grain accumulation in front of the threshing cylinder. In the simulation this variation does not exist as no random irregularities are introduced into the simulation model.

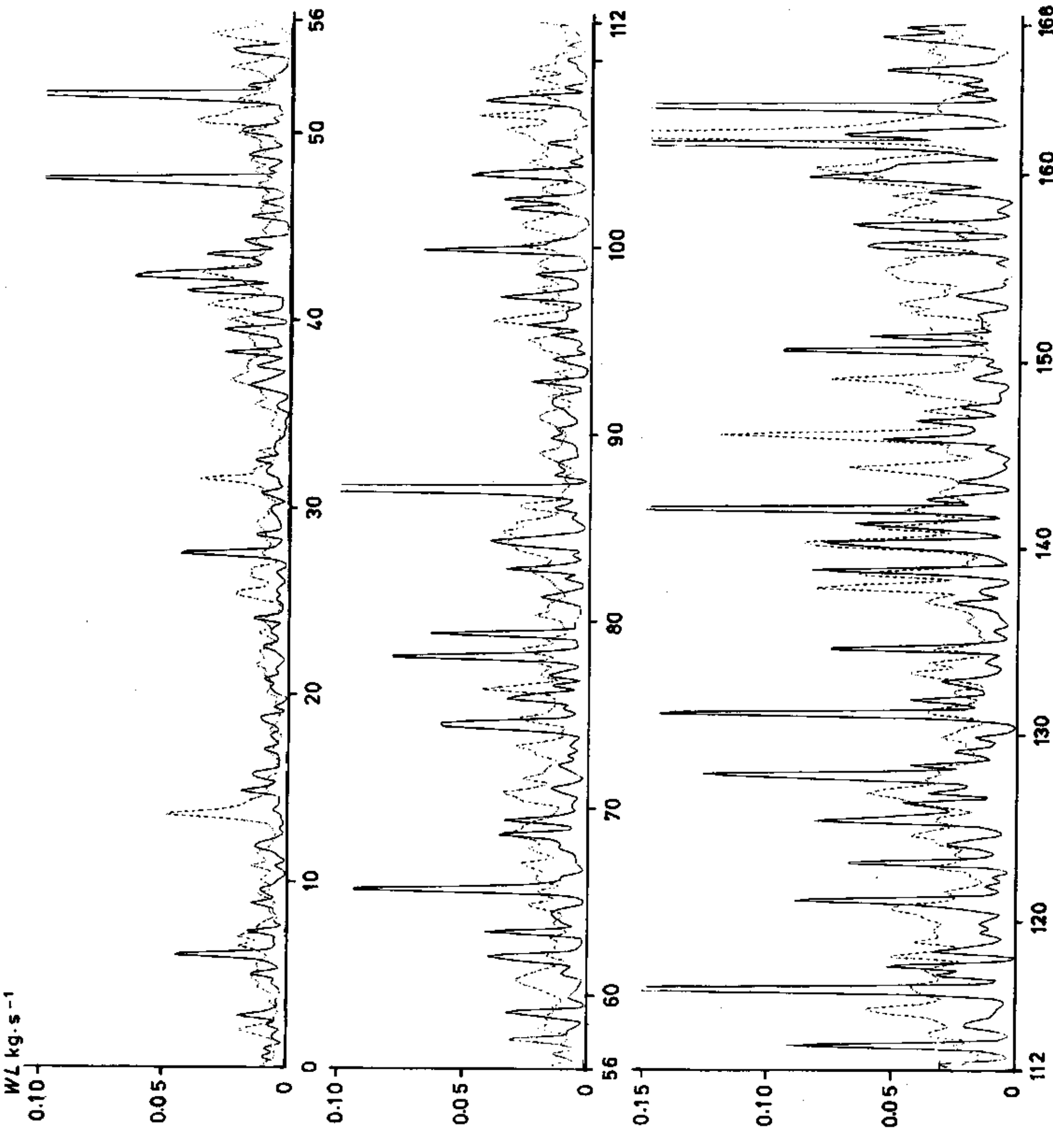



Figure 6.2.1.7. Simulated (----) and measured (——) values of walker loss of the data of field test ("swath") 12

The average loss levels however show a good conformity as can be recognised in two ways. First, the loss peaks of measured loss are always accompanied by relatively low levels in the immediate neighbourhood. Second, at the total test length different measured mean loss levels can be recognised: first a stretch of 40 m low loss, then up to 110 m an increased level and the last stretch shows the highest loss, including high peaks. The simulated loss shows the same pattern.

The dynamic behaviour of the simulated loss shows roughly what could be expected and is in conformity with what is needed for our simulation since the loss is heavily filtered when used as input signal for a control system. The slow variation in the level is simulated correctly.

### 6.2.2. *Machine speed*

The machine speed in our simulation is controlled manually by the machine speed control considered in chapter 5.3.1. In the control scheme some time constants affecting the behaviour of the hydraulic drive had to be estimated. The simulation was done with the parameter values given in fig. 2.4.2.1. The simulated behaviour of this control could not be compared with reality because no such control system has been tested in practice on machine B (see A 1.1).

However, a torque control system was tested on machine A (Loo, 1977) using in principle similar driving parts as machine B, thus allowing the assumptions of the model to be tested. In particular the integrating action and the first-order transfer function of the machine transmission can be considered.

Fig. 6.2.2.1 shows the block diagram of the torque feedback control system with the parameter values that are used in the simulation program (Reumkens, 1983). See also 2.3.1 and 2.4.1. At field tests with the torque feedback control system the actual machine speed and auger torque were measured and recorded. The apparent straw density was then calculated from these measurements and averaged per 0.2 m traversed distance and stored in data files. These data were used as input for the simulation of the torque feedback control system. The values for the machine speed, machine acceleration and auger torque averaged per 0.2 m, output of simulation are plotted in fig. 6.2.2.2. This is also done with the values of

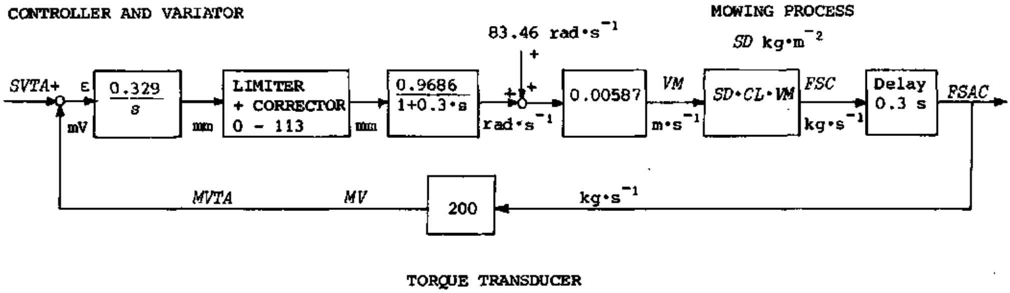



Figure 6.2.2.1. Simulation model of auger torque feedback control system of machine A working in first gear *SVTA* = set value auger torque (300-400 mV). *MVTA* = measured value auger torque

the same variables measured during the field tests. The dimension of auger torque was calculated in terms of measured feed rate (*FSM*).

The plots show that, for the $P_c$ value of 0.70 in the control system, the behaviour of the simulated machine does not deviate essentially from that obtained with the field-test system, so that the assumptions of the time constants used in the simulation are correct. Special attention was paid to the calculated and measured accelerations of the forward machine speed because the integrating action of the torque feedback control system has been adjusted during the field tests in such a way that the maximum acceleration and deceleration values were decreased until they were comfortable for the operator. In fig. 6.2.2.2 can be seen that, in general, the value of 0.4 $m \cdot s^{-2}$ was not exceeded in such adjustment, so that for the machine speed control of machine B this level was also used as the maximum tolerable level.

### 6.2.3. *Threshing speed*

The threshing speed in the simulation is the result of the interaction of the output of the speed control system given by *DV* and the straw feed rate at the threshing cylinder *FST*, as is explained in 2.3.3 and reviewed in fig. 2.3.3.7. The data given in this figure are also used during the simulation. In the absence of a real system there is nothing to compare the simulation with as yet. However, the results of some simulated values of the tension in the V-belt (*FOB*) shows good agreement with what was to be expected. In table 6.2.3.1 a comparison is given of the *FOB* values

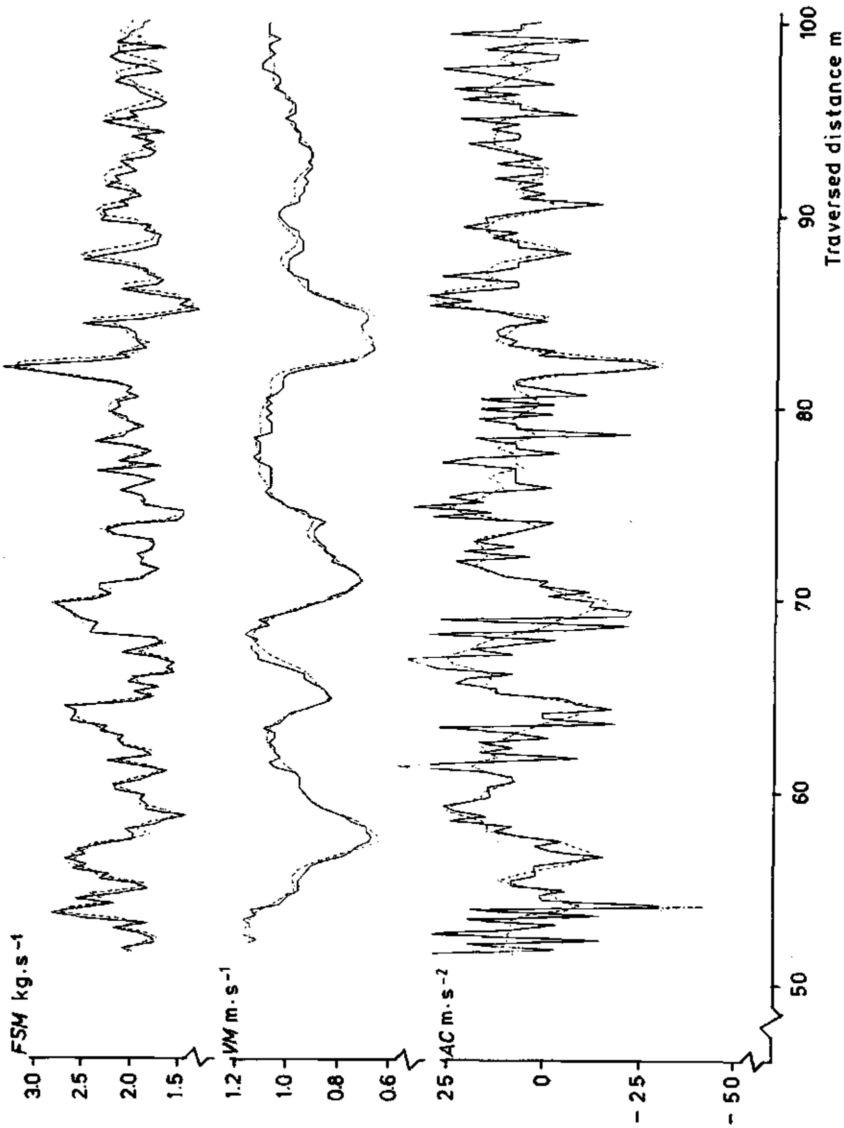



Figure 6.2.2.2. Simulated (-----) value of straw feed rate *FS* and measured (——) value of auger torque in the unity $kg \cdot s^{-1}$, machine speed *VM* and machine acceleration *AC* of the auger torque feedback control system of machine A

Table 6.2.3.1. Mean values of tension in the V-belt driving the threshing cylinder (*FOBAV*) in the various control systems in cost situation 2 and *SVTS* = 80%

| Control system | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| *FOBAV* (N) | 1246 | 1377 | 1430 | 1455 | 1500 |

of the various control systems.

### 6.2.4. *Control systems*

In this section the simulation of the control systems will be discussed. Some parameter values will be explained here. Where such a value is called a default value this means that other values are also investigated in 6.3. In 6.2.4.8 plots are shown comparing the behaviour of the different control systems.

#### 6.2.4.1. *Filtering and sample interval subroutine*

The control systems described in chapter 5 are so complex that it will be useful to program them in a micro-processor. In consequence, the measured values of losses and speeds will be sampled and averaged over a certain sample interval (*TD*). This sampling operation in our simulation is carried out by means of the subroutine "MECEF" in which is included a digital filter action to obtain the desired behaviour of the speed optimisation calculation. A discrete smoothing filter is used (Verbruggen, 1975) that works as a first-order low-pass filter with a breakpoint frequency of $f_b = 1/\tau_f$. When *MEANIN* is the value of the input averaged over the sample interval (*TD*) then the output of the filter is calculated as *MEANOUT*. In Fortran:

```
MEANOUT = {(1 - GF)*MEANOUT} + GF*MEANIN
```

The values of *GF* and *TD* determine $f_b$ as follows

$$f_b = \ln\left(\frac{1}{1-GF}\right) / TD$$

The subroutine "MECEF" also generates initial values for a correct start of the program. The default length of the sample interval (*TD*) is 0.5 s which is considered to be a reasonable value considering the microprocessors now available. The default values of the filter breakpoint frequencies are explained in the following sections. The subroutine MECEF is given in the appendix.

#### 6.2.4.2. *Control systems inputs*

The variables given below are input for the control systems.

*Machine speed*

The machine speed, calculated by the process simulation passes the MECEF subroutine without being filtered (*GF* = 1), but is held during the sample interval. No noise is added.

*Threshing cylinder speed*

The calculated threshing cylinder speed is direct input, without added noise, filter action and value retention during the sample interval.

*Straw feed rate*

The feed rate measurement is represented by the measurement of either the auger torque or the displacement of the elevator chain as explained in 3.1. The variable to be used can be selected by a switch. Then measurement noise is added as described in 4.2. The sum of the measured variable and the noise then passes the MECEF subroutine to be filtered and held during the sample interval. The dimension of feed rate remains $kg \cdot s^{-1}$ so that no conversion is needed anywhere in the calculation. In fig. 6.2.4.2.1 the measured variable in the straw feed rate dimension is shown with as well as without noise together with the output of the MECEF subroutine. In this case the sample interval was 0.5 s but no additional filtering was done. In this figure we can get an impression of the noise and the effect of noise on the sampled data. Not much variation caused by the noise remains and the delay caused by the sample interval can be recognised.

*Threshing separation efficiency*

The threshing separation efficiency calculated with the model is, as explained in 3.4, multiplied by 100, delayed for 9.0 s and added to noise at the default value of maximally ± 3% absolute. The total is then held for the sample interval but is not filtered.

*Walker loss*

Noise, with a default amplitude of maximally 0.4 times the loss level of

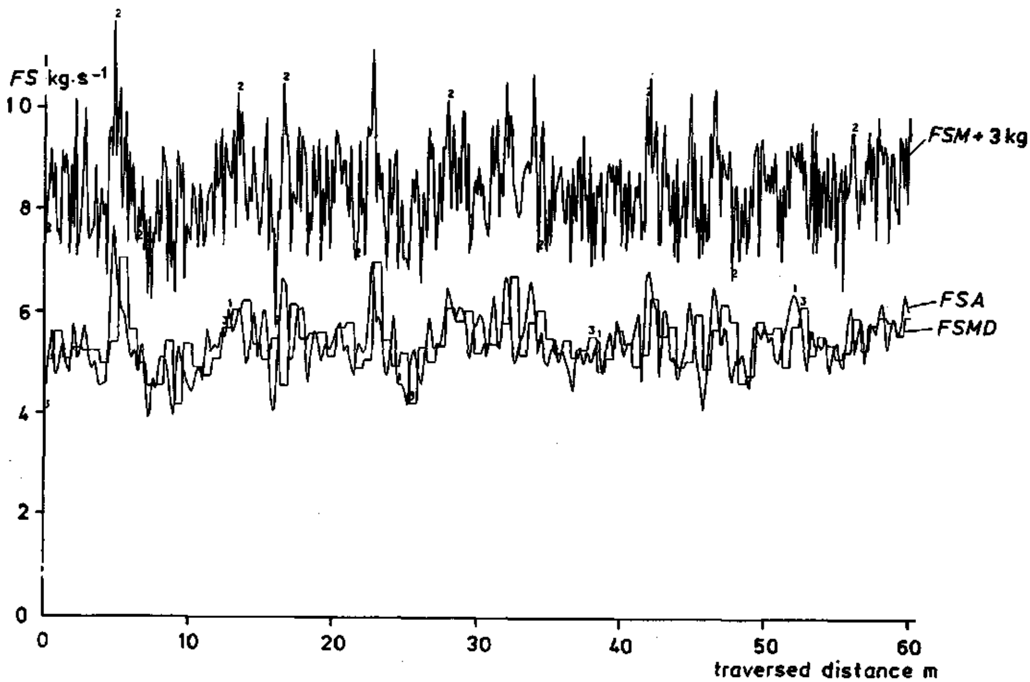



Figure 6.2.4.2.1. Straw feed rate (*FS*) taken at different places of the simulation model: line 1 is *FSA*, the calculated feed rate at the auger; line 2 is *FSA* with added noise (but plotted 3 $kg \cdot s^{-1}$ higher) *FSM*, line 3 is the sampled *FSM* value *FSMD*

0.007 $kg \cdot s^{-1}$ is added to the walker loss, calculated by the model of the process. Then it passes the subroutine MECEF to be filtered and held during the sample interval.

### 6.2.4.3. *Manual control (system o)*

The speed of the machine is set at the value that was measured in the field. The change in speed at the end of a swath to the speed of the other swath is simulated by a first-order transfer function with a time constant of 2 s as this is a roughly the pattern in which the operator does it.

To research the effect of other speeds on the costs, these speeds were raised and lowered by 10% and 20%.

6.2.4.4. *Loss control system (system 1)*

As explained in chapter 5, the value $q$ of the equation $WL = c \cdot \exp(q \cdot VW)$ has to be estimated. This is done by delaying the value of $VW$ for 10.5 s and filtering both $WL$ and $VW$ with the MECEF subroutine and the breakpoint frequency (equal for both), and then calculating $q$. This means that for each sample interval another value of $q$ is found, so that the setpoint value for the machine speed control is also constant during the sample interval.

This calculation of the optimum speed is done in a CSMP implicit function that calculates by iteration until, in our case, the difference between the last and the second-last output is less than 2%. A value of 1% was too small in our simulations because the limit of 100 iterations was not reached in some cases, resulting in an undesired stop of the simulations. The response of different variables of the control system to a simulated step function in straw density has already been shown in figure 5.4.1.2. The behaviour of the system when apparent straw density is the input of the simulation is demonstrated in fig. 6.2.4.4.1. The breakpoint frequency of the smoothing filter was 0.17 $rad \cdot s^{-1}$ in this case. The response of $q$ is then too fast. In some exploratory simulations better results were found at breakpoint frequencies near 0.014 $rad \cdot s^{-1}$ so that this value was chosen for the default. The system then controls the slow variations of loss alone. In figure 6.2.4.8.1 can be seen how the machine speed varies over the tested swaths. One has to realise that the apparent straw density input of each swath was used three times in succession for this control system. To compare the behaviour of the different control systems more easily, the traversed distance of control system 1 in the plot was divided by 3.

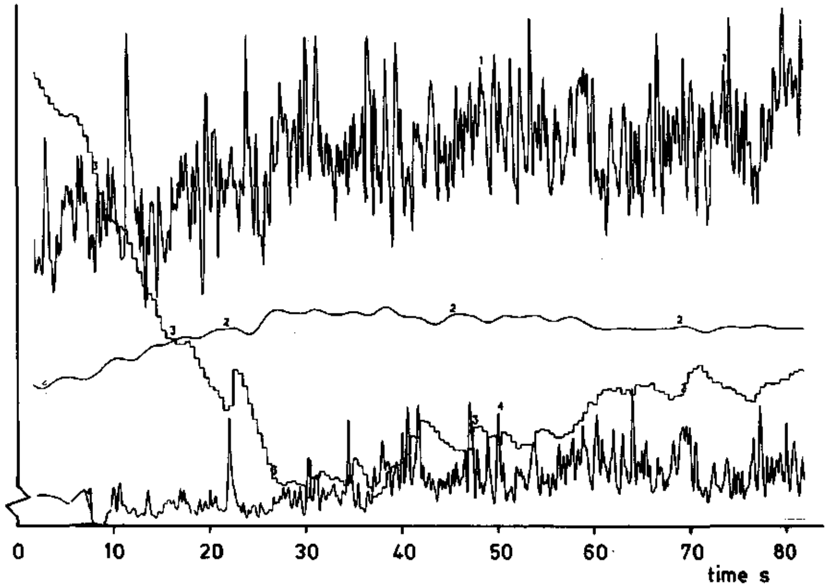



Figure 6.2.4.4.1. The behaviour of variables in the loss control system as a response to the input of apparent straw density, line 1 is the simulated measured feed rate including measurement noise, line 2 is the machine speed, line 3 is the value of $q$ in the calculation and line 4 is the walker loss

### 6.2.4.5. *Loss feed rate control system (system 2)*

The optimum speed calculation for this system, giving the set-point value for the machine speed control, is also obtained by means of the *CSMP* implicit function. The loss feed rate equation used here, is a two-parameter equation of the form ln *WL=D0+D1·FS* as explained in 5.4.2. If this control system is to be used in practice, these two parameters have to be estimated "on line". Parameter estimation for this system, however, still requires some further research. In the present study we have been obliged to simplify the estimation by doing it "off line". The results, however, will be entered as near "on line" as possible. How it will be done is explained below.

A 4.2.1.c explains how the *D0* and *D1* values are calculated on the experimental data of feed rate (*FS*) and walker loss (*WL*) of the uncontrolled runs of each swath,of which also the apparent straw density datafiles are made and *BETA* and *WEP* are estimated for the simulation. In fig. 6.2.4.5.1

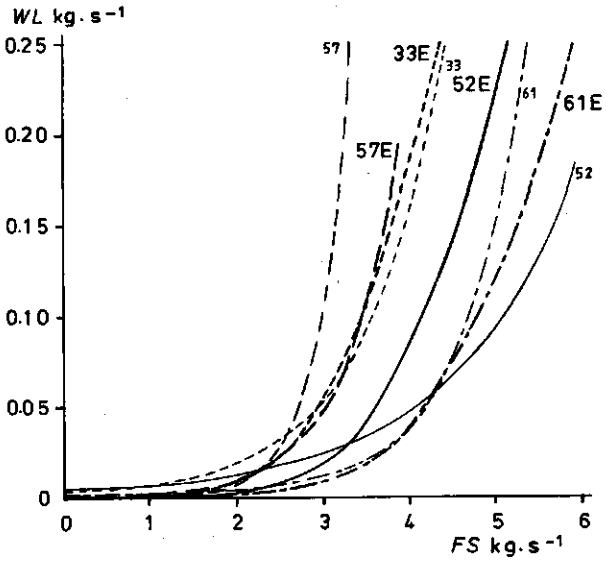



Figure 6.2.4.5.1. Curves of walker loss (*WL*) related to straw feed rate *FS* of 4 swaths, like they are a result of the simulation of the process when *FS* is increased slowly (indicated by the slight lines and additional E) and they are the result of the equation: $WL = D0 + D1 \cdot FS$ used in the optimum speed calculation (indicated by the thick lines and just the swath numbers)

curves are shown of the above-mentioned equation and calculated *D0* and *D1* values for four of the eight swaths (arbitrarily chosen out of the 8 as examples). They are indicated by the thick lines and swath numbers.

These curves can be compared to the curves of the relation between losses and feed rate, found, using the simulation model of the process with *BETA* and *WEP* values calculated as explained in 6.2.1. These lines, indicated by the thin lines and swath numbers including an "E", represent the walker loss levels at the various straw feed rate levels, when the simulated process is in steady state at those levels. The mean level of walker loss and feed rate that occurred at the field test, is indicated in the plot by (×).

The curves of the simulation model and those of the equation with calculated *D0* and *D1* are fairly similar at that point in the plot. In terms of the control system simulation this means that the loss-to-feed rate relation, used to calculate the set value of the machine speed control, accords reasonably well with the relation simulated in the process, but the relations are not exactly similar.

This will also be the case if such a system is applied in practice. The difference arises owing to disturbances in the process and/or the difference in form of the simplified equation and of the real separation process equation. This is how the difference is included in our simulation. If the control system were to be used in practice and the mean level of feed rate shifted due to another optimum machine speed, the estimated values of *D0* and *D1* might change.

This is not possible in our simulation as the *D0* and *D1* are estimated "off line". Figure 6.2.4.5.1 shows that the two curves of swath 52 as well as those of swath 57 deviate and do so the more, the more the mean feed rate differs from the feed rate level in the calculation of *D0* and *D1* (the levels of (x)). This will result in a greater deviation of the calculated optimum speed from the optimum speed obtained when the loss feed rate relation of the simulated process is used.

The simulation results are influenced by this imperfection, and are so the more, so more the automatically controlled speeds deviate from the manually controlled, speeds, since the levels indicated by (×) are also the manual control levels. The total costs of this control system are raised by this imperfection.

To investigate the effect of this imperfection continued field research and simulations with "on line" parameter estimation are needed.

The optimum speed calculation of this control system also needs a value for the calculated straw density (*SDM*) as explained in 5.2.1. In the simulation this value is calculated by dividing the measured feed rate variable including noise (*FSM*) by the harvested area (*VW*). The quotient is then filtered as explained in 5.1.2.2 by means of the MECEF subroutine. The default value of the breakpoint frequency of the filter was set at 0.4 $rad \cdot s^{-1}$ based upon the value chosen in 5.4.2 and some initial simulations showing the expected behaviour. In fig. 6.2.4.5.1 the calculated straw density and the output of the filter are shown to give an impression of the measurement noise, filtering and sampling in the simulation. The input into the simulation was a constant apparent straw density level of 0.6 $kg \cdot m^{-2}$ and a step of 25% at $t$=20 in addition to that level. The straw feed rate was measured by the auger torque and default noise was added.

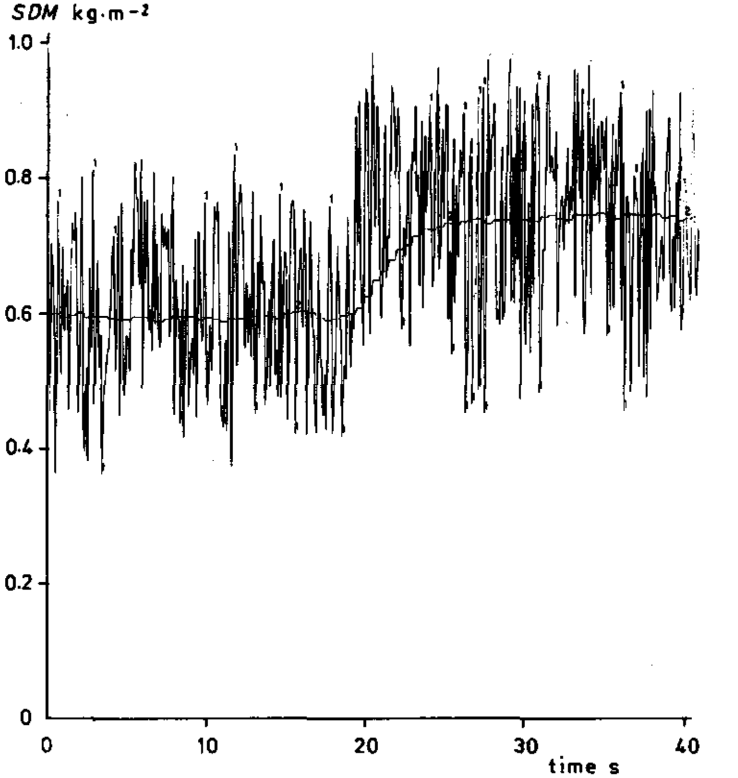



Figure 6.2.4.5.2. Straw density in the simulation. Line 1 represents the straw density as it is calculated by dividing the measured feed rate (thus including the measurement noise) by the measured machine speed. Line 2 represents the sampled and filtered signal of the straw density of line 1 (the breakpoint frequency of the first order low pass filter was 0.4 $rad \cdot s^{-1}$). The input was the apparent straw density at a level of 0.6 $kg \cdot m^{-2}$ until $t$ = 20 s and thereafter 0.75 $kg \cdot m^{-2}$

6.2.4.6. *Loss-feed rate-threshing speed control system (system 3)*

The machine speed control of this system is similar to those of system 2. The threshing cylinder speed of this system is controlled by the threshing speed control whose input, the optimum threshing speed $VT_o$, is given by $VT_o = 24.0 + 2.4 \cdot AFS$ according to 5.2.3. In the simulation the value for *AFS* is found by dividing the *FSM* value, as explained in 6.2.4.2, by the width of the threshing cylinder.

6.2.4.7. *Loss-feed rate-threshing separation control system (system 4)*

The machine speed control of this system is also similar to those of system 2. The threshing cylinder speed is controlled by the measured feed rate (*FSM*) (see 6.2.4.2) and the difference between the set value of the threshing separation efficiency (*SVTS*) and the measured threshing separation efficiency (*TSEM*) as explained in 5.2.4 and 5.4.4.

The default level of *SVTS* was chosen to be 90% as was *thought to be a reasonable* value, because the threshing separation efficiency should be large enough for low walker loss, so that the threshing speed would thus become high enough to give low threshing loss but not too high to result in so much straw breakage that sieve loss would become high.

If such a system is used in practice, these arguments will be used, too. The operator is able to inspect the extent to which there is broken grain and threshing loss and will then choose the value of *SVTS* and the concave adjustment. The other argument about straw breakage affecting sieve loss and even walker loss will also be considered and acted on in the field.

These factors have not been brought into the simulation model so cannot affect our choice of *SVTS*, when only the calculated costs are taken into consideration. However, these arguments were nevertheless used by us to choose the level of 90% in the simulation, although minimum costs were obtained when higher values of *SVTS* were used (see 6.3.3.8).

The default value of 2v that affects the speed of adaption of *VFSC* in the relation between optimum threshing speed and feed rate was $2.5 \cdot 10^{-3}$ as explained in 5.4.4. To show how fast the adaption occurs, fig. 6.2.4.7.1 demonstrates the response of the value of *VFSC*, the threshing speed (*VT*) and the threshing separation efficiency (*TSE*) to a sudden change in crop properties resulting in a decrease in threshing separation efficiency. This change was caused by a step function in *BETA* changing the value from 1.75 to 1.60 at $t$=10 in a preparatory simulation.

As can be seen in the plot, the process was still moving to steady state starting from the initial conditions. The straw density input into the simulation model has a constant value. As a result of the dealy in the measurement of the threshing separation efficiency (see 3.4), the threshing speed (*VT*) and, as a result of that, the threshing separation efficiency

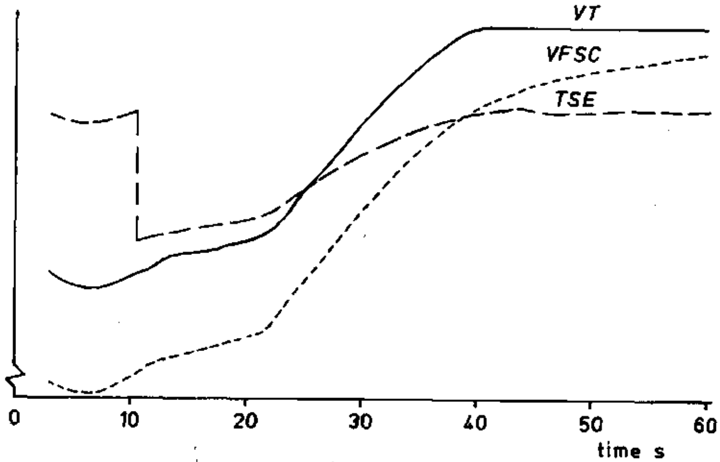



Figure 6.2.4.7.1. The response of *VFSC* (line 2), the parameter in the threshing speed to threshing separation efficiency adaption, *VT* (line 3) and *TSE* (line 1) at a simulated decrease of *BETA* at t = 10 as can be seen in the sudden decrease of *TSE* at that moment

(*TSE*) start to increase faster at $t$=20 than they did before.

At about $t$=40 *VT* reaches its limit, but *VFSC* still increases, because *TSE* did not reach the value of *SVTS*. This is because *VT* has to decrease in the event that *TSE* drops below *SVTS*. Hence, as soon as *VT* reaches its maximum (or minimum) *VFSC* must remain at its last level. This was incorporated into the simulation by the corrector structure statement described in A 6.1.2.

### 6.2.4.8. *Comparison of control systems in simulation*

The response of walker loss of the control systems to a step disturbance in the values of *BETA* and straw density is shown in fig. 5.5.1. The behaviour of the systems during the simulation runs will be shown in the figures which follow.

The machine speed is shown in fig. 6.2.4.8.1 as a function of traversed distance. Since the speed also varies in a relatively short distance, the lines will cross each other too much. In order to obtain a clear plot the speed output was put through a first-order low-pass filter with a breakpoint frequency of 0.2 rad$\cdot$s$^{-1}$. Although the traversed distance of the loss control (system 1) is three times as long as those of the others,

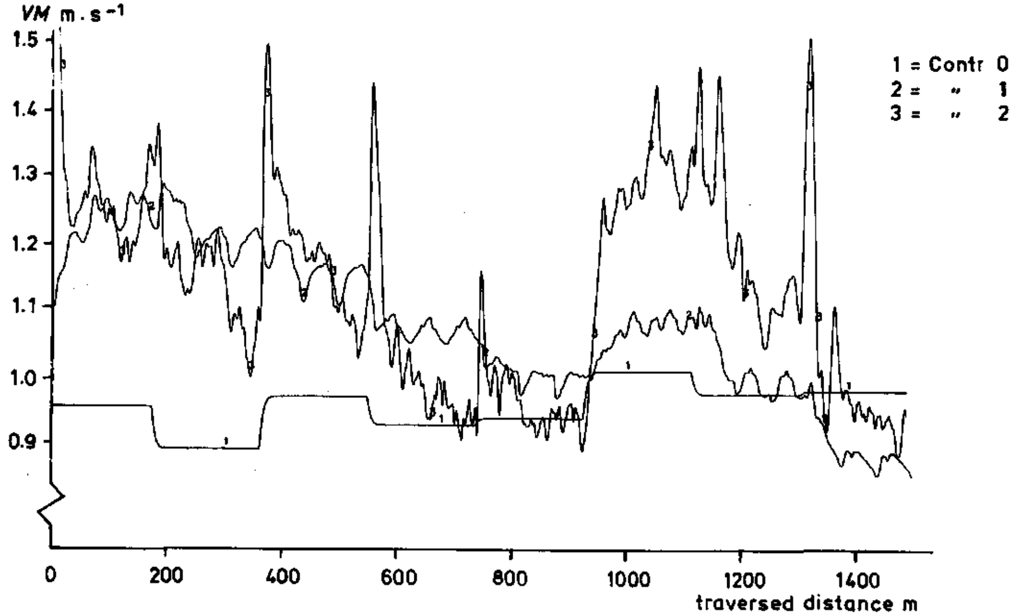



Figure 6.2.4.8.1. Machine speed (*VM*) during the simulations of the 8 consecutive swaths at cost situation 2, for the manual control (line 1), control system 1 (line 2) and control systems 2,3,4 (line 3)

the traversed distance in the plot have been made equal in order to compare the reactions of the systems to the swath data. This means that within the traversed distance of each swath, system 1 has been offered three times the straw density data of this swath.

The figure shows the speeds of systems 0, 1 and 2 in cost situation 2 for the given default values of parameters. The machine speeds of systems 3 and 4 are equal to those of system 2.

The threshing cylinder speed is shown in fig. 6.2.4.8.2 (also filtered as explained above for machine speed) for systems 2, 3 and 4. This speed is given for cost situation 2 and the default values of the parameters. For control system 4 two lines were plotted, the set values of threshing separation efficiency, *SVTS*, being adjusted at 90 and 80%, respectively. In the latter case (80%) the threshing speed does not reach its upper limit as at 90%. This clearly shows the need of extra criteria for the threshing speed control of system 4, for instance the grain and straw breakage as indicated in 6.2.4.7. Further research has to be done on this aspect.

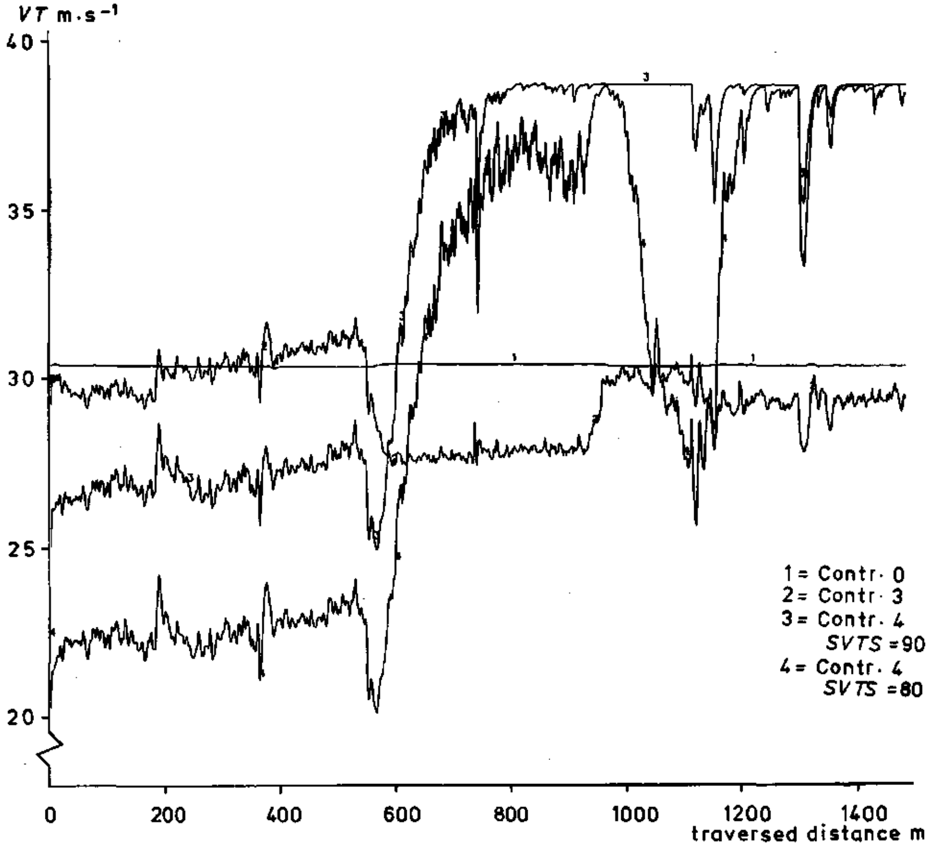



Figure 6.2.4.8.2. Threshing cylinder speed (*VT*) during the simulations of the 8 consecutive swaths for cost situation 2 and control systems 0,1 and 2 (line 1), control system 3 (line 2), control system 4 at desired threshing separation efficiency 90% (line 3) and 80% (line 4)

The results on total costs of the various control systems are plotted in fig. 6.2.4.8.3 for a short distance and in fig. 6.2.4.8.4 for the total simulation of 8 swaths. The lines had to be shifted to obtain a clear plot. For the same reason in fig. 6.2.4.8.4, the output was put through a low-pass filter with a breakpoint frequency of 0.1 $rad \cdot s^{-1}$.

It is interesting to see how the cost lines of control system 1 show larger peaks than the other systems caused by an overshoot due to the delay in the process. Control system 4 shows compared to system 3 higher costs in the first 600 metres, but much lower costs after that.

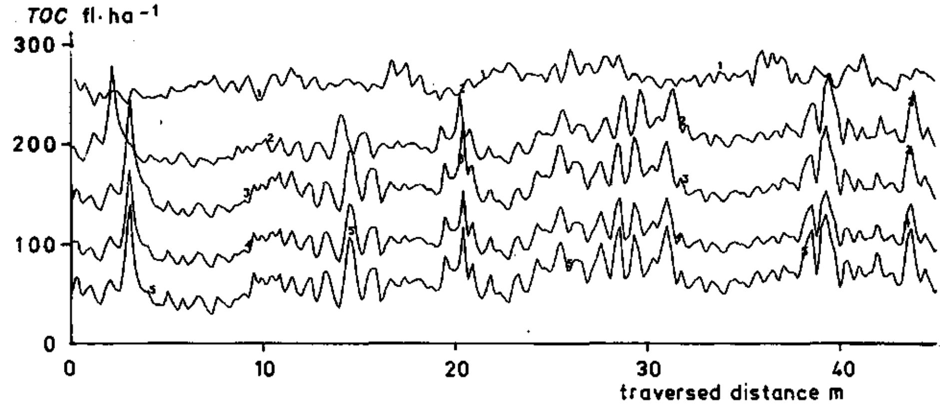



Figure 6.2.4.8.3. Total costs (*TOC*) calculated for the simulation of a short part of the first swath for the various control systems: line 1 = *TOC* of manual control, line 2 = (*TOC* of control system 1) - 50.00 fl ha$^{-1}$, line 3 = (*TOC* control system 2) - 100.00 fl·ha$^{-1}$, line 4 = (*TOC* of control system 3) - 150.00 fl·ha$^{-1}$, line 5 = (*TOC* of control system 4) - 200.00 fl·ha$^{-1}$

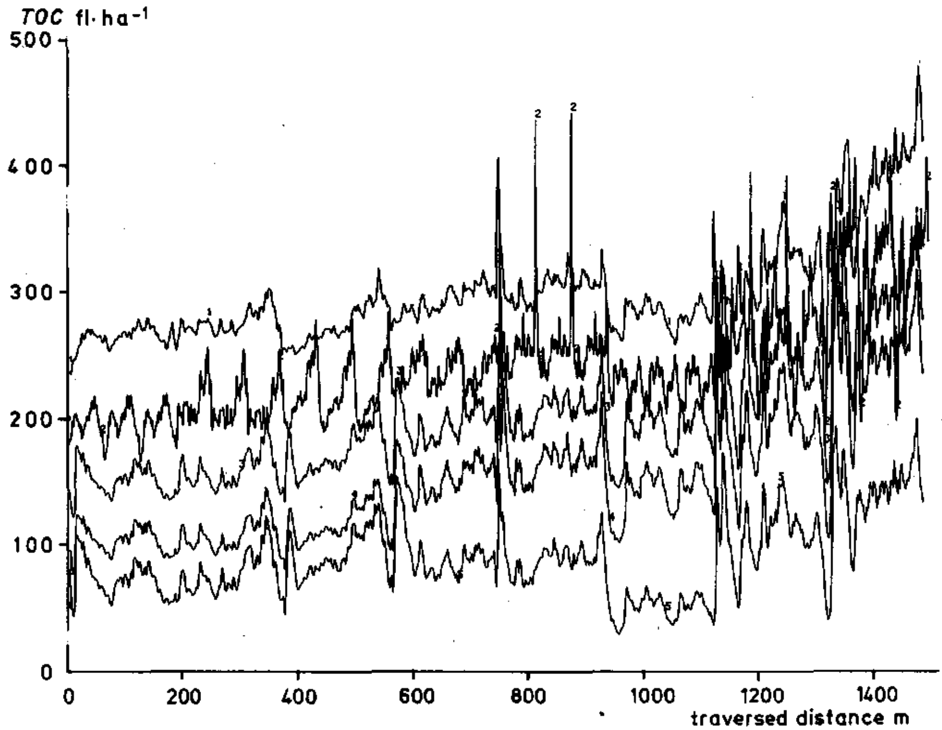



Figure 6.2.4.8.4. Total costs (*TOC*) calculated for the simulation of the 8 consecutive swaths in cost situation 2, for the various control systems as indicated in figure 6.2.4.8.3

## 6.3. SIMULATION RESULTS AND DISCUSSION

### 6.3.1. *Introduction*

The first simulation runs were executed with data of two swaths to try out the chosen parameter values. Then runs were done for final parameter adjustment using data of all 8 selected swaths, with fairly different results in some cases.

When one parameter is varied in the runs discussed in this chapter, all the others are set at the default values mentioned in 6.2. In most cases the calculations were only done for the IJ.D.A. cost situations 2 and 6 (see table 6.1.3.3.1) to reduce calculation time. In general only total costs are compared, but sometimes the separate cost factors or speeds will be studied, too.

### 6.3.2. *Manual control*

The conditions recorded during the field tests with the combine harvester of the IJsselmeerpolders Development Authority large-scale grain farm were defined as the standard of the manual control for our research. The operators at this farm are well trained and have wide experience. In addition they are informed regularly about the losses occurring with their machines by a special quality inspection team. The machine operators are instructed to drive at such a speed that total machine losses will be about 0.5%, this being the optimum level calculated with an operational research optimisation model for the cereal harvest (Kampen, 1969; Hagting, 1976; Fokkens, 1981). For this reason the speeds selected by the combine operators of this farm will in general be nearer the optimum than those elsewhere. To investigate the effect of other machine speeds on costs, the calculations were also done with machine speeds that were increased or decreased by 20% (as well as 10% for the cost situations 2 and 6). Table 6.3.2.1 shows the results for all situations and speed deviations.

These results demonstrate the difference in total costs for the various cost situations. The costs to the farmer and contractor for the timeliness loss calculation for 25% weather risk (situations 1 and 5) are close to those calculated by other authors. The timeliness loss risk percentage of

Table 6.3.2.1. Costs of combine harvesting with manual control at machine speeds measured at the IJ.D.A. grain farm calculated for various cost situations explained in table 6.1.3.3.1 and various speed deviation factors (all costs in $fl \cdot ha^{-1}$).
*TOC* = total costs, *CM* = machine costs, *CLO* = machine loss costs, *CTI* = total timeliness loss costs, *CVW* = costs of wear of V-belt

| Situ- | Mean machine speed | | | | | *TOC* Machine speed deviation factor | | | |
|---|---|---|---|---|---|---|---|---|---|
| ation | *TOC* | *CM* | *CLO* | *CTT* | *CVW* | 0.8 | 0.9 | 1.1 | 1.2 |
| 1 | 478.95 | 420.57 | 55.78 | 2.45 | 0.16 | 468.45 | | | 505.61 |
| 2 | 299.21 | 204.85 | 52.73 | 41.47 | 0.16 | 341.17 | 311.31 | 297.49 | 302.74 |
| 3 | 1052.99 | 420.57 | 55.76 | 576.50 | 0.16 | 1469.40 | | | 786.25 |
| 4 | 461.85 | 204.85 | 52.73 | 204.12 | 0.16 | 778.75 | | | 386.22 |
| 5 | 519.56 | 461.65 | 52.76 | 1.99 | 0.16 | 568.44 | | | 502.55 |
| 6 | 306.77 | 199.74 | 52.73 | 54.13 | 0.16 | 309.41 | 305.87 | 311.60 | 319.73 |

16 $^2/_3$% (situation 3) introduces large timeliness loss costs that are not realistic. They indicate the reason why farmers in the Netherlands restrict the area to be harvested to 100 ha per combine per year.

The costs for the large scale grain farm of the IJsselmeerpolders Development Authority (IJ.D.A.) are much lower (situation 2), even for the timeliness loss risk of 16 $^2/_3$% (situation 4). A reason is the fact that the IJ.D.A. will also harvest at grain moisture conditions above 23%. Cost situation 6, where harvest time is fixed, but the number of machines is variable, manifests costs very close to those in situation 2. This indicates that the area per machine (175 ha) is near the optimum in relation to the timeliness loss curve used for situation 2. It can be concluded therefore that this timeliness loss curve and the machine cost assumptions used in this study with results similar to those of the operations research model of the IJ.D.A. cereal harvest.

When we consider the cost figures of the other speed calculations, then it is clear that the selected speeds are fairly near the optimum for situations 2 and 6. For cost situation 2, minimum costs are found at 1.1 times the selected machine speeds, but for cost situation 6 the minimum costs are found at 0.9 times the selected machine speeds. It indicates that the selected speeds are indeed close to the optimum at the IJ.D.A. farm. The fact that a slower speed is optimum for situation 6 and a higher speed for cost situation 2, indicates, moreover, that the timeliness loss is an important cost factor.

Consideration of cost situation 4 shows that even 1.2 times the machine speed gives lower costs. The automatically controlled systems show optimum speeds that are 1.5 times the hand-controlled mean speed.

It is interesting to study the effect of the timeliness loss risk on farmers' costs.

In cost situation 1 the optimum speed is less than 0.8 times the selected speeds, but in cost situation 3 the speeds have to be in excess of speed deviation factor 1.2. This is due to the grain moisture limitations of 23% chosen for the cost situation of the farmer, giving less workable time, hence rapid increase of timeliness losses. This shows the important role of the chosen timeliness loss curve and the need for the curve to be changed in a control system when the timeliness loss expectation changes because of past weather and weather expectations. It is the same mechanism that a farmer uses intuitively when he increases his mean machine speed when harvest conditions threaten to deteriorate.

Cost situation 5, in which the area to be harvested is variable, also demonstrates a higher machine speed to be more advantageous.

The automatic control systems give information as to the optimum machine speeds (table 6.3.3.2). These cannot be directly compared to the mean speed that is found to be optimum for manual control,because the last named is calculated by changing the speeds for all swaths by the same ratio whereas, in automatic control, the speed of each individual swath is optimally adjusted.

When speeds are adjusted by automatic control,the total costs are influenced. The differences in costs compared to manual control are not only interesting when calculating the investments worth making for automatic control, but they also have to be compared with the effects and costs of other improvements to the combine harvester.

The data of the hand-controlled situation make it possible to a certain extent to calculate the benefits of a theoretical improvement in harvesting capacity. In addition, it is interesting to compare the results of these simulations with those simulated on the same hypothesis for the total harvesting optimisation model of the IJsselmeerpolders Development Authority (IJ.D.A.).

The Department of Operations Research of the IJ.D.A. was for this reason asked to calculate the financial benefit, if machines were used with a harvesting capacity 10% greater than those in actual fase. The machine losses would remain the same but the other cost factors would decrease then, because of the 10% increased machine speed (see 2.2). The timeliness losses are also included in this calculation so that the results can be compared with our cost situation 2. In the IJ.D.A. simulations each machine also harvests 175 ha of winter wheat. The calculated benefit of total harvesting costs proved to be 34.50 $fl \cdot ha^{-1}$. These costs include transport, drying and storage in addition to the cost factors used in this study.

In our simulation the benefit was calculated as demonstrated in table 6.3.2.2.

The machine costs (*CM*) and timeliness loss costs (*CTI*) were taken from the increased speed calculation while the machine loss costs (*CLO*) were taken from the normal speed. The costs of wear of threshing V-belt were also taken from the normal speed because they are not taken into consideration in the IJ.D.A. calculations either.

The calculations were also done for the speed increases from 1.1 to 1.2, 0.8 to 0.9 and 0.9 to 1.0. The benefit is dependent on the chosen normal speed level and is greater, the lower the normal machine speed. The benefit of our simulation does not include the contribution of the costs of transport, drying and storage, because they are *assumed* to be independent of capacity variations to the extent that they vary in our simulations. The role of these factors in the IJ.D.A. simulation is present but was not recorded and their contribution is thus unknown. Knowing that the normal speed at the IJ.D.A. is 0.90 $m \cdot s^{-1}$ and the recorded speed of our hand-controlled situation is 0.963 $m \cdot s^{-1}$ means that we may compare the benefit of 34.50 $fl \cdot ha^{-1}$ of the IJ.D.A. level to the 23.13 $fl \cdot ha^{-1}$ of table 6.3.2.2.

The dependence of the benefit from speed level can only be explained by the relatively large increase of timeliness loss at lower speeds, when the same calculations are made for other cost situations (for 20% increase) then the data of table 6.3.2.3 are found.

For cost situation 1 ... 4 the timeliness loss costs make the largest contribution to the cost decrease, whereas it is the machine cost in si-

Table 6.3.2.2. Cost reduction thanks to increased machine capacity at different machine speeds related to measured speed

| capacity increase | | *CM* | *CLO* | *CTI* | *CVW* | *TOC* fl·ha$^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|
| from | to | fl·ha$^{-1}$ | fl·ha$^{-1}$ | fl·ha$^{-1}$ | fl·ha$^{-1}$ | increased capacity | normal capacity | difference |
| 1.0 | 1.1 | 203.02 | 52.73 | 28.46 | 0.16 | 284.37 | 299.21 | 14.84 |
| 1.1 | 1.2 | 201.54 | 65.75 | 20.10 | 0.26 | 287.65 | 297.49 | 9.84 |
| 0.9 | 1.0 | 204.85 | 41.78 | 41.47 | 0.08 | 288.15 | 311.31 | 23.13 |
| 0.8 | 0.9 | 206.97 | 32.69 | 62.48 | 0.03 | 302.17 | 341.17 | 39.00 |

Table 6.3.2.3. Decrease in total costs thanks to increase in machine capacity by 20% in different cost situations. A in fl·ha$^{-1}$ and B in percentages of costs of the low speed (so 0.8 or 1.0)

| A fl·ha$^{-1}$ increase compared to measured speed | Cost Situations 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 0.8 - 1.0 | 10.83 | 62.13 | 437.73 | 337.06 | 70.20 | 22.82 |
| 1.0 - 1.2 | 3.12 | 24.68 | 296.51 | 103.80 | 46.78 | 15.20 |
| **B** % | | | | | | |
| 0.8 - 1.0 | 2.3 | 18.2 | 30.0 | 43.3 | 12.3 | 7.4 |
| 1.0 - 1.2 | 0.7 | 8.2 | 28.2 | 22.5 | 9.0 | 5.0 |

tuations 5 and 6. This confirms the general impression that a large capacity is advantageous to decreasing in machine costs and timeliness loss risk.

### 6.3.3. *Automatic control*

#### 6.3.3.1. *Control systems*

The effects of control systems on costs and speeds are shown in table 6.3.3.1.1 for situation 2 and in table 6.3.3.1.2 for the other situations.

Table 6.3.3.1.1. Costs and speeds of the different control systems in cost situation 2 (IJ.D.A., 16 2/3%)
*TOC* = total costs, *VMAV* = mean machine speed ($m \cdot s^{-1}$),
*ACAV* = mean of absolute values of acceleration of machine ($m \cdot s^{-2}$),
*VTAV* = mean threshing cylinder speed ($m \cdot s^{-1}$), *CM* = machine costs,
*CLO* = machine loss costs, *CTI* = timeliness loss costs,
*CVW* = costs of wear of V-belt (all costs in $fl \cdot ha^{-1}$)
*) indicates speed deviation to measured speed at hand control

| Control system | *TOC* | *VMAV* | *ACAV* | *VTAV* | *CM* | *CLO* | *CTI* | *CVW* |
|---|---|---|---|---|---|---|---|---|
| | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $m \cdot s^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ |
| 0 | 299.21 | 0.963 | 0 | 30.51 | 204.85 | 52.73 | 41.47 | 0.16 |
| 1 | 293.53 | 1.077 | 0.001 | 30.50 | 202.74 | 62.64 | 27.86 | 0.29 |
| 2 | 299.18 | 1.123 | 0.023 | 30.49 | 202.01 | 71.31 | 25.50 | 0.36 |
| 3 | 301.93 | 1.123 | 0.022 | 29.39 | 202.02 | 74.01 | 25.50 | 0.39 |
| 4 | 289.62 | 1.123 | 0.022 | 33.97 | 202.06 | 60.82 | 25.50 | 1.27 |
| 0 (1.2)* | 302.69 | 1.156 | 0 | 30.49 | 201.54 | 80.70 | 20.10 | 0.36 |
| 0 (0.8)* | 341.12 | 0.771 | 0 | 30.54 | 209.69 | 32.69 | 98.71 | 0.03 |

Table 6.3.3.1.2. Costs of control system 4 in the various cost situations for default adjustment of threshing speed control and threshing speed controlled by additional filtering of the measured straw feed rate input (breakpoint frequency of filter is 0.014 $rad \cdot s^{-1}$)

| Total costs | $fl \cdot ha^{-1}$ | | | | | |
|---|---|---|---|---|---|---|
| Cost situation | 1 | 2 | 3 | 4 | 5 | 6 |
| Default | 468.24 | 289.62 | 670.80 | 365.31 | 486.30 | 301.82 |
| Filtered | 468.33 | 290.16 | 673.30 | 365.85 | 487.66 | 302.40 |
| Machine loss costs $fl \cdot ha^{-1}$ | | | | | | |
| Default | 41.86 | 60.82 | 119.33 | 84.03 | 85.81 | 54.12 |
| Filtered | 41.90 | 61.35 | 121.84 | 84.56 | 87.14 | 54.64 |

The results of hand control, including 1.2 and 0.8 times the hand-controlled speed are also given to show the benefits of control systems if other speeds were chosen in hand control.

It can be concluded that the differences are very small.First they will be discussed for situation 2 and compared to those encountered manual control.

The total costs of control system 1 are 1.9% lower, mainly due to the decrease in timeliness loss.

Control system 2 shows the same costs, since the increased mean machine speed causes on increase in machine loss equal to the decrease in timeliness loss.

Costs of system 3 are slightly increased because of increased machine losses due to a less than optimum threshing speed.

As threshing speed is increased in system 4, this brings the minimum costs to 3.2% less than is the case in manual control. If these costs are compared to those of manual control at speeds that are 1.2 times the measured ones, the costs are 4.5% less and, if compared to 0.8 times the measured speeds they are 17.8% less.

The general conclusion for this cost situation is that a slight increase in machine speed, brought about by control system 1, causes a smaller increase in machine losses (*CLO*) than the decrease of timeliness loss (*CTI*). A larger increase in machine speed, realised by system 2 or a better chosen manually controlled speed of 1.2 times the original speeds gives equal increase and decrease of machine losses and timeliness losses, respectively.

It seems from this result that in control system 1 the calculated set value for the speed control was more close to the optimum than in control system 2. This indicates that the simplifications in the calculation of *D0* and *D1* were more badly than to the advantages of a fast feed rate control. So the conclusion will be drawn that a simple, but good estimation of the loss-feed rate relation is more beneficial than control of fast feed rate variations.

When systems 3 and 4 are compared, it can be concluded that the adaption of mean threshing speed to the threshing separation efficiency in system 4 is more beneficial than that of threshing speed to the fast variations in feed rate in system 3.

A real comparison of these effects, however, cannot be made with precision by comparison of system 3 with system 4,because the mean level of threshing speed is not the same. For this reason control system 4 was simulated with heavily filtered measured feed rate input. The breakpoint frequency of the first order low-pass filter was 0.014 rad•$s^{-1}$, so that the speed of the threshing cylinder just changed slowly. In table 6.3.3.1.2 the results are shown for both the default and filtered case in all cost situations. The differences are very small,so it can be concluded that it is only the adjustment of the mean threshing speed that is important.

Table 6.3.3.1.2. Costs of control system 4 in the various cost situations for default adjustment of threshing speed control and threshing speed controlled by additional filtering of the measured straw feed rate input (breakpoint frequency of filter is 0.014 rad•$s^{-1}$)

| Total costs | fl•$ha^{-1}$ | | | | | |
|---|---|---|---|---|---|---|
| Cost situation | 1 | 2 | 3 | 4 | 5 | 6 |
| Default | 468.24 | 289.62 | 670.80 | 365.31 | 486.30 | 301.82 |
| Filtered | 468.33 | 290.16 | 673.30 | 365.85 | 487.66 | 302.40 |
| Machine loss costs fl•$ha^{-1}$ | | | | | | |
| Default | 41.86 | 60.82 | 119.33 | 84.03 | 85.81 | 54.12 |
| Filtered | 41.90 | 61.35 | 121.84 | 84.56 | 87.14 | 54.64 |

If the differences arising in the various control systems are also studied in the other cost situations by means of the results of table 6.3.3.1.3,

Table 6.3.3.1.3. Total costs and mean speeds of the control systems in the different cost situations

| Total Costs fl•ha$^{-1}$ | | | | | | |
|---|---|---|---|---|---|---|
| Costsituation: | 1 | 2 | 3 | 4 | 5 | 6 |
| Control system | | | | | | |
| 0 | 478.95 | 299.21 | 1052.99 | 461.85 | 519.56 | 306.77 |
| 1 | 468.62 | 293.53 | 678.98 | 374.96 | 495.20 | 302.04 |
| 2 | 470.46 | 299.18 | 704.85 | 384.71 | 506.26 | 309.01 |
| 3 | 476.67 | 301.93 | 692.02 | 382.05 | 502.97 | 312.43 |
| 4 | 468.24 | 289.62 | 670.80 | 365.31 | 486.30 | 301.82 |
| Mean machine speed m•s$^{-1}$ | | | | | | |
| 0 | 0.963 | 0.963 | 0.963 | 0.963 | 0.963 | 0.963 |
| 1 | 0.893 | 1.077 | 1.439 | 1.262 | 1.190 | 0.985 |
| *) | 0.93 | 1.12 | 1.50 | 1.31 | 1.24 | 1.02 |
| 2,3,4 | 0.915 | 1.123 | 1.449 | 1.294 | 1.230 | 1.051 |
| *) | 0.95 | 1.17 | 1.51 | 1.34 | 1.30 | 1.09 |

*) speed relative to the hand controlled speed

we can conclude as follows.

The results in cost situation 6 are comparable to those in cost situation 2, described above.

Differences are greater for situation 4 (IJ.D.A., 16 $^2/_3$%) where the benefits of control systems 1 ... 4 compared to manual control are respectively 18.8%, 16.7%, 17.3% and 20.9%. This result is the outcome of the speed difference compared to manual control (factor 1.3).

The differences in cost situation 1 are slight, just as in cost situation 2, that is 2.1%, 1.7%, 0.5% and 2.2%, respectively.

The optimum machine speed in cost situation 3 is 1.5 times the speed at manual control so that the the cost difference between it and manual control is also great. Compared to each other the effect of the automatic control systems is smaller. Compared to system 1 the differences are +3.8%, +1.9% and -1.2% for systems 2, 3 and 4 respectively.

The data of cost situation 5 demonstrate the same tendencies as in situation 6, although the difference to manual control is greater, that is 4.7%. Compared to control system 1 systems 2, 3 and 4 give a cost difference of +2.2%, +1.6% and -1.7%, respectively.

The general conclusions to be drawn from these results are:

1. The manually controlled machine speeds and the optimum machine speeds calculated and adjusted by the control systems for cost situations 1, 2 and 6 are very much the same. There can be two reasons for this:

   First: Assuming that the cost values and timeliness loss curve chosen for the simulation are correct, the operator of the IJ.D.A. machine selected machine speeds very close to the optimum.

   Second: Assuming that the hand-chosen machine speeds are indeed optimum speeds, the chosen timeliness loss curve of the 25% weather risk is realistically related to weather and loss data used by the IJ.D.A. in their simulation of the grain harvest.

   It should be noted here that the machine losses in our simulation are higher than those of the optimum level of 0.50% calculated by IJ.D.A. The walker loss and the breakage loss were 0.98% each, the threshing loss was 0.50% and sieve loss 0.21%, together 2.7% averaged for all the manually controlled runs. It can thus also be concluded that the manually controlled speeds were too high compared to the standard loss level of the IJ.D.A. so that it was purely fortuitous that it was so close to the optimum.

2. Control system 1 gives lower total costs than control system 2 for all the cost situations. This means that a simple loss model and slow control of the mean levels and low-frequency variation in the crop parameter values and feed rate, gives a better contribution to cost minimisation than fast feed rate control. The simplification, needed for our simulations of the parameter estimation of control system 2, can be one reason, but the results clearly demonstrate that fast feed rate control is less important than control of slow varying crop properties including mean straw density.

3. The results of control system 3 and 4 also demonstrate that, for the threshing speed control, adaption to crop parameter variation is more beneficial than fast control of threshing speed. The differences compared to control systems 1 and 2, however, are slight, so that an expensive threshing separation measurement system is not quickly recovered.

### 6.3.3.2. *The time constant of the integrating action of the machine speed control*

The default value of the factor $P_c$ that determines the integrating action of the speed control was 25.0. The effect of other values has been studied and is shown in tables 6.3.3.2.1 and 6.3.3.2.2.

Table 6.3.3.2.1. Effects of time constant of machine speed control integration $P_c$ in control system 2
*TOC* = total costs, *VMAV* = mean machine speed, *ACAV* = mean machine acceleration, *WLAV* = mean walker loss, *CLO* = machine loss costs, *CM* = machine costs

| $P_c$ | *TOC* | *VMAV* | *ACAV* | *WLAV* | *CLO* | *CM* |
|---|---|---|---|---|---|---|
| | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $m \cdot s^{-2}$ | $kg \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ |
| 15 | 299.34 | 1.123 | 0.015 | 0.0611 | 71.51 | 202.07 |
| 20 | 299.02 | 1.122 | 0.019 | 0.0606 | 71.11 | 202.08 |
| 25 | 299.37 | 1.124 | 0.022 | 0.0610 | 71.45 | 202.06 |
| 30 | 299.02 | 1.122 | 0.025 | 0.0605 | 71.02 | 202.08 |
| 35 | 299.19 | 1.123 | 0.029 | 0.0607 | 71.17 | 202.07 |
| 40 | 299.28 | 1.123 | 0.033 | 0.0607 | 71.22 | 202.07 |
| 45 | 299.16 | 1.123 | 0.038 | 0.0605 | 71.04 | 202.07 |

It was concluded from these data that there is no effect on loss and speed, and thus on costs. Thus the chosen value based on the agreements of 5.3.1 was correct. A faster reaction of the speed control to the set point, calculated by the slower-acting cost minimisation calculation, merely introduces higher accelerations but not lower costs.

Table 6.3.3.2.2. Percentages of calculation steps in which the absolute value of the machine acceleration (*AC*) exceeds the given level

| $P_c$ | *AC* m·s$^{-2}$ | | | |
|---|---|---|---|---|
| $P_c$ | m·s$^{-2}$ > 0.1 | > 0.2 | > 0.3 | > 0.4 |
| 15 | 1.07 | 0.13 | 0.0 | 0.0 |
| 20 | 1.68 | 0.34 | 0.0 | 0.0 |
| 25 | 2.40 | 0.69 | 0.12 | 0.067 |
| 30 | 3.02 | 0.91 | 0.32 | 0.17 |
| 35 | 3.59 | 0.99 | 0.32 | 0.12 |
| 40 | 4.10 | 1.13 | 0.42 | 0.19 |
| 45 | 5.46 | 1.50 | 0.56 | 0.29 |

### 6.3.3.3. *The filter action of control system 1*

The breakpoint frequency of the low-pass filter in the loss feedback loop of control system 1 affects the mean machine speed and the machine losses.

Table 6.3.3.3.1 shows the data from which can be concluded that the default breakpoint frequency $f_b$ of 0.014 rad·s$^{-1}$ results in minimum costs in cost situations 2 and 6. It is also demonstrated that the low-cost area is wide. The minimum machine loss is found at $f_b$=0.030 rad·s$^{-1}$, which means that the control system may be very slow in acting, in fact much slower than is needed for stability, for instance $f_b$= 0.16 rad·s$^{-1}$ as is given in 5.4.1.

### 6.3.3.4. *The chosen value of c in the parameter estimation procedure in control system 1*

The loss model of control system 1 was in 5.2.2 defined as $WL=c\cdot\exp(q\cdot VW)$. The parameter $q$ is estimated "on line" in the simulation. The value of parameter $c$ was not "on line" estimated,but set at a value 3.4·10$^{-4}$ based on the mean measured in field experiment on the 8 swaths considered. To investigate the sensitivity of this choice, other values were also tested and the results given in table 6.3.3.4.1. The lower the value of $c$, the steeper the loss curve and the greater the decrease in speed. The effect on total costs is, however, small when $c$ is not given too high a value. The chosen default value leads to minimum costs in cost situation 2. If

Table 6.3.3.3.1. Effects of the breakpoint frequency $F_b$ of the low-pass filter in the measured walker loss of control system 1 for cost situation 2 and 6.
*TOC* = total costs, *VMAV* = mean machine speed, *CM* = machine costs, *CLO* = machine loss costs, *CTI* = timeliness loss costs, *CVW* = costs of wear of V-belt.

situation 2

| $f_b$ | *TOC* | *VMAV* | *CM* | *CLO* | *CTI* | *CVW* |
|---|---|---|---|---|---|---|
| $rad \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ |
| 0.0030 | 294.50 | 1.099 | 202.39 | 66.34 | 25.46 | 0.31 |
| 0.0064 | 293.81 | 1.085 | 202.61 | 63.93 | 26.97 | 0.30 |
| 0.014 | 293.53 | 1.077 | 202.74 | 62.64 | 27.86 | 0.29 |
| 0.030 | 293.54 | 1.075 | 202.76 | 62.32 | 28.17 | 0.29 |
| 0.064 | 293.84 | 1.077 | 202.73 | 62.55 | 28.28 | 0.29 |
| 0.16 | 299.32 | 1.124 | 202.01 | 71.45 | 25.50 | 0.36 |
| 0.33 | 297.84 | 1.096 | 202.44 | 67.49 | 27.60 | 0.31 |
| 0.4 | 300.14 | 1.100 | 202.37 | 70.01 | 27.44 | 0.32 |
| situation 6 | | | | | | |
| 0.0030 | 303.17 | 1.016 | 194.97 | 53.78 | 54.17 | 0.24 |
| 0.0064 | 302.32 | 0.996 | 196.78 | 51.13 | 54.18 | 0.23 |
| 0.014 | 302.04 | 0.985 | 197.73 | 49.90 | 54.18 | 0.23 |
| 0.030 | 302.06 | 0.982 | 197.98 | 49.67 | 54.18 | 0.23 |
| 0.064 | 302.55 | 0.985 | 197.73 | 50.41 | 54.18 | 0.24 |
| 0.16 | 309.00 | 1.052 | 192.06 | 62.32 | 54.32 | 0.30 |
| 0.33 | 314.68 | 1.018 | 194.80 | 65.40 | 54.17 | 0.31 |
| 0.4 | 318.54 | 1.025 | 194.29 | 69.76 | 54.17 | 0.33 |

the value $c$ is too high and the loss falls below that level, negative values of $q$ will be calculated. This results in an equation that cannot besolved and the simulation stops. This in fact occured for $c = 6.7 \cdot 10^{-3}$. A very strange thing occurred for $c$=$2.5 \cdot 10^{-3}$ in cost situation 6. The speeds became very low in the first swath and were at maximum in the others. No explanation was found for this phenomenon.

Table 6.3.3.4.1. Effects of the value c in the parameter estimation procedure $WL = c \cdot \exp(q \cdot VW)$ of control system 1 for cost situation 2 and 6.
*TOC* = total costs, *VMAV* = mean machine speed, *CLO* = machine loss costs

| | | situation 2 | | | | situation 6 | | |
|---|---|---|---|---|---|---|---|---|
| ln c | c | *TOC* $fl \cdot ha^{-1}$ | *VMAV* $m \cdot s^{-1}$ | *CLO* $fl \cdot ha^{-1}$ | | *TOC* $fl \cdot ha^{-1}$ | *VMAV* $m \cdot s^{-1}$ | *CLO* $fl \cdot ha^{-1}$ |
| - 5.0 | $6.7.10^{-3}$ | -- | 0.0*) | -- | | 321.05 | 1.179 | 83.21 |
| - 6.0 | $2.5.10^{-3}$ | 299.09 | 1.156 | 76.01 | **) | -- | -- | -- |
| - 8.0 | $3.4.10^{-4}$ | 293.53 | 1.077 | 62.64 | | 302.04 | 0.985 | 49.90 |
| -11.0 | $1.7.10^{-5}$ | 293.64 | 1.006 | 53.08 | | 300.90 | 0.886 | 38.85 |

*) The simulation stopped after 22 seconds.

**) The first swath was harvested at a very low speed of 0.093 $m \cdot s^{-1}$ and the others at maximum machine speed.

### 6.3.3.5. *The filter action of control system 2*

The default value of the breakpoint frequency of the low-pass filter ($f_b$) in the calculation of straw density was chosen as 0.4 $rad \cdot s^{-1}$ in accordance with 5.4.2. The results of table 6.3.3.5.1 show minimum total costs

Table 6.3.3.5.1. Effects of the breakpoint frequency $f_b$ of the low pass filter of calculated straw density of control system 2 for cost situation 2 and 6.
*TOC* = total costs, *VMAV* = mean machine speed, *CM* = machine costs, *CLO* = machine loss costs, *CTI* = timeliness loss costs, *CVW* = costs of wear of V-belt.

| Costsituation | 6 | 2 | | | | | |
|---|---|---|---|---|---|---|---|
| $f_b$ $rad \cdot s^{-1}$ | *TOC* $fl \cdot ha^{-1}$ | *TOC* $fl \cdot ha^{-1}$ | *VMAV* $m \cdot s^{-1}$ | *CM* $fl \cdot ha^{-1}$ | *CLO* $fl \cdot ha^{-1}$ | *CTI* $fl \cdot ha^{-1}$ | *CVW* $fl \cdot ha^{-1}$ |
| 0.05 | 308.99 | 299.25 | 1.117 | 202.11 | 71.60 | 25.17 | 0.37 |
| 0.1 | 308.43 | 298.73 | 1.117 | 202.11 | 70.92 | 25.34 | 0.36 |
| 0.2 | 308.39 | 298.67 | 1.118 | 202.10 | 70.65 | 25.58 | 0.35 |
| 0.4 | 309.00 | 299.18 | 1.123 | 202.01 | 71.31 | 25.50 | 0.36 |
| 0.5 | 309.43 | 299.29 | 1.125 | 201.98 | 71.63 | 25.33 | 0.36 |
| 0.6 | 311.30 | 299.69 | 1.134 | 201.86 | 72.77 | 24.71 | 0.36 |

at $f_b$ = 0.2 rad•s$^{-1}$ for cost situations 2 and 6 mainly because of the minimum machine loss. The differences are very slight so the adjustment of $f_b$ was correct.

The machine speed control for system 4 is the same as for system 2, hence the effect of breakpoint frequency in this system was also studied and the results are to be found in table 6.3.3.5.2. Minimum cost is found in this case for 0.1 rad•s$^{-1}$ for both situations 2 and 6, also thanks to minimum loss costs.

Table 6.3.3.5.2. Effects of the breakpoint frequency $f_b$ of control system 4 (see text table 6.3.3.5.1.).

| Cost situation | 2 | 6 | | | | | |
|---|---|---|---|---|---|---|---|
| $f_b$ | *TOC* | *TOC* | *VMAV* | *CM* | *CLO* | *CTI* | *CVW* |
| rad•s$^{-1}$ | fl•ha$^{-1}$ | fl•ha$^{-1}$ | m•s$^{-1}$ | fl•ha$^{-1}$ | fl•ha$^{-1}$ | fl•ha$^{-1}$ | fl•ha$^{-1}$ |
| 0.05 | 288.92 | 301.23 | 1.049 | 192.32 | 53.23 | 54.34 | 1.34 |
| 0.1 | 288.79 | 300.97 | 1.048 | 192.40 | 52.89 | 54.33 | 1.35 |
| 0.2 | 288.91 | 301.10 | 1.049 | 192.32 | 53.11 | 54.32 | 1.35 |
| 0.4 | 289.40 | 301.64 | 1.052 | 192.07 | 53.90 | 54.32 | 1.34 |
| 0.5 | 289.29 | 302.10 | 1.054 | 191.92 | 54.51 | 54.32 | 1.35 |
| 0.6 | 290.60 | 303.15 | 1.058 | 191.54 | 55.95 | 54.32 | 1.34 |

In fig. 5.4.2.2 it can be seen that for $f_b$ = 0.4 rad•s$^{-1}$ the response to a step in the straw density input shows no overshoot so that in the cost optimisation the value for $f_b$ may be much smaller than is necessary for stability. Quiet behaviour and following the low-frequency and mean level variations of the disturbances of the process is found to offer better cost minimisation results than trying to follow the high-frequency variations.

### 6.3.3.6. *The integrating action of the threshing speed control*

The default value of the factor *PCTC*, that adjusts the integrating action of the threshing speed control, was set at 0.10$^{-4}$ in accordance with 5.3.2. Other values were tested for control system 4 and cost situation 2. The results are given in table 6.3.3.6.1 and show minimum costs for *PCTC*=10.10$^{-4}$ but the difference in costs compared to the default value is very slight. It can be concluded therefore that the value chosen for control theory

Table 6.3.3.6.1. Effects of the time constant of the integrating action of the threshing speed control *PCTC*, in *PCTC/s*, for control system 4 and cost situation 2.
*TOC* = total costs, *VTAV* = mean threshing cylinder speed,
*CLO* = machine loss costs, *CVW* = costs of wear of V-belt,
*FOBAV* = mean tension in V-belt, *TSEAV* = mean threshing separation efficiency, *WLAV* = mean walker loss.

| *PCTC* | *TOC* | *VTAV* | *CLO* | *CVW* | *FOBAV* | *TSEAV* | *WLAV* |
|---|---|---|---|---|---|---|---|
| x $10^{-4}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | N | % | $kg \cdot s^{-1}$ |
| 4 | 289.99 | 34.01 | 61.15 | 1.24 | 1394.42 | 82.55 | 0.0522 |
| 6 | 289.73 | 33.99 | 60.92 | 1.24 | 1395.77 | 82.53 | 0.0519 |
| 8 | 289.62 | 33.97 | 60.82 | 1.24 | 1396.99 | 82.50 | 0.0518 |
| 10 | 289.41 | 33.96 | 60.60 | 1.23 | 1397.86 | 82.50 | 0.0515 |
| 12 | 289.50 | 33.95 | 60.70 | 1.23 | 1399.93 | 82.47 | 0.0516 |

reasons is also a good one for cost minimisation reasons.

### 6.3.3.7. *The integrating action in the adaption of threshing speed-to-feed rate relation in control system 4*

The default value of the proportional factor $2v$ in control system 4 is $2.5 \cdot 10^{-3}$ (see 5.2.3 and 5.4.4). The effect of other values was also investigated and shows that values below the default value are too low. The total costs are not minimum but the important thing is to realise that the threshing speed adapts too slowly, remaining at the value of the later swath too long . As for the input of crop properties into our simulation, the optimum would have been a value of $5 \cdot 10^{-3}$. (see table 6.3.3.7.1)

The optimum value of this factor depends very much on the conditions, so that more research in actual practice is required.

### 6.3.3.8. *The set value of threshing separation efficiency of control system 4*

The optimum threshing speed is influenced by the set value of the threshing separation efficiency (*SVTS*). The effects are demonstrated in tables 6.3.3.8.1 and 6.3.3.8.2. It becomes clear that increasing *SVTS* values give rise to increasing values of the threshing speed and, as a result, to increasing threshing separation efficiency and decreasing loss costs and total costs.

Table 6.3.3.7.1. Effects of the value of the proportinal factor *2v* in the integrating action of calculation of *VFSC* of control system 4 for cost situation 2.
*TOC* = total costs, *CLO* = machine loss costs, *VTAV* = mean threshing speed, *TSEAV* = mean threshing separation efficiency, *WLAV* = mean walker loss, *FOBAV* = mean V-belt tension, *CVW* = costs of wear of V-belt.

| *2v* | *TOC* | *VTAV* | *CLO* | *TSEAV* | *WLAV* | *FOBAV* | *CVW* |
|---|---|---|---|---|---|---|---|
| $\times 10^{-3}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | % | $kg \cdot s^{-1}$ | N | $fl \cdot ha^{-1}$ |
| 0.1 | 308.32 | 28.25 | 80.23 | 73.58 | 0.0687 | 1497.87 | 0.53 |
| 1 | 291.30 | 33.12 | 62.75 | 81.19 | 0.0532 | 1411.07 | 1.06 |
| 2.5 | 289.62 | 33.97 | 60.82 | 82.50 | 0.0518 | 1396.99 | 1.24 |
| 5 | 289.22 | 34.18 | 60.38 | 82.88 | 0.0515 | 1394.03 | 1.28 |
| 10 | 289.98 | 34.18 | 61.13 | 82.96 | 0.0525 | 1395.52 | 1.28 |
| 20 | 294.71 | 34.61 | 65.77 | 82.21 | 0.0576 | 1403.90 | 1.37 |
| 40 | 305.74 | 34.43 | 76.65 | 79.95 | 0.0691 | 1445.91 | 1.53 |

Table 6.3.3.8.1. Effects of the set value for the threshing separation efficiency (*SVTS*) of control system 4 for cost situation 2.
*TSE* = threshing separation efficiency, *VTAV* = mean threshing speed, *TOC* = total costs, *CLO* = machine loss costs, *CBLE* = costs of extra breakage loss under adverse conditions, *TLAV* = mean threshing loss, *BLAV* = mean breakage loss, *WLAV* = mean walker loss, *BLEAV* = mean extra breakage loss under adverse conditions

| *SVTS* | *TSE* | *VTAV* | *TOC* | *CLO* | *CBLE* | *TLAV* | *BLAV* | *WLAV* | *BLEAV* |
|---|---|---|---|---|---|---|---|---|---|
| % | % | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $kg \cdot s^{-1}$ | $kg \cdot s^{-1}$ | $kg \cdot s^{-1}$ | $kg \cdot s^{-1}$ |
| 80 | 76.46 | 30.61 | 314.06 | 85.43 | 2.29 | 0.0249 | 0.0411 | 0.0771 | 0.2056 |
| 85 | 79.86 | 32.44 | 300.54 | 71.79 | 2.67 | 0.0210 | 0.0460 | 0.0632 | 0.2299 |
| 90 | 82.50 | 33.97 | 289.62 | 60.82 | 3.04 | 0.0180 | 0.0500 | 0.0518 | 0.2499 |
| 95 | 84.71 | 35.64 | 279.91 | 51.10 | 4.30 | 0.0154 | 0.0546 | 0.0416 | 0.2730 |

Table 6.3.3.8.2. Effect on total costs (*TOC* in fl·ha$^{-1}$) of the set value for the threshing separation efficiency (*SVTS*) of control system 4 for cost situation 1 ... 6.

| cost situation | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| *SVTS* | | | | | | |
| 80 | 486.68 | 314.06 | 704.31 | 393.93 | 515.52 | 325.29 |
| 85 | 476.76 | 300.54 | 686.05 | 377.93 | 499.19 | 311.90 |
| 90 | 468.24 | 289.62 | 670.80 | 365.31 | 486.30 | 301.82 |
| 95 | 460.97 | 279.91 | 656.20 | 353.51 | 473.98 | 292.67 |

The increase of the costs of grain breakage loss under adverse conditions (*CBLE*) is less than the decrease in machine cost for the parameter values chosen in our simulation (see 2.3.2), even for the last step in *SVTS* from 90% to 95%. It could therefore be concluded that *SVTS* might be increased to above 95%,but it must be realised that no straw breakage is included in the model, so that the negative effect of increased threshing speed on walker loss and especially sieve loss is unknown.

The threshing speed reaches its maximum in swath 5 ... 8 when *SVTS*=90%. When *SVTS*=85% it does so most of the time as can be concluded from table 6.3.3.8.3 and figure 6.2.4.8.2. These aspects of threshing speed make it clear that the effect of straw breakage on walker and sieve losses should be included in the simulation model as well as in the control system. However, much more research into these aspects is required,before this can be done.

The results in the tables of this section also demonstrate the importance of the threshing separation efficiëncy. Manufacturers of combine harvesters are aware of this,as can be concluded from the newly designed combine harvesters having extra rotating grain separation elements.

### 6.3.3.9. *The straw feed rate monitor*

The straw feed rate can be measured by either the auger torque or the displacement of the elevator chain. Auger torque was taken as the default case. Table 6.3.3.9.1 shows the total costs for both. The positive effect of auger torque measurement is very slight especially for control systems

Table 6.3.3.8.3. Effects of two different set values of the threshing separation efficiency (*SVTS*) for the individual swaths of the simulation. The swaths are indicated by these sequence number (Sw) and the field test number (Tn). *TSE* = threshing separation efficiency, *VTAV* = mean threshing speed, *CLO* = machine loss costs, *TOC* = total costs, *CBLE* = costs of extra grain breakage under adverse conditions, *TLAV* = mean threshing loss, *BLAV* = mean breakage loss, *SLAV* = mean sieve loss, *WLAV* = mean walker loss, *BLEAV* = mean breakage loss under adverse conditions

| | | *TSE* | | *VTAV* | | *CLO* | | *TOC* | | *CBLE* | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | | $m \cdot s^{-1}$ | | $fl \cdot ha^{-1}$ | | $fl \cdot ha^{-1}$ | | $fl \cdot ha^{-1}$ | |
| *SVTS* %: | | 85 | 90 | 85 | 90 | 85 | 90 | 85 | 90 | 85 | 90 |
| Sw | Tn | | | | | | | | | | |
| 1 | 61 | 84.5 | 89.4 | 24.2 | 26.7 | 78.81 | 57.41 | 294.08 | 272.58 | 0.00 | 0.33 |
| 2 | 39 | 85.3 | 90.3 | 24.5 | 27.1 | 75.10 | 53.10 | 299.41 | 277.24 | 0.01 | 0.40 |
| 3 | 12 | 84.9 | 89.9 | 25.0 | 27.7 | 93.98 | 68.51 | 317.57 | 291.45 | 0.00 | 0.98 |
| 4 | 55 | 68.2 | 71.7 | 32.0 | 34.0 | 58.98 | 52.53 | 296.28 | 290.26 | 2.01 | 2.44 |
| 5 | 57 | 81.7 | 82.3 | 38.1 | 38.5 | 43.23 | 41.35 | 291.94 | 290.10 | 4.44 | 4.49 |
| 6 | 52 | 93.7 | 94.8 | 37.5 | 38.8 | 37.94 | 34.83 | 255.74 | 252.79 | 7.16 | 7.53 |
| 7 | 37 | 64.1 | 66.0 | 37.1 | 38.4 | 94.66 | 89.47 | 313.20 | 308.21 | 3.53 | 3.91 |
| 8 | 33 | 78.9 | 79.1 | 38.4 | 38.6 | 90.47 | 90.30 | 334.95 | 334.80 | 4.21 | 4.24 |

| | | *TLAV* | | *BLAV* | | *SLAV* | | *WLAV* | | *BLEAV* | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\times 10^{-4}$ | | $kg \cdot s^{-1}$ | | $kg \cdot s^{-1}$ | | $kg \cdot s^{-1}$ | | $kg \cdot s^{-1}$ | | $kg \cdot s^{-1}$ | |
| *SVTS* %: | | 85 | 90 | 85 | 90 | 85 | 90 | 85 | 90 | 85 | 90 |
| Sw | Tn | | | | | | | | | | |
| 1 | 61 | 219 | 151 | 313 | 380 | 129 | 129 | 847 | 590 | 1564 | 1901 |
| 2 | 39 | 169 | 112 | 271 | 332 | 120 | 120 | 721 | 482 | 1353 | 1658 |
| 3 | 12 | 184 | 126 | 301 | 376 | 140 | 144 | 966 | 682 | 1507 | 1880 |
| 4 | 55 | 289 | 256 | 371 | 418 | 63 | 63 | 353 | 308 | 1853 | 2080 |
| 5 | 57 | 180 | 173 | 548 | 557 | 64 | 63 | 248 | 232 | 2741 | 2785 |
| 6 | 52 | 94 | 84 | 777 | 813 | 133 | 133 | 334 | 298 | 3886 | 4065 |
| 7 | 37 | 332 | 311 | 527 | 571 | 89 | 89 | 895 | 843 | 2633 | 2855 |
| 8 | 33 | 208 | 207 | 556 | 559 | 86 | 86 | 770 | 769 | 2779 | 2794 |

Table 6.3.3.9.1. Total costs (*TOC*) and walker loss (*WL*) affected by the choice of straw feed rate monitor.

| | Cost situation 2 | | | | Cost situation 6 | | | |
|---|---|---|---|---|---|---|---|---|
| control system | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| *TOC* $fl \cdot ha^{-1}$ | | | | | | | | |
| auger torque | 293.53 | 299.18 | 301.93 | 289.62 | 302.04 | 309.00 | 312.44 | 301.8 |
| displacement | 293.51 | 299.39 | 303.06 | 289.68 | 302.05 | 309.76 | 313.68 | 302.4 |
| *WL* $kg \cdot s^{-1}$ | | | | | | | | |
| auger torque | 0.0485 | 0.0609 | 0.0627 | 0.0518 | 0.0316 | 0.0473 | 0.0494 | 0.041 |
| displacement | 0.0486 | 0.0607 | 0.0638 | 0.0527 | 0.0316 | 0.0481 | 0.0507 | 0.042 |

3 and 4 because of the decrease in walker loss caused by an increase in threshing separation efficiency. These results from the threshing speed control which, thanks to the longer delay, has ample time to bring the speed to the optimum. The other cost components do not differ, because machine speed is not affected.

### 6.3.3.10. *The level of the simulated measurement noise*

The added noise was set at zero, at twice the default levels and at half those levels (see 6.2.4.2) to check the sensitivity on costs. The results are given in table 6.3.3.10.1.

Table 6.3.3.10.1. Effects of noise levels related to the default level; for cost situation 2 and the control systems referred to. *TOC* = total costs, *CLO* = machine loss costs, *VMAV* = mean machine speed

| Control system | 1 | | | 2 | | | 4 | | |
|---|---|---|---|---|---|---|---|---|---|
| factor to default | *TOC* | *CLO* | *VMAV* | *TOC* | *CLO* | *VMAV* | *TOC* | *CLO* | *VMA* |
| noise level | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | m·s |
| 0 | 293.52 | 62.69 | 1.078 | 298.95 | 70.99 | 1.121 | 289.36 | 60.46 | 1.1 |
| 1.5 | 293.52 | 62.69 | 1.078 | 298.92 | 70.94 | 1.121 | 289.40 | 60.47 | 1.1 |
| 1 | 293.53 | 62.64 | 1.077 | 299.18 | 71.31 | 1.123 | 289.62 | 60.82 | 1.1 |
| 2 | 293.51 | 62.64 | 1.077 | 299.27 | 71.67 | 1.126 | 289.69 | 61.19 | 1.1 |

For control system 1 only the noise in walker loss measurement has an effect on costs. The effect is negligible, because of the low breakpoint frequency of the filter in the control, so that almost all noise was filtered out. In practice this has also to be done.

In control system 2 it is just the noise in the straw feed rate measurement which has an effect. The effect on costs remains slight, because also here the filter has done its work.

In case of control system 4 the threshing separation efficiency (*TSE*) was measured with added noise. This noise is also heavily filtered because of the small proportional factor in the calculation of *VFSC* (see 6.3.3.7).

The noise was coloured by means of high-pass filter. The breakpoint frequency of this filter was also varied. The default value was 0.1 rad•s$^{-1}$. Table 6.3.3.10.2 shows results for breakpoint frequencies of 1, 0.1, 0.01, and 0.001 rad•s$^{-1}$.

Table 6.3.3.10.2. Effects of the breakpoint frequency of the high pass filters of the noise generators for cost situation 2 and control system 1 and 4.
*TOC* = total costs, *VMAV* = mean machine speed, *WLAV* = mean walker loss.

| Control system | 1 | | | 4 | | |
|---|---|---|---|---|---|---|
| $f_b$ | *TOC* | *VMAV* | *WLAV* | *TOC* | *VMAV* | *WLAV* |
| rad•s$^{-1}$ | fl•ha$^{-1}$ | m•s$^{-1}$ | kg•s$^{-1}$ | fl•ha$^{-1}$ | m•s$^{-1}$ | kg•s$^{-1}$ |
| 1.0 | 293.52 | 1.078 | 0.0486 | 289.07 | 1.123 | 0.0516 |
| 0.1 | 293.53 | 1.077 | 0.0485 | 289.62 | 1.124 | 0.0518 |
| 0.01 | 293.52 | 1.077 | 0.0485 | 290.03 | 1.132 | 0.0534 |
| 0.001 | 293.60 | 1.079 | 0.0488 | 291.00 | 1.199 | 0.0654 |

The effects are again negligibly small. At the smallest breakpoint frequency a relatively large variation in the low frequencies remains in the signal, thus brings about the highest deviation compared to the real value, resulting in extra costs. The effects on mean machine speed in control system 4 in this situation was remarkable and was probably caused by the negative noise values that were fortuitously in the majority, making the simulation output stochastic to a certain extent and providing the reason why the high-pass filter in the noise generator was introduced.

The effect of noise on straw feed rate (*FS*) and threshing separation efficiency (*TSE*) was investigated separately at double the noise level. In table 6.3.3.10.3 the effect of noise on *FS* can be seen to be the principal reason for increased costs mainly in the form of the increased loss costs.

Table 6.3.3.10.3. Effect of noise superposed on the measurement of feed rate (*FS*) and threshing separation efficiency (*TSE*), in turn, in control system 4 and cost situations 2 and 6. The noise levels are twice the default levels.
*TOC* = total costs, *CLO* = cost of machine loss, *VMAV* = mean machine speed

| Cost situation | 2 | | | 6 | | |
|---|---|---|---|---|---|---|
| | *TOC* | *CLO* | *VMAV* | *TOC* | *CLO* | *VMAV* |
| | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ |
| no noise | 289.36 | 60.46 | 1.122 | 301.62 | 53.88 | 1.051 |
| just noise on *FS* | 289.41 | 61.02 | 1.127 | 301.96 | 54.34 | 1.053 |
| just noise on *TSE* | 289.47 | 60.61 | 1.123 | 301.75 | 54.01 | 1.051 |
| noise on *FS* and *TSE* | 289.69 | 61.19 | 1.126 | 302.19 | 54.58 | 1.053 |

### 6.3.3.11. *The sequence of simulated swaths*

The control systems react to the variation in crop parameters in their own specific way. In this simulation the crop parameter values differ in a sequence determined by the swath sequence. The slower the adaption to crop parameters and the more the successive parameter values differ, the longer the time that the system works below optimum level. Thus the chosen swath sequence in fact affects the results.

This can be investigated by changing the swath sequence in the simulation. The sequence in which the swath data were recorded during the field measurements was chosen as the alternative, which corresponds to the increase in the trial numbers, that is 12, 33, 37 ... instead of 61, 39, 12 ... of the default sequence, selected to make the differences greater.

Table 6.3.3.11.1 shows the cost data for each control system and for cost situation 6. The differences are slight (maximum 1.5% for control system 4) so that it can be concluded that the sequence has not much impact.

Table 6.3.3.11.1. Effect on total costs of the sequence of the swaths during the simulation for cost situation 6 (costs in fl•ha$^{-1}$)

| Control system | 0 | | 1 | | 2 | | 3 | | 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Swath sequence | *TOC* | *CLO* | *TOC* | *CLO* | *TOC* | *CLO* | *TOC* | *CLO* | *TOC* | *CLO* |
| Default | 306.77 | 52.73 | 302.04 | 49.90 | 309.00 | 62.31 | 312.44 | 65.68 | 301.82 | 54.12 |
| Tests | 307.46 | 53.55 | 302.18 | 49.21 | 308.79 | 62.40 | 312.34 | 65.91 | 297.34 | 49.91 |

The difference in the hand-controlled situation is remarkably large, for which reason the origin of this phenomenon was studied in the cost data on each individual swath. The default sequence of the swath is given in table 6.3.3.11.2. The differences are merely in the origin of the losses and are caused by the differences in feed rate at the beginning of each swath owing to the adaption of machine speed that takes about 4.0 seconds. In control system 4 the reason is the time required for the adaption of threshing speed.

Table 6.3.3.11.2. Effect on costs and loss of the individual swaths depending on the swath sequence during the simulation of hand controlled runs and cost situation 2. The default (Def.) sequence is given in the table while the tests (Test) sequence is the increasing number sequence (12,33, 37, ...).

| Swath test | Total costs fl•ha$^{-1}$ | | Machine loss costs fl•ha$^{-1}$ | | Timeliness loss costs fl•ha$^{-1}$ $^{-1}$ | | Mean walker loss kg•s$^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| number | Def. | Test | Def. | Test | Def. | Test | Def. | Test |
| 61 | 273.66 | 276.56 | 15.77 | 18.96 | 58.10 | 57.89 | 0.0071 | 0.0094 |
| 39 | 278.17 | 283.41 | 17.33 | 22.87 | 54.56 | 54.29 | 79 | 120 |
| 12 | 283.92 | 283.22 | 27.55 | 27.10 | 57.55 | 57.28 | 173 | 169 |
| 55 | 298.32 | 298.15 | 45.92 | 45.82 | 50.06 | 50.04 | 195 | 193 |
| 57 | 314.12 | 314.07 | 58.49 | 58.46 | 54.34 | 54.33 | 315 | 315 |
| 52 | 298.69 | 295.00 | 42.13 | 38.73 | 61.51 | 61.15 | 280 | 255 |
| 37 | 320.79 | 326.59 | 77.89 | 84.02 | 44.94 | 44.58 | 517 | 576 |
| 33 | 386.60 | 382.78 | 136.79 | 132.43 | 52.05 | 52.58 | 1180 | 1146 |

### 6.3.3.12. *Sample interval*

The sample interval (*DT*) of the "digital" control causes a delay in the information transfer. This affects the optimum adjustment of speeds and hence the costs. Table 6.3.3.12.1 shows the effect for the various control systems in cost situation 2. No real differences are found in control system 1 as this system is in itself slow. In control systems 2, 3 and 4 it is clear that the shortest interval is optimal, although the difference between 0.1 s and 0.25 s is not of importance and that between 0.25 s and 0.5 s i slight. From 0.5 to 1 s the cost increase is about 10%, which is

Table 6.3.3.12.1. Effects of the sample interval (*DT*) of the control calculation.
*TOC* = total costs, *VMAV* = mean machine speed

| Control system | 1 | | 2 | | 3 | | 4 | |
|---|---|---|---|---|---|---|---|---|
| | *TOC* | *VMAV* | *TOC* | *VMAV* | *TOC* | *VMAV* | *TOC* | *VMAV* |
| *DT* | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $m \cdot s^{-1}$ |
| 0.1 | 293.57 | 1.078 | 298.83 | 1.120 | 301.52 | 1.120 | 289.20 | 1.120 |
| 0.25 | 293.60 | 1.079 | 298.83 | 1.120 | 301.57 | 1.120 | 289.20 | 1.119 |
| 0.5 | 293.53 | 1.077 | 299.18 | 1.123 | 301.93 | 1.123 | 289.62 | 1.124 |
| 1.0 | 298.61 | 1.076 | 301.52 | 1.131 | 304.96 | 1.132 | 291.89 | 1.132 |

too large. It is caused by the increase in machine loss due to the increased machine speed.

### 6.3.3.13. *Time constant in the first-order transfer of the walker separation model*

The determination of the time constant in the first-order transfer, modelling the redistribution of straw on the straw walkers, was too vague as can be seen from 2.3.4. To investigate the importance of the effect of this parameter (*TAUW*) on the simulation results, it was varied. In addition to the default value of 0.8 s, 0.5 and 1,2 s were also tested. The effects in cost situation 2 are shown in table 6.3.3.13.1.

Table 6.3.3.13.1. Effects of the value of the time constant (*TAUW*) in the redistribution process on the straw walkers. The differences are given in percentages.
*TOC* = total costs, *WLAV* = mean walker loss, *VMAV* = mean machine speed.

| Control system | 0 | | 1 | | | 2 | | 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | *TOC* | *WLAV* | *TOC* | *WLAV* | *VMAV* | *TOC* | *WLAV* | *TOC* | *WLAV* |
| *TAUW* | $fl \cdot ha^{-1}$ | $kg \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $kg \cdot s^{-1}$ | $m \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $kg \cdot s^{-1}$ | $fl \cdot ha^{-1}$ | $kg \cdot s^{-1}$ |
| 0.5 | 300.21 | 0.0358 | 294.68 | 0.0489 | 1.071 | 300.55 | 0.0626 | 290.80 | 0.053 |
| diff. % | 0.35 | 3.4 | 0.39 | 0.8 | 0.6 | 0.5 | 2.7 | | |
| 0.8 | 299.16 | 0.0346 | 293.53 | 0.0485 | 1.077 | 299.18 | 0.0609 | 289.62 | 0.0518 |
| diff. % | 0.23 | 2.0 | 0.23 | 0.4 | 0.4 | 0.3 | 1.6 | | |
| 1.2 | 298.47 | 0.0339 | 292.85 | 0.0483 | 1.081 | 298.43 | 0.0599 | 288.96 | 0.050 |

Walker loss decreased with increasing *TAUW*. This could be expected because the straw feed variations are flattered then. In combination with the non-linear transfer of walker loss to feed rate this results in a lower mean level.

The hand-controlled situation showed differences of 3% and 2% and the effect can only be described as slight. The reduced loss brings about an increase in machine speed in control system 1, but some difference remains (0.8% and 0.4%). Differences in control systems 2 and 4 are about the same as in hand control as, in our simulation, there is no feedback of simulated loss to machine speed.

The differences in total costs are the same for all systems because the walker loss cost is just a small part of the total costs. Thus *TAUW* does not influence the simulation results.

### 6.3.3.14. *Optimum parameter values for the simulation*

In some of the preceding sections the default parameter values were found not to be the optimum although they were close. To investigate the effect of this deviation, simulation runs were done with the optimum parameter values in situation 2 for all control systems. Table 6.3.3.14.1 demonstrates how these runs differ from those with default values. The differences are very slight (less than 0.4%) so that they do not affect the conclusions of the preceding sections.

Table 6.3.3.14.1. Costs calculated in simulation runs with default values of parameters and runs with optimum values. The altered values were: $P_c = 20.0$, $PCTC = 10.0 \cdot 10^{-4}$, $2v = 5.0 \cdot 10^{-3}$ and $f_b$ of control system 2 = 0.1 $rad \cdot s^{-1}$
*TOC* = total costs, *CLO* = machine loss costs

| Control system: | 1 | | 2 | | 3 | | 4 | |
|---|---|---|---|---|---|---|---|---|
| | *TOC* | *CLO* | *TOC* | *CLO* | *TOC* | *CLO* | *TOC* | *CLO* |
| | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ |
| Default | 293.58 | 62.64 | 299.37 | 71.45 | 302.06 | 74.11 | 289.62 | 60.82 |
| Optimal | 293.58 | 62.64 | 298.82 | 70.79 | 301.63 | 73.53 | 288.94 | 59.98 |

Finally, the effect of calculation step *DELT* was checked in control system 4 and cost situation 6 (see table 6.3.3.14.2). The value 0.05 s compared to 0.1 s, represented a cost decrease of 1.11 $fl \cdot ha^{-1}$, due mainly to a decrease in calculated wear of the V-belt, as the forces in the V-belt are proportional to the differences in threshing cylinder speed between the consecutive calculation steps, and the shorter the steps, the slighter the differences. Since the wear cost factor is an estimated one based on simulations with *DELT* = 0.1 s, this factor may only be used for that "*DELT*" value.

It was concluded therefore that the chosen calculation interval was short enough.

Table 6.3.3.14.2. Costs calculated in simulation runs with the usual calculation time interval *DELT* = 0.1 and the value 0.05, *TOC* = total costs, *CLO* = machine loss costs, *CVW* = costs of wear of V-belt, *WLAV* = mean walker loss.

| *DELT* | *TOC* | *CLO* | *CVW* | *WLAV* |
|---|---|---|---|---|
| s | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $fl \cdot ha^{-1}$ | $kg \cdot s^{-1}$ |
| 0.10 | 301.82 | 54.12 | 1.30 | 0.0413 |
| 0.05 | 300.71 | 53.93 | 0.36 | 0.0411 |

## 6.4. CONCLUSIONS FROM SIMULATIONS

The main conclusions drawn from consideration of the simulation results are given here. The general conclusions will be presented in the next chapter.

Comparison of simulated with measured data demonstrates a fair degree of harmony. The results of the simulated control systems could not be tested in the field as the necessary hardware is not yet available, but their behaviour was not unexpected. The selected system parameter values are close to the optimum values for simulation. The chosen parameter values for the cost factors and the timeliness loss curve relating to a weather risk of 25% result in realistic total cost data.

The input of the simulations has been taken from the crop and weather conditions recorded for the fields and machines of the IJsselmeerpolders Development Authority large-scale grain farm (IJ.D.A.). The speeds then selected by the machine operator were defined as standard for the manually controlled situation assumed in this study.

The cost decrease achieved with an assumed machine capacity increase of 10% thanks to a machine design improvement was found to be 23.13 fl·ha$^{-1}$ (≈ 8%) for our simulations on the basis of the cost situation of the IJ.D.A. This value can be compared to the decrease calculated by the Department For Operational Research of IJ.D.A. itself as 34.50 fl·ha$^{-1}$. As these values are much influenced by the mean machine speed and the shape of the timeliness loss curve they are in fact of the same order. This allows them to be used in comparing the differences between control systems. The cost decrease is much higher in the case of cost situations in which the timeliness loss risks are lower than 25%.

The calculated total costs of the various cost situations considered differ a great deal. The timeliness loss has a great influence on the costs.

The timeliness loss curve based on 16 2/3% weather risk results in high costs and indicates the importance of timeliness loss in harvest seasons with unfavourable weather. In an attempt to escape these high costs in such situations, farmers often prefer to use machines with a large harvest capacity compared to the capacity they need for the area to be harvested. However, this results in high machine costs.

This also indicates that the timeliness loss curve to be considered in control systems has to be adapted to the conditions, should they change during the harvest season. The farmer also reacts intuitively by harvesting faster or longer per day when the weather becomes more unfavourable.

When timeliness losses are constant (fixed harvest period) or when the risk factor is 25% (harvest period variable), there is a wide range of optimum speeds, so that selected machine speeds may vary ± 10% without any considerable effect on total costs.

The effect on cost decrease by the control systems for the simulated IJ.D.A. cost situations (2 and 6) is very slight (from 3.2% to -0.1%). Minimum costs are found for the loss-feed rate-threshing separation control system (4), followed by the loss control system (1) and the loss-feed rate control system (2). The costs for loss-feed rate-threshing speed control system (3) are even higher than those of manual operation. The manually selected speeds were very close to the speeds that were optimally adjusted by the control systems. In such a case no control system gives much benefit.

It has to be realised, however, that the manually selected speeds used as a standard in this study are samples that are perhaps fortuitously correct. In addition, the machine operators of the IJ.D.A. are trained to select speeds that will result in a total machine loss level of about 0.5%. This level was calculated as optimum by means of a cereal harvest optimisation model, many of whose data were also used in the cost calculation of our simulation. In other cost situations, such as 3 and 4 where, due to other timeliness loss curves, higher speeds are chosen by the control systems, the difference from manual operation is considerable, but in this case the operator would probably also have selected higher speeds in manual control if he is familiar with the cost background.

Control of machine speed, which adapts not only to slow loss variations affected by crop properties, but which also adapts to expected timeliness losses owing to the weather during the course of the harvest, will bring savings. Control of the high frequency variations in straw density, however, will bring no worthwhile extra savings.

Machine speed can be controlled by a simple loss control system *assuming* the presence of an accurate grain loss measurement device. A manual control system, including regular inspection of loss and the awareness of the optimum loss level will possibly give the same effect.

The control of threshing speed has to be achieved by optimising the mean threshing speed, since reacting to the high-frequency feed rate variations brings no benefit.

It is evident from the above-mentioned conclusions that other factors such as selection of the feed rate monitor, the sample interval and the value of control parameters are not important in cost minimisation.

The optimisation of the threshing speed is beneficial because total machine loss costs are very greatly influenced by the threshing speed. A control system is needed that considers the threshing loss and grain breakage as well as the sieve and walker loss caused by straw length reduction.

Consideration of the simulation results brought insight into the effects of the assumptions and simplifications on simulation:

*Cost situations*

The results of the various cost situations clearly showed the sensitivity of the optimisation to the chosen cost parameter values. The effect on the optimum speeds is slight except for the timeliness loss curve. The importance of this curve leads to the conclusion that the adaption of control to the change in timeliness loss expectations will be a very important tool for optimisation.

*High-frequency disturbances*

The importance of the high-frequency variations in feed rate was found to be slight, so that the assumptions made on filtering, and control by a combination of quasi steady state calculation of optimum speeds and dynamic speed feedback are permissible.

*Parameter estimation*

The decision to perform off-line parameter estimation in simulating the loss-feed rate control system (2) had an effect on the results.
It are the assumptions made in the simulation, and not the differences between the systems themselves, that caused a loss control with lower

overall costs than obtained with loss-feed rate control, where there was no continuous feedback of loss in the simulation. The loss control system did have feedback so that one parameter value of the simple loss-to-feed rate equation used in the calculation of optimum machine speed was estimated continuously, while the second parameter was adjusted at a fixed level roughly estimated on the basis of the knowledge of the loss-to-feed rate relation of the input used. In practice, this information does not exist, so that some kind of an estimation procedure is needed. This can best be done by a two-parameter estimating procedure, like that suggested for the loss-feed rate control system, but in that case "on line". In such a case it is more important to make a slowly adapting good estimate than a faster but less accurate one.

*Selection of control systems*

The selected control systems clearly showed the importance of each extra input signal used. It has become clear that the threshing speed control requires additional information on grain breakage and the effects of straw breakage. If this is provided, then the problem of interaction between machine speed and threshing speed control is solved.

# 7. Final conclusions and recommendations

1. The cost savings of automatic machine and threshing speed control are small compared to well-planned manually controlled adjustment. Well planned means that under certain harvest conditions the optimum loss level is regularly calculated and inspected. In this case the cost savings of each of the tested control systems are not higher than what could have been achieved by machine design improvements,giving a net capacity increase of approximately 5%.

   In the event that no such well planned conditions occur, the savings will be much greater. This means that when both the optimisation of the harvest operation and the loss measurement are included in the control system,one can be sure that the chosen speeds are close to the optimum and that less experienced operators will also work with minimum costs.

   A control system with measurement devices for several functions,also provides process information that enables better manual adjustments to be made.

2. Automatic machine speed control is profitable as the control system reacts to the mean level variations in crop properties and straw density. The control system cannot react correctly to the crop property variations, including straw density, occurring over a short distance. This is because of the delay in the process and the considerable measurement noise. No worthwhile extra cost savings occur for that reason.

   The automatic control system can be a loss control, but knowledge of the correct shape of the loss-to-feed rate curve is very important, so that a good estimate of this curve is needed to ensure that the system calculates the right optimum speed. For this reason the loss-feed rate control system described in this study is recommended.

A loss measuring device that is more accurate than the devices available nowadays is essential to the control.

If a well trained operator knows the optimum loss level *and* has an accurate loss measuring device at his disposal he will also be able to select machine speeds that result in costs close to minimum harvest costs, as the optimum speed range is fairly wide (see also point 4 in this chapter).

3. Threshing speed control is also profitable, as the separation at the threshing cylinder affects machine loss very much. Such a control system just needs to react to the mean level variations of crop properties and feed rate. It is essential in such a system to optimise the threshing speed based on all effects of threshing, that is threshing loss, grain breakage, threshing separation efficiency and straw breakage affecting walker and sieve loss. Obviously, the system will be complicated and costly, and requires various measuring devices. Some parameters like threshing loss and grain breakage which are difficult to establish with a measurement device, can be put into the system by hand.

   A threshing speed control that reacts to high-frequency variations of straw feed rate gives no extra cost reduction compared to control of low-frequency variations in feed rate and crop properties.

4. The impact of timeliness loss on the calculation of optimum machine speed is great but in general somewhat neglected as it is difficult to calculate properly. An automatic control system based on a microprocessor makes it possible to include such calculations in the control system. Then the change in weather conditions in the course of the harvest period can also be included. The machine operator will adjust the extent of the expected timeliness losses at the microprocessor and the control system will compute the optimum speed. In such control systems the cost minimisation is adapted to the conditions of the specific harvest season and the benefit of the system will probably be greater than has been calculated in this study, as it also minimises

costs for a period longer than one season. Further research is needed into the way the timeliness loss curve has to be adjusted to the specific weather until then the immediate weather forecast, the area still to be harvested, the loss sensitivity of the crop to be harvested and other factors.

The question then arises as to the role the farmer's personal computer or accessible programs at large computers can play in this calculation. In view of the important role of the timeliness loss and the wide range of speeds that give costs close to the optimum, one can imagine that if the optimum loss level can be computed more precisely with the aid of an off-line computer, and the combine harvester is equipped with a good loss measuring system, the costs will also be close to the minimum level of the "on-line" control systems with fewer computation facilities. Combination of the two systems is also feasible.

5. The loss-measuring systems available nowadays only observe a nonconstant fraction of the real loss. The fraction is unknown, hence the absolute loss level is also unknown. In this study (section 3.3.2) the principle of a system is worked out that estimates an absolute loss level. For such a system a microprocessor is needed for proper calculation.

   A microprocessor is needed for automatic control of machine speed but even more for automatic control of threshing speed,as the optimisation of threshing speed, in view of threshing loss, walker loss, sieve loss, threshing separation efficiency and grain damage is a rather complex phenomenon.

   A microprocessor used on the combine harvester could handle a large number of other useful tasks. The inspection of several functions in the machine and the processes in the machine, as well as the calculation of mean levels, capacities and costs. The last settings before an emergency stop or end of a swath can be stored and used again when restarting.

   Even if no automatic control is introduced, the use of a microprocessor on the machine will be worthwhile for calculation of the optimum setting of manual adjustments, including the settings for the concave, sieves and eventually the optimum frequency of the walker movements.

6. In future, more research will be needed in the areas mentioned below.
   a) The main general conclusion of this study is the great importance to be attached to an accurate loss-measuring device for both automatic control and manual control. The commercial loss-measuring devices just give information as to change of loss levels. New measuring devices have to be developed. Possibly such units will be built into threshing and separation process inspection devices as indicated in chapter 3.3.2. Other measurement principles too, such as radiation or reflection have to be considered as only the mean level of loss has to be known so that long averaging periods may be incorporated in the calculation.
   b) "On-line" automatic machine speed control for optimum operation has to be compared with "off-line" computer calculations, together with manual loss control. For such comparison, a model has first to be developed in which the relation between the timeliness loss curve and the factors affecting timeliness loss is worked out. Then the harvest optimisation must be worked out and quantified by harvest strategy adaption to timeliness loss expectation.
      Finally, computer programs have to be developed for the farmers personal computer to calculate optimum strategies for combine harvesting.
      Further research on low-frequency and mean level variation in crop properties affecting machine loss has to be included.
   c) The mean level variations in crop properties affecting loss have to be analysed in more detail also in order to develop parameter-estimation techniques for the loss-to-straw feed rate equations for machine speed control.
   d) A system for the calculation of the optimum threshing speed including the concave adjustment has to be developed in which threshing loss, breakage of grain, walker loss and sieve loss have to be included. If this research is supported by computer simulation, the model must include the straw breakage and its effect on walker loss and sieve loss. Estimation of the threshing coëfficient must then be improved. Finally, the interaction of machine speed control and threshing speed control has to be studied.

7. From the conclusions arrived at in this study, some idea can be obtained of the systems, that can be expected to be developed in future.

In a relatively short time an "off-line" manual control system based upon a computer calculation of optimum loss level and loss measurement on the combine harvester can be developed. The optimum loss level can be calculated weekly or after a period in which the timeliness loss expectation has changed. The loss level has to be controlled manually by means of an improved loss-measuring system or by very regular (hourly) comparison of grain-loss monitor readings with real loss in the field.

On the longer term a microprocessor-based automatic control system can be developed that includes the following qualifications given in the order of introduction:

- automatic control of machine speed by means of the loss-feed rate control system worked out in this study and including the adaption to changing timeliness loss expectations;
- a threshing and separation inspection system that gives information about the walker loss, grain flow, threshing cylinder separation efficiency and walker separation;
- a continuous calculation of optimum threshing speed and concave adjustment using the information provided by the above-mentioned inspection system and the manual input, on the extent of threshing loss, grain breakage and straw breakage. The threshing speed then has to be altered by hand when so indicated by the system output.

# Appendix

A 1.1.a. *Harvesting cereals with the combine harvester*

*The combine harvester*
There are combine harvesters in use that are pulled and driven by a tractor, but it is quite common for combine harvesters to be self-propelled. Such a machine is equipped with an engine and 4 wheels and can be operated by one person. The following operations are performed by the machine: mowing, conveying, threshing, separation of grain and straw, cleaning, intermediate storage of the grain and unloading of the grain. Figure A 1.1.1 gives a side view of such a machine as used in this study and figure A 1.1.2 a cross section. A smaller machine with a different set-up

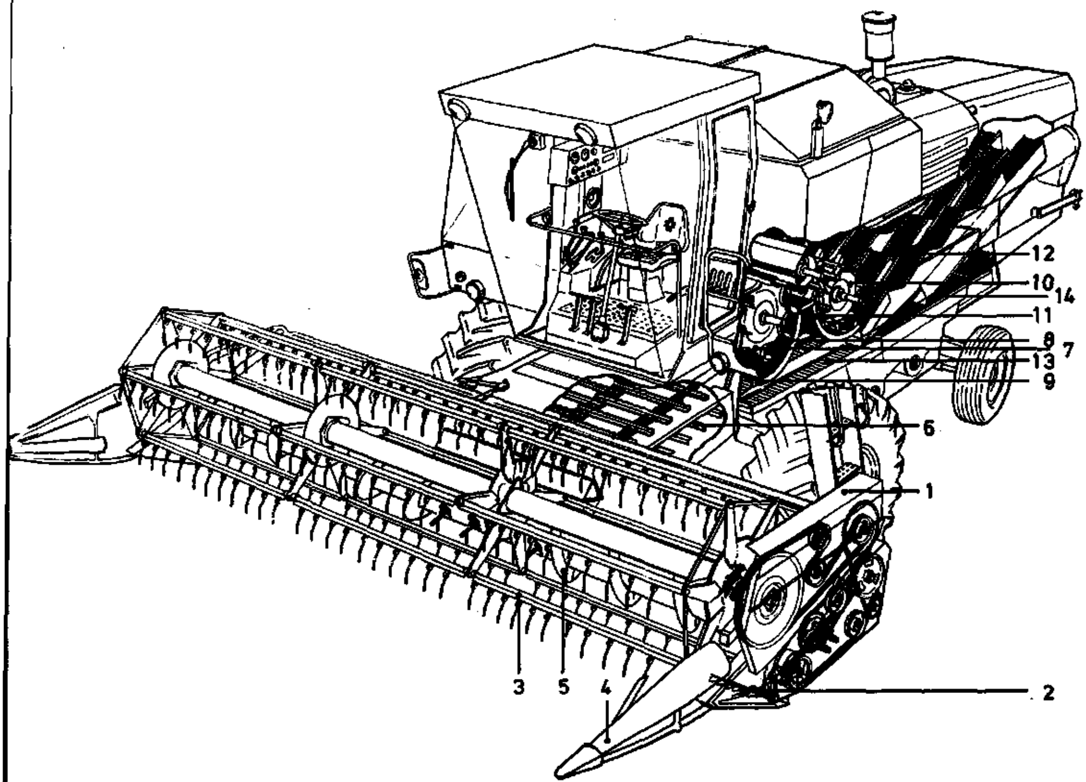



Figure A 1.1.1. Side view of the combine harvester, considered in this study (see text)

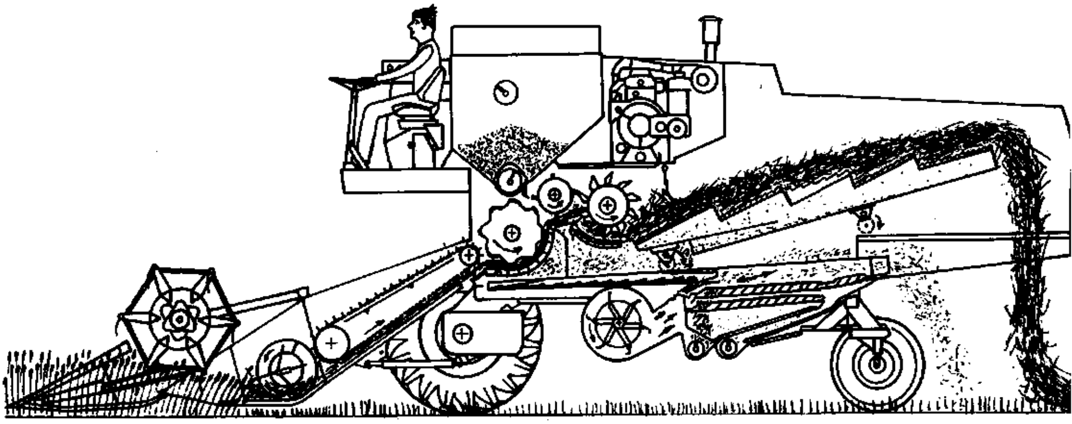


Figure A 1.1.2. Cross-section of combine harvester B

(see fig. A 1.1.3) was used at the start of the study. Machine specifications are given in table A 1.1.1.

At the front is the header (1) where the crop is cut by means of a cutter bar (2), the crop being positioned with a reel (3) and separated from the rest of the crop by crop dividers (4). The mowing width is 6.0 m, while the width of the elevator is 1.60 m. The mowed crop is conveyed to the centre of the cutting table by means of an auger (5) and carried over to the elevator (6), which conveys it to the threshing cylinder (7).

The bars of the threshing cylinder (8) beat the straw and the ears and owing to the speed of about 30.0 $m \cdot s^{-1}$ the ears are accelerated so the grains are loosened from the ears. The grain then is separated from the straw via the concave for 70-99%. The grain remaining in the ears is known as threshing loss and leaves the machine in the straw. The damaged grain is called breakage loss. Figure A 1.1.4 shows a flow diagram of the grain and the straw in the machine.

The grain that is not separated by the concave is transported, together with the straw, to a rotary separator (10) where about half of the remaining grain is separated via a grate (11). Threshing loss, breakage

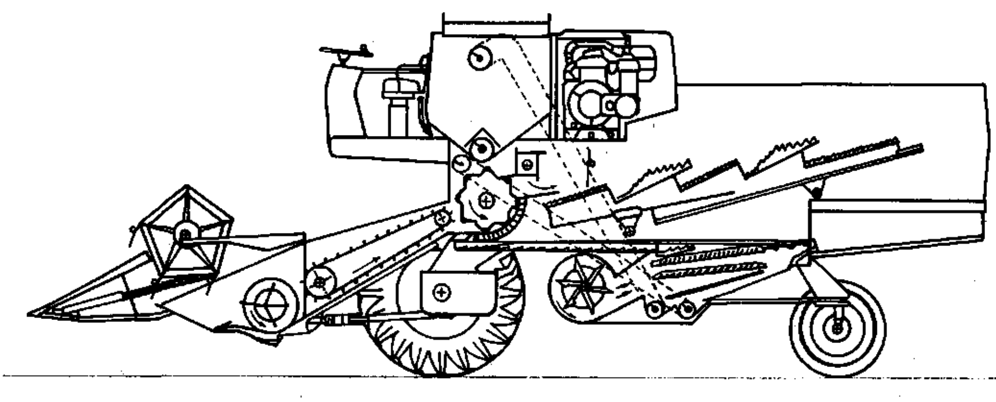


Figure A 1.1.3. Cross-section of combine harvester A

Table A 1.1.1. Specifications of the combine harvesters used in this study

| | | Machine A | Machine B |
|---|---|---|---|
| Manufacturer: | | Sperry New Holland | Ditto |
| Type : | | M 140 | 8080 |
| Maximum width, without header | m | 3.04 | 3.53 |
| Maximum length, without dividers | m | 7.70 | 8.82 |
| Maximum height, without cabin | m | 3.12 | 3.78 |
| Gathering width of header | m | 4.5 | 5.90 |
| Feeding-auger speed | $s^{-1}$ | 3.2 | 3.2 |
| Straw-elevator speed | $m \cdot s^{-1}$ | 2.23 | 2.63 |
| Threshing-cylinder diameter | m | 0.60 | 0.6 |
| width | m | 1.25 | 1.56 |
| rasp bars | number | 8 | 8 |
| Concave arc length | m | 0.609 | 0.609 |
| bars | number | 14 | 14 |
| Rotary separator, diameter | m | - | 0.59 |
| speed | $m \cdot s^{-1}$ | - | 23.5 |
| concave length | m | - | 0.63 |
| Straw walkers, number | m | 5 | 6 |
| length | m | 3.80 | 3.30 |
| speed | $s^{-1}$ | 3.67 | 3.67 |
| stroke | m | 0.11 | 0.11 |
| Weight | kg | 6000 | 8800 |

loss and the concave separation depend on the speed of the threshing cylinder and the throughput of straw mass.

Then the straw-grain mixture is processed by the straw walkers (12), consisting of 6 side by side fixed narrow sieves mounted on crankshafts. They carry out rotational movements with shifts of phase, so the straw is thrown up and the grain passes through the straw and the sieves. This treatment separates almost all the remaining grain from the straw, the straw being conveyed to the rear and dropped on the ground. The grain remaining (threshed) in the straw leaving the straw walkers, is called the walker loss (*WL*) (0.01%-5%).

The separated part of the grain is collected in a grain pan (13) and conveyed by a shaking action to the sieves (14). Two reciprocating sieves separate the grain from the chaff and short straw with the aid of an air stream generated by a fan.

The cleaned grain is transported into the grain tank for temporary storage. The partly threshed loose ears are conveyed to a small threshing cylinder for final threshing. Grain discharged from the machine together with the straw and chaff from the sieves is called the sieve loss.

The sieve and walker loss together are called separation losses. Threshing loss, breakage loss and separation losses are in this study known as machine losses.

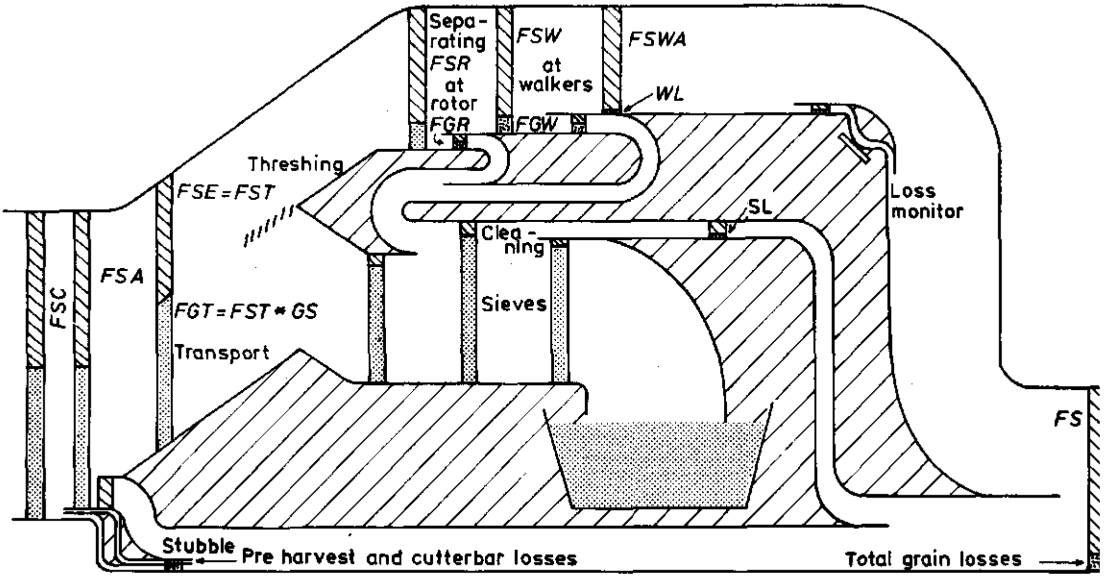



Figure A 1.1.4. Diagram of the flow of straw (*FS..*) and grain (*FG..*) of machine B. Straw is equivalent to material other than grain (m.o.g)

*Cereal harvest organization*

When the grain tank is filled or almost filled, the grain is discharged by a conveyer into a grain wagon which is either driving alongside the combine harvester or parked at the end of the field. The wagon pulled by a tractor transports the grain to a storage place where the grain is weighed, cleaned and, if necessary, dried. For proper coordination of the harvesting and transportation, the wagon should wait for the combine or there should be one or more wagons waiting at the field as intermediate storage for hauling by a tractor. Sometimes it is the combine harvester that has to wait.

Other waiting periods arise out of machine breakdowns, rest periods, machine maintenance and weather conditions (showers). Much of the necessary maintenance can be carried out when one has to wait until a wet crop has dried in the field. Too damp straw causes machine failures and malfunctioning of the threshing and separation parts.

The cereal harvest can only start when the crop has reached so-called combine ripeness. For wheat this is the case when the grain moisture content has once been 20% or less.

The IJsselmeerpolder Development Authority (IJ.D.A.), where part of the research was done, starts harvesting wheat after the "combine-ripe" stage and when the grain moisture content is smaller than 28% (Van Kampen, 1969; Hagting, 1976). There is no need for drying when the moisture content is smaller than 17%. So one could wait with harvesting until a moisture content of < 17% has been reached by the natural drying process.

In Western Europe this process possibly takes too long, thus giving a too small number of workable hours. It also causes field losses after the crop reaches combine ripeness; these losses are called the timeliness losses and comprise shatter loss, animal consumption, seed sprouting, dry matter decrease and losses occurring at the header at mowing: cutting loss and header loss.

Consequently, harvesting at higher moisture contents results in an increase in the number of workable hours and lower timeliness losses. Lower timeliness losses and drying costs can also be achieved with a machine of higher capacity. The same effect can be obtained by increasing the driving speed of the combine harvester, but this brings an increase in the machine losses.

A 1.1.b *Control system terminology*

In this section there is a very brief explanation of control engineering and the terminology used in it. A detailed description can be found in Jacobs (1974) and Cool (1979).

A primary objective of most control systems is to make some physical variable take on a desired value; for example to give the speed of the machine a value that is optimal in financial terms. This is to be achieved by adjusting some mechanism for example, adjusting the position of the piston of a hydraulic cylinder that actuates the V-belt variator.

The non-instantaneous nature of the response is accounted for by regarding the physical controlling variable and the controlled variables as the input and output of a dynamic system, called the controlled process.

The effect of uncertainties, that is disturbing phenomena, can be reduced by using feedback as shown in fig. A 1.1.5, where a control element adjusts the controlling variable u depending upon the difference ε between the desired value or set value x and the fed back, actual value y of the controlled variable, for instance the actual speed. Measuring instruments are needed in the feedback path to measure the controlled output.

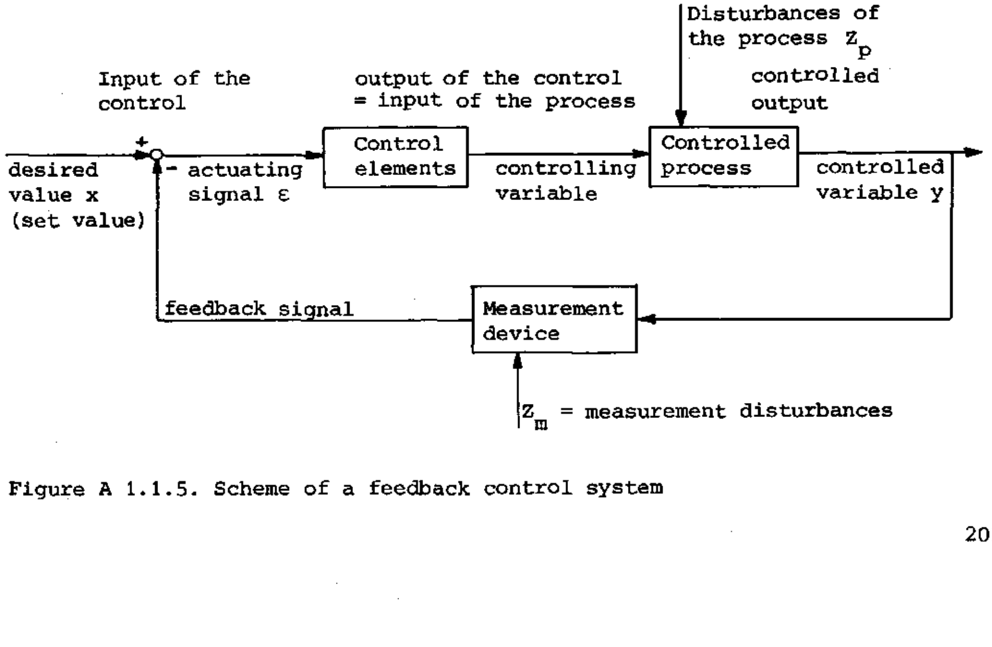



Figure A 1.1.5. Scheme of a feedback control system

Undesired variation in input variables which affect the value of the output, occur in the process as well as in the measurement instruments (called disturbances).

Disturbances are one of the most common reasons why a controlled variable may depart from its desired value and why feedback control is necessary. The disturbances will be regarded in this study as composed of variations in mean levels and in the time domain as slowly and quickly varying levels that can be split up by Fourier analysis into harmonic variations, or frequency functions in other words.

The disturbances in the process of this study are mainly due to natural variation in crop properties. These variations can be modelled as coloured noise. A very important part of the disturbances are weather-affected crop properties that result in variations in mean level, as is the case also in variation caused by breed and variety of the crop under consideration.

The controlled process includes pure time delays. When the measured controlled output differs from the desired value because of a disturbance in the process a control action will be taken. The result of this action is only evident in the controlled output after the delay in the process. This results in deviations from the desired value and in addition it can cause stability problems. The controlled output can show large oscillations when the control is not properly adjusted. This can be found out by observing the response of the controlled output to a step in the input of the control $\varepsilon$. If the transient shows sufficiently damped behaviour, the adjustment is safe.

The stability of the control system can also be investigated with the help of the frequency response to harmonic variations at the input of the open loop, that means without feedback. The graphical representation of the transfer function $G(s) = y(s)/x(s)$ evaluated for the imaginary values of $s(= j\omega)$, is called a Nyquist plot (Jacobs, 1974). From the curve of the figure can be derived whether the closed loop system is stable or not.

Where the disturbances themselves can be measured they can become the input of the control. The system is then called a feed forward control system and is shown in fig. A 1.1.6. In our study such a system is used for control of threshing speed on the basis of the straw feed rate variations measured before the straw enters the threshing cylinder.

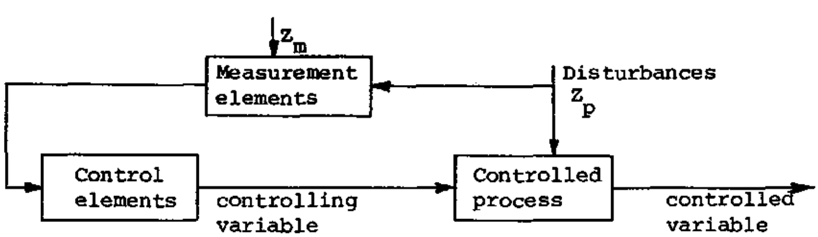



Figure A 1.1.6. Scheme of a feed forward control system

The desired value or set value x of the control system is derived from an optimum speed calculation in the way shown in fig. A 1.1.7. The criterion for the optimisation is minimum harvest costs and the input for this calculation is the value of one variable or more, measured in the process and some cost functions. The task of the speed control is to adjust the speed to the value calculated by the optimisation.

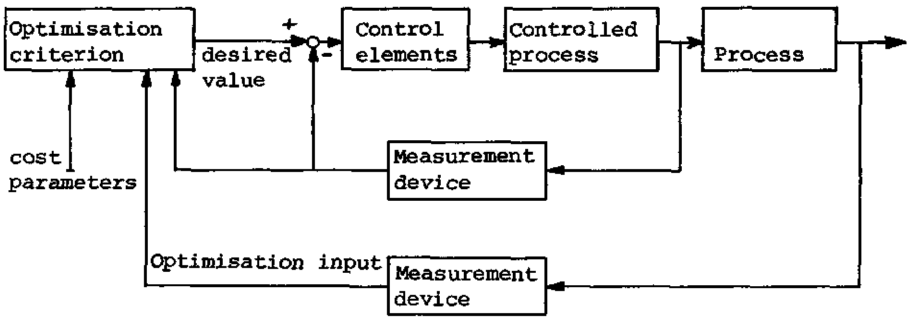



Figure A 1.1.7. Scheme of a control system including calculation of set point by optimisation

## A 1.2. LITERATURE

### A 1.2.1. *Introduction*

In this appendix the references of interest to this study are reviewed. The chronological and systematic succession are shown to be parallel. The conclusion drawn from this study is given in chapter 1.2.

### A 1.2.2. *Feed rate control*

The actual straw feed rate of the combine harvester (*FS* in $kg \cdot s^{-1}$) is derived from the product of machine speed (*VM* in $m \cdot s^{-1}$), mowing width (*CL* in m) and straw density on the field (*SD* in $kg \cdot m^{-2}$), so $FS = VM \cdot CL \cdot SD$. As the straw density varies, adjustment of the machine speed can be applied to control the feed rate. In some cases feed rate controls are called driving-speed controls. For this reason the distribution of crop density has been recorded by many researchers, including Kühn, 1969; Eimer, 1966; Feiffer, 1964; Huisman, 1974 and is usually given in terms of a variation coefficient (see also 4.2.2).

As early as 1956 the Russian researcher Dymnich (1956) reported on a tractor-drawn combine harvester with a feed rate control. In this case the torque of the threshing cylinder is utilized as an input variable to control the throughput. The torque is measured mechanically and the tractor governor is adjusted by a three-way switch and an electromotor. The only result he reported was a variation coefficient of the feed rate of 3.38% at a loss level of 1%.

Nastenko (1959) reports a control system on a self-propelled combine harvester in which the mechanically measured torque of the threshing drum affects the position of the hydraulic valve of the V-belt variator in the driving mechanism.

Since that time other Russian writers have described throughput-control systems on SK-3 combine harvesters.

Bogdanova (1960), in presenting a survey of control systems, has referred to the torque of the threshing cylinder, the thickness of the straw layer under the elevator and the thickness of the straw layer on the walker as feed rate sensors.

Nakhamkin (1960) describes various electrical/hydraulical systems using the input-variable thickness of the straw layer. Gulgaev (1960) presents an electrical/mechanical system with the torque of the threshing cylinder.

It was not until 1962 that Michajlov went into the subject of the expected advantages. He ascertained that the yields of areas of 150 $m^2$ and even 1 $m^2$ have a Gaussian distribution with an average variation coefficient of 20%. Since there is an exponential relation between the straw feed rate and the losses, the average losses will be lower when the variation coefficient is lower (see A 1.2.7).

He calculated that, at a straw feed rate of 3 $kg \cdot s^{-1}$, a decrease in the coefficient of variation from 20% or 30% respectively to a value of 0% will give 25% or 33% lower losses respectively. Taking a loss level of 1.5%, then the straw feed rate increase will be theoretically 10% or 13% respectively. Consequently the effect largely depends on the value of the coefficient of variation, but also on the shape of the loss curve and the adjusted feed rate level. In the article no attention is paid to the magnitude of the variation of the feed rate when the measurement established the loss curve. If the variation had been lower, it would have resulted in a lower and flatter loss curve, with less effect. Measurement on a field of 8 hectares with a controlled combine harvester showed a capacity increase of 11%. There is no indication as to how equal loss levels of both controlled and non-controlled machines are dealt with. This is the greatest problem during field measurements in addition to that of the quantification of the operator's influence on the controlled and non-controlled machines.

Feiffer (1964) from the DDR also reports on a high variation in the straw density ( 4.2.1) and concludes that, in order to maintain the feed rate at a constant level, it should be possible to vary the driving speed within a range of 1-2 metres at a rate of 0.1 $m \cdot s^{-1}$.

According to Feiffer, an other benefit of a control system is to reduce engine and transmission overload. In view of the fact that there is a time lag between mowing the crop and measuring the feed rate at the elevator, he proposes to carry out measurement at the auger or at the cutter bar.

Rumjantsev (1964) reports on an electric-hydraulic feed rate control at SK-3 and SK-4 combine harvesters. The straw feed rate sensor measured the thickness of the straw layer in the straw elevator. He states that the coefficient of variation dropped by a factor of 1.2 to 2.4 at a straw feed rate level of about 3 $kg \cdot s^{-1}$ due to application of the control. He also mentioned an increase in capacity of 43%, but indicated that this figure is rather high and should be re-investigated.

Gurarri (1964) was the first person to simulate the control system. He compared the stability of a feed rate control, calculated by means of simulation with an analog computer, with field results.

The desired value or set value x of the control system is derived from an optimum speed calculation in the way shown in fig. A 1.1.7. The criterion for the optimisation is minimum harvest costs and the input for this calculation is the value of one variable or more, measured in the process and some cost functions. The task of the speed control is to adjust the speed to the value calculated by the optimisation.

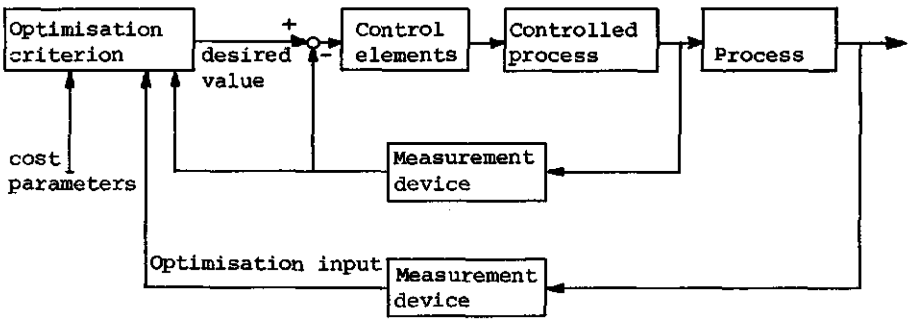



Figure A 1.1.7. Scheme of a control system including calculation of set point by optimisation

## A 1.2. LITERATURE

### A 1.2.1. *Introduction*

In this appendix the references of interest to this study are reviewed. The chronological and systematic succession are shown to be parallel. The conclusion drawn from this study is given in chapter 1.2.

### A 1.2.2. *Feed rate control*

The actual straw feed rate of the combine harvester (*FS* in $kg \cdot s^{-1}$) is derived from the product of machine speed (*VM* in $m \cdot s^{-1}$), mowing width (*CL* in m) and straw density on the field (*SD* in $kg \cdot m^{-2}$), so $FS = VM \cdot CL \cdot SD$. As the straw density varies, adjustment of the machine speed can be applied to control the feed rate. In some cases feed rate controls are called driving-speed controls. For this reason the distribution of crop density has been recorded by many researchers, including Kühn, 1969; Eimer, 1966; Feiffer, 1964; Huisman, 1974 and is usually given in terms of a variation coefficient (see also 4.2.2).

As early as 1956 the Russian researcher Dymnich (1956) reported on a tractor-drawn combine harvester with a feed rate control. In this case the torque of the threshing cylinder is utilized as an input variable to control the throughput. The torque is measured mechanically and the tractor governor is adjusted by a three-way switch and an electromotor. The only result he reported was a variation coefficient of the feed rate of 3.38% at a loss level of 1%.

Nastenko (1959) reports a control system on a self-propelled combine harvester in which the mechanically measured torque of the threshing drum affects the position of the hydraulic valve of the V-belt variator in the driving mechanism.

Since that time other Russian writers have described throughput-control systems on SK-3 combine harvesters.

Bogdanova (1960), in presenting a survey of control systems, has referred to the torque of the threshing cylinder, the thickness of the straw layer under the elevator and the thickness of the straw layer on the walker as feed rate sensors.

Nakhamkin (1960) describes various electrical/hydraulical systems using the input-variable thickness of the straw layer. Gulgaev (1960) presents an electrical/mechanical system with the torque of the threshing cylinder.

It was not until 1962 that Michajlov went into the subject of the expected advantages. He ascertained that the yields of areas of 150 $m^2$ and even 1 $m^2$ have a Gaussian distribution with an average variation coefficient of 20%. Since there is an exponential relation between the straw feed rate and the losses, the average losses will be lower when the variation coefficient is lower (see A 1.2.7).

He calculated that, at a straw feed rate of 3 $kg \cdot s^{-1}$, a decrease in the coefficient of variation from 20% or 30% respectively to a value of 0% will give 25% or 33% lower losses respectively. Taking a loss level of 1.5%, then the straw feed rate increase will be theoretically 10% or 13% respectively. Consequently the effect largely depends on the value of the coefficient of variation, but also on the shape of the loss curve and the adjusted feed rate level. In the article no attention is paid to the magnitude of the variation of the feed rate when the measurement established the loss curve. If the variation had been lower, it would have resulted in a lower and flatter loss curve, with less effect. Measurement on a field of 8 hectares with a controlled combine harvester showed a capacity increase of 11%. There is no indication as to how equal loss levels of both controlled and non-controlled machines are dealt with. This is the greatest problem during field measurements in addition to that of the quantification of the operator's influence on the controlled and non-controlled machines.

Feiffer (1964) from the DDR also reports on a high variation in the straw density ( 4.2.1) and concludes that, in order to maintain the feed rate at a constant level, it should be possible to vary the driving speed within a range of 1-2 metres at a rate of 0.1 $m \cdot s^{-1}$.

According to Feiffer, an other benefit of a control system is to reduce engine and transmission overload. In view of the fact that there is a time lag between mowing the crop and measuring the feed rate at the elevator, he proposes to carry out measurement at the auger or at the cutter bar.

Rumjantsev (1964) reports on an electric-hydraulic feed rate control at SK-3 and SK-4 combine harvesters. The straw feed rate sensor measured the thickness of the straw layer in the straw elevator. He states that the coefficient of variation dropped by a factor of 1.2 to 2.4 at a straw feed rate level of about 3 $kg \cdot s^{-1}$ due to application of the control. He also mentioned an increase in capacity of 43%, but indicated that this figure is rather high and should be re-investigated.

Gurarri (1964) was the first person to simulate the control system. He compared the stability of a feed rate control, calculated by means of simulation with an analog computer, with field results.

Since 1965 there have been publications on feed rate control in North America and Western Europe as well.

Friesen (1965) reported on a mechanical/hydraulical feed rate control system with the torque measured at the threshing cylinder. In the field this system was shown to react positively to crop-density differences, but the effects on losses have not been measured. It was expected that the operator would be less fatigued and that this would lead to lower losses and higher capacity.

Likewise, Goss (1965) makes no mention of any capacity effects of a feed rate control system using the absolute air pressure in the intake manifold of the petrol engine as input variable. Eimer (1966) expects the straw feed to become more uniform and jam the machine less.

Kalimullin (1966) describes a mechanical system of movable crop-holding pins at the front of the auger that will smooth the straw feed. Depending on the vertical position of the pending auger, the pins hold the crop more or less, and together with the action of the auger, a more uniform feed to the threshing cylinder is affected.

Compared with a normal feed at a level of 2.7 $kg \cdot s^{-1}$ he measured a decrease in mean threshing torque (9.9 → 8.4 kgm), in maximum threshing torque (36.2 → 15.5 kgm), in variation coëfficient of the threshing torque (43.3 → 39.9%), and in separation losses (2.4 → 1.0%). These results clearly show the advantages of uniform feed.

Bogdanova (1967) suggests a system in which small feed rate variations are controlled by varying the elevator speed. No other reports on this system have been found, presumably because it cannot work. Since the elevator not only carries out the conveyance to the threshing cylinder but also the takeover from the auger, this type of control introduces new irregularities in the takeover.

Nakonetschny (1967) states that a control system with feed rate measurement at the elevator increases productivity by 10%, but fails to say how this has been calculated.

Eimer (1970) mentions the necessity of varying the reel speed in accordance with the variation in machine speed. As high-frequent feed rate variations cannot be suppressed sufficiently by a machine speed control, because of the inertia of the control system and the machine, he proposes to suppress the effect of those variations by means of a threshing cylinder speed control and a concave adjustment control (see 1.3.4). Mention is also made of the need to measure losses.

Brouër (1970) deals with a simulation in CSMP computer language and test-results of a control system (continuing the line of Goss, 1965) based on the variations in absolute air pressure in the intake manifold of the petrol engine of the combine (or the governor stroke from either a petrol or a diesel engine). The digital computer simulation was done in order to obtain optimal parameter values for the control system. It could not be used for calculating the benefit of the system. By means of this simulation it was found that the response time of the system was 5 seconds at a delay of 1 second between mowing and threshing. This means that only long-term changes in the density of the crop could be followed. Therefore it has been suggested to measure the straw feed rate at the front of the machine.

A fluidic sensor to sense the amount of crop just before it reaches the combine was tested but did not work. A gamma radiation sensor in the feeder conveyor did not work properly either because it needed too long an integration interval.

An electrical/hydraulical straw feed rate control system based on the torque of the auger has been developed as part of the present writer's research (Huisman, 1974a, 1974b). The effect of this control was slight, due to an error in the adjustment and in the system itself.

An improved system has been put forward by Naaktgeboren (1976) and Van Loo (1977). This system is capable of suppressing variations with frequencies below 0.48 rad$\cdot$s$^{-1}$, but enlarges variations between 0.48 and 2.8 rad$\cdot$s$^{-1}$. Above 2.8 rad$\cdot$s$^{-1}$ the control system doesn't have any effect at all. It has been shown that this system lowers the variation coefficient of the straw feed rate from 12.2% to 4.1%. The straw feed rate data consisted of values averaged over 20 s.

Also, the difference in loss level (loss effect) or in feed rate level ( feed rate effect) of a controlled situation compared with a non-controlled situation were calculated. It is expressed as the difference in level as a percentage of the non-controlled situation. This calculation was based on the theory that will be mentioned in A 1.2.7 and on the decrease in the coëfficient of variation from 12.2 to 4.1%. When the loss effect is calculated, the feed rate level is kept constant and vice versa. The results depend on the loss-feed rate curve. They were calculated for a specific spring and winter wheat situation. The feed rate level and the loss level, also affect the result. Table A 1.2.2.1 shows the results of these calculations.

Table A 1.2.2.1. Feed rate effect and loss effect influenced by the loss level and straw feed rate level

| | spring wheat | | winter wheat | |
|---|---|---|---|---|
| Loss level in kg$\cdot$s$^{-1}$ | 0.005 | 0.02 | 0.005 | 0.02 |
| Feed rate effect in % | 3.6 | 5.2 | 0.3 | 2.1 |
| Feed rate level in kg$\cdot$s$^{-1}$ | 1.3 | 5.3 | 1.3 | 5.3 |
| Loss effect in % | 1.6 | 28.1 | 0.14 | 2.3 |

This shows the dependence of the results on the situation. As circumstances are continually changing, the total effect during some harvest seasons cannot be predicted from these data. Moreover, the effects are underestimated because the variation was calculated for the average values of feed rate at 20 s interval. In this way only variations in frequencies less than about 0.08 rad$\cdot$s$^{-1}$ are taken into consideration, although the controller can suppress frequencies smaller than 0.5 rad$\cdot$s$^{-1}$.

Besides the feed rate control systems, that are meant to keep the losses at a desired level, similar systems, relating to the power of the engine, have been reported on.

Jofinov (1967) deals with a system adapting the driving speed to the delivered engine power where a higher driving speed could be tolerated in view of the losses incurred. The throttled engine compression has been taken as an input parameter in this system. In the case of an engine power surplus, the driving speed is controlled by the threshing-cylinder torque.

Reichel (1969) refers to a system controlling the driving speed of self-propelled agricultural machines (in general) with the fuel consumption as input parameter. The adjusted value of the fuel consumption of a harvester can be derived from the walker loss.

Since 1972, Kawamura has been publishing on a small-head-feeding type of rice combine harvester with a straw feed rate control system (Kawamura, 1972, 1974, 1975, 1977). By means of simulations and field measurements, a control system has been developed in which the driving speed has been optimized by measurement of the thickness of the straw layer at the intake and adaptation of the engine speed. The aim is the optimal use of the available engine power and the prevention of engine jamming.

Kruse (1982) reports on a similar system in a rotary combine for corn. A microprocessor-based machine-speed control has been tested. The control purpose is to utilize the available engine power completely, circumstances permitting. The rotational speed of the engine and the feeder torque are used as input parameters. When the feeder torque reaches a certain minimum value, the power control is switched on. If the feeder torque reaches a certain maximum, then the driving speed is slowed down to prevent jamming. The economical advantages arising out of these systems are again not calculated.

A 1.2.3. *Loss controls*

Since the development of the acoustic grain-loss sensor (Feiffer, 1967; Reed, 1968) it has been proposed to use this signal as input variable for feedback control systems. Reed (1969) mentions this, but doesn't present any results obtained with such a system.

Kühn (1968) suggests the combination of a loss control with a feed rate control. The desired value of the feed rate control can be derived as a result of the loss measurement. This method can be used to solve the problem of the big time lag between generating the feed rate and sensing the loss caused by this feed rate, resulting in a slow control. He ascertained that, at a similar feed rate, the losses vary by a factor of 10 because of differences in the moisture content of straw, the ripeness and the green parts. Eimer (1970) and Huisman (1974b) stress the necessity for this. Maler (1974) indicates the possibility of having the operator controlling the driving speed, on the basis of the measured losses.

A big disadvantage of these acoustic grain-loss sensors is that the ratio between the amount of registered grain and the real loss is not constant, which precludes them from use as absolute loss-measuring devices. Therefore they should be regularly calibrated several times per hour, but this is seldom done (see also the results of this study in 3.3.1). Nevertheless, some researchers have tested similar systems in practice.

Fekete (1981) published the results of tests in Hungary on 5 machines equipped with feed rate/loss controls. As to this system, all that has been made clear is that the auger torque signal is used as a feed rate parameter and that the losses are measured by a loss monitor having acoustic sensors.

The probability distribution of the auger torque signal of the automatically controlled machine shows the peak at a lower auger-torque level than is the case with a manually controlled machine. In the power-density spectrum less power was found at frequencies below 7.5 $rad \cdot s^{-1}$. A reduction in the power density of the corn head drive torque, has been noted in the frequency range of 0.63-3.14 $rad \cdot s^{-1}$. In tests with wheat and corn, where the losses have been kept equal at levels between 0.9 and 1.3%, it was found that the feed rates of the automatically controlled machine were from 9 to 20% higher than those of non-controlled machines.

During the whole harvest season the net capacity in wheat and rape-seed was respectively 5.2% and 22% higher. Under the constraints of the circumstances the harvesting costs were 6-7% lower. These data have not been specified with regard to the harvested area, the circumstances and their variations. Therefore it is difficult to check their validity in other situations.

McGechan (1982) published results of a research project in Scotland, in which the influence of control systems on the decrease of the combined results of separation loss and timeliness losses has been researched analytically. Two not varied loss equations as a function of the feed rate, so-called loss-feed rate curves, from publications of Philips (1974) and Audsley (1974) have been used. The losses, according to not-calibrated grain-loss monitors and the driving speed were recorded from 3 machines, working under practical conditions. Assuming a crop yield of 5000 $kg \cdot ha^{-1}$ and a grain-straw ratio of 1, the variation of the realised loss was converted to variations of crop densities via both loss curves. Based on statistical assumptions this variation was converted into standard deviations of three sources:

$\sigma_1$ = correlated in that it changed slowly through the crop
$\sigma_2$ = uncorrelated and therefore totally unpredictable
$\sigma_3$ = sampling variability introduced by the grain-loss monitor

These data were later used to calculate analytically the total loss in given assumed situations:

a) constant-speed operation
b) constant-loss operation
c) optimal control system based on a grain-loss monitor
d) a table auger torque control system

In this calculation the timeliness losses are included, based on a 200 ha cereal farming operation in Scotland.

Furthermore it was possible to calculate by simulation, using the recorded crop density profiles, the effects of a control system based on a grain-loss monitor and one based on a table auger torque-control system. The results showed that the benefits according to simulations using the loss-control system were smaller than those obtained with the analytical calculations. For the most likely loss equations it was analytically calculated, that compared to a constant-speed operation, an optimum control system based on a grain-loss monitor alone, resulted in a smaller loss of a mere 0.4 ton (i.e. £.40,--), based on a total yield of 1000 tons. In a crop that showed a maximum benefit, this was 0.9 ton. A system with a table auger control system increases these statistics by 20%. The constant loss operation, which is the theoretical upper limit, presented benefits amounting respectivily to 1.4 and 2.2 tons. The conclusion was that such an advantage is too small to justify the development of a control-system. The evaluation system, if used fundamentally, can give correct approaches to reality, but some assumptions will possibly affect the results.

1) A fixed loss curve has been used. Since greatly differing loss curves apply in reality, the variation in straw density is incorrectly calcu-

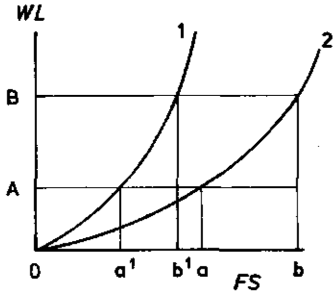



Figure A 1.2.1. Effect of shape of loss-to-feed rate relation on calculated feed rate. When relation (1) was used in the study by McGechan the calculated feed rate variation was a'-b' while real variation was a-b because of real relation (2)

lated (see fig. A 1.2.1). Assume curve 1 was used. When the loss variations occur within the area A-B and in reality loss curve 2 applies, then the straw density variation will be calculated based on feed rate variations $a^1$-$b^1$ while they are a-b in reality. This mistake can then no longer be corrected during the calculations. Therefore the advantage of a constant system is underestimated when the real loss curve is flatter, and overestimated when the real loss curve is steeper. Moreover, the benefit of a loss-control system adapting to the shifting of loss-feed rate curves cannot be calculated in this way.

2) The grain-loss monitor and the torque measurements have not been calibrated regularly. Since the ratio between the monitor output and the real losses varies, the measured loss curve will vary in steepness, even when the real loss curve does not change. This results in the same effect as has been mentioned at 1). Such an effect can have a great deal of influence in view of the fact that the choice of loss curve has much influence on the calculated results.

The real benefits have to be investigated by means of simulations in which the real loss curves are used and correct loss measurement is involved.

### A 1.2.4. *Threshing speed control*

The crop flow varies at the threshing cylinder due to the variation in driving speed, working width and straw density in front of the cutter bar and due to the redistribution in the auger and at the point of transfer to the elevator. A feed rate control system isn't capable of suppressing the highly frequent irregularities in the feed rate. As the concave and walker separation are (negatively) related to the feed rate, the walker loss will vary positively with these feed rate variations. Since the rotational speed of the threshing cylinder and the concave adjustment can affect the concave separation and so walker loss, it is possible to correct the variations in walker loss in this way.

With this in mind, Eimer (1973, 1974) developed a control system in which the measured feed rate controls the threshing cylinder speed as well as the machine speed. An increase in feed rate results at first in an increase in threshing speed. The decreased concave separation is compensated, to a certain extent, by the higher threshing speed. When the increase in feed rate continues, the driving speed will also be slowed down in accordance with the feed rate control system. The problem of this system is that the relation between optimal threshing speed and feed rate has to be known. Since this relation greatly depends on the crop conditions, it has to be adapted accordingly. Eimer has investigated the effect of the control system on an irregular feed for one specific relation of threshing speed to straw feed rate. The results of tests at an average feed rate level of 3 $kg \cdot s^{-1}$ for a threshing cylinder 1 m in width, at which 6 $kg \cdot s^{-1}$ straw is put through for 0.8 seconds, followed by 0.8 seconds without feed, are given in the table below.

Table A 1.2.4.1. Results of tests with threshing cylinder control of Eimer (1974)

| crop: | | wheat: | | rye: | |
|---|---|---|---|---|---|
| Threshing cylinder control | : | off duty | on duty | off duty | on duty |
| Concave separation % | : | 88 | 92 | 78 | 86 |
| Threshing loss % | : | 0.8 | 1.1 | 1.5 | 0.8 |
| Breakage loss % | : | 0.1 | 0.1 | 0.15 | 0.3 |
| Max. torque threshing cylinder Nm: | | | | 230 | 120 |

During field measurements in 1969 with wheat and rye it was established that at similar loss levels in wheat and rye, respectively 40% and 25% higher driving speeds, compared to what a trained operator can perform, could be realised. An average of 20% was also mentioned. There was no mention as to how this research was carried out.

Mailander (1979) and Brizgis (1980) reported on a threshing cylinder speed control system which adapts the speed to the moisture content of soybeans or corn. Mailander applies a relation between the moisture content and the desired speed, based on the loss due to damaged beans. The system of Brizgis was tested by simulations with CSMP III. Owing to the slow character of the system it cannot be compared to the threshing speed - feed rate system.

### A 1.2.5. *Process models*

The models of the process in the combine harvester are important mainly because they make it possible to investigate coherence of the dynamics of the process and the control system. Artner (1971) claims that the benefit of control systems depends on the disturbances and the dynamics of the system. An analysis of the process, that is of the signals and the system, is therefore necessary. For the signal analysis the input and output signals have to be investigated. For the system analysis, models are needed. As nonlinear transfers occur, the use of analog computers is desirable. Artner himself does not present any results. Nowadays time-dependent systems can be simulated on digital computers, for instance with CSMP (Continuous System Modelling Program, developed by IBM).

Kirk (1977) reported on a simulation model in Fortran of a combine harvester and compared the results with field measurements. He applies descriptive models partially described by Pickering (1974). He concluded that the prediction of the loss of the walker and the sieves by means of the feed auger torque at its only input, was moderately accurate. Some details of the model will be analysed in chapter 2. As far as is known, the model has not been applied in practice. Models of the threshing and walker separation are available. There are no detailed calculations known with models investigating the effect of control systems.

### A 1.2.6. *Cost models*

The research done by McGechan (1982) is discussed in A 1.2.3. He used a cereal harvest model to calculate the total harvest costs and calculated the optimum machine speed and used it to calculate the optimum loss level and the benefits of the control systems at that level. In this study just two loss curves were used and therefore the control systems could not react to the change of loss curves.

This is also the constraint in the studies of Oving (1980) and Baumgartner (1969). In these studies even the speed of the machine is not variable. Their results therefore differ from those of Kampen (1969), Boyce (1972), and Philips (1974), where the machine speed is one of the variables that can be optimised. They all agree that a high-capacity machine is worthwhile, because of the timeliness loss. Philips (1974) calculated that the total costs were minimal at a machine loss level of 13 kg per ha for British conditions. Kampen (1969) reports that the optimum total machine loss level for the situation at the large-scale grain farm of the IJsselmeerpolders Development Authority is 0.5%.

The optimum loss level for conditions of Fed. German Rep. seems to be 1% (Eimer, 1966) and for the DDR 1.5% (Heinrich, 1968). In all these models however, no adaptation of the optimal loss level to the shape of the loss curve is included.

### A 1.2.7. *Effect of variation in feed rate on the loss-feed rate relation*

Michaijlov (1962) already reported on the Gaussian distribution of the straw feed rate around an average value, as having an impact on the loss level when the loss-feed rate relation is nonlinear. This has been studied quantitatively (Huisman, 1977; Van Loo, 1977) to calculate the influence of a decrease in coëfficient of variation (*CV*) on the feed rate and losses (see figure A 1.2.2).

Assume a loss-feed rate relation according to $WL = \underline{k}\cdot\exp(a\cdot FS)$ (the drawn line is from field measurements in oats; $k = 2.2\cdot10^{-2}$ and $a = 0.944$, *WL* in % and *FS* in $kg\cdot s^{-1}$) and the feed rate distributed around an average value $\underline{\mu}$ (in the figure 4 $kg\cdot s^{-1}$) is Gaussian. We will consider the manual-control situation where $\underline{\sigma}_h = 0.488$, so that $CV = 12.2\%$ (line: --------) and the situation with a feed rate control as it was measured in the field $\underline{\sigma}_c = 0.164$, so $CV = 4.1\%$ (line: — — —). The values of $\underline{\sigma}$ are calculated from mean values of the feed rate over periods of 20 s.

For a Gaussian distribution this yields

$$p(FS = x) = \frac{1}{\underline{\sigma}\sqrt{2\pi}} \exp\left(\frac{-(x - \underline{\mu})^2}{2\underline{\sigma}^2}\right) \qquad (a.1.1)$$

Multiplication of $p$ by the loss feed rate relation results in a function of *FS* (in the figure line: ------), so that

$$p(FS = x)\cdot WL(FS = x) = \frac{1}{\underline{\sigma}\sqrt{2\pi}} \exp\left(-\frac{(x - \underline{\mu})^2}{2\underline{\sigma}^2}\right)\cdot k \exp(ax) = \frac{1}{\underline{\sigma}2\sqrt{\pi}} \exp\left(ax - \frac{(x - \underline{\mu})^2}{2\underline{\sigma}^2}\right) \qquad (a.1.2)$$

This function can be transformed to

$$\frac{k}{\underline{\sigma}\sqrt{2\pi}} \exp\left(a\underline{\mu} + \tfrac{1}{2}a^2\underline{\sigma}^2 - \frac{1}{2\underline{\sigma}^2}(x - (\underline{\mu} + a\underline{\sigma}^2))^2\right) \qquad (a.1.3)$$

which shows that the equation is symmetrical at $\underline{\mu} + a\underline{\sigma}^2$.
Consequently the average loss refers to a feed rate which is $a\underline{\sigma}^2$ higher than $\underline{\mu}$. Thus the average loss is

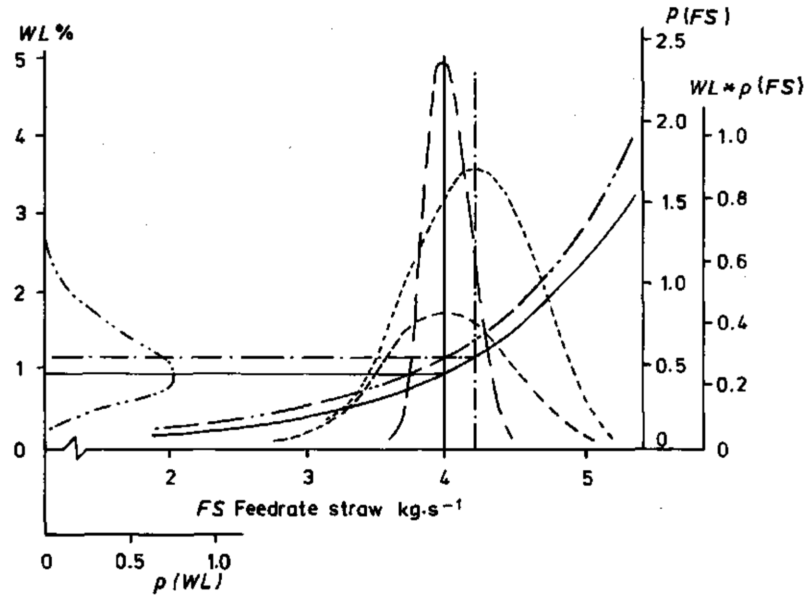



Figure A 1.2.2. Effect of a gaussian supposed probability density function of straw feed rate on the loss-to-feed rate relation. $\underline{\sigma}_f$ = standard deviation of feed rate
(———— ) = walker loss ($WL$) curve for $\underline{\sigma}_f \approx 0$ : $WL_o = 0.022 \exp(0.944 \cdot FS)$;
(—————) = probability density function of feed rate ($p(FS)$), for $\underline{\sigma}_f = 0.488$ measured at constant machine speed for periods of 20 s;
(—— ——) = $p(FS)$ for $\underline{\sigma}_f = 0.164$ measured at controlled speed by a feed rate control system;
(--------) = product function of $WL_o \cdot p(FS)$;
(——.——.) = theoretical mean level of loss, and pertaining centre of product function in the case of $\underline{\sigma}_f = 0.488$ (constant speed);
(..—— ——) = loss curve for $\underline{\sigma}_f = 0.488$;
(..——..——) = probability density function of loss $p(WL)$ for $\underline{\sigma}_f = 0.488$

$\overline{WL} = k \cdot \exp(a \cdot (\underline{\mu} + a\underline{\sigma}^2))$ (line —— · · —— —— · · ——) (a.1.4)
from which it appears that the "shift" of the loss curve compared to the original curve depends on $a$ and $\underline{\sigma}$. Note that the original curve refers to a *hypothetical* situation where $\underline{\sigma} \approx 0$. However, this example shows that if $\underline{\sigma}$ changes, for instance, because a manually controlled harvester is replaced by one with automatic control, there will be different loss levels for the same average feed rate.

In this way the ratio can be calculated between the average feed rate levels for both these situations for a given loss level. When this is done for the previously mentioned loss-curve values $k$ and $a$, $\underline{\sigma}_h$ and $\underline{\sigma}_c$, then the following values are found for $\underline{\mu}_c/\underline{\mu}_h$:

1.038 for $WL$ = 0.5%
1.046 for $WL$ = 1%
1.054 for $WL$ = 2%

The values for $WL$ = 1% vary between 1.01 and 1.06 for a large number of loss curves. In the figure it can be seen (-..-..-) that, when the feed rate has a Gaussian distribution the loss will have a skew distribution.

## A 2.2. COST FACTORS

The cost factors will be considered for the IJsselmeerpolder Development Authority large-scale grain farm (IJ.D.A.), the contractor and the grain farm. They utilise the combine harvester in wheat for respectively 175, approximately 100 and 100 ha per year.

### A 2.2.1. *Variable costs per hectare (MVC)*

*IJ.D.A.*

According to the information of Fokkens (1983) the costs for 1982 were

| | |
|---|---|
| for maintenance + wear | 33.-- fl•ha$^{-1}$ |
| and for fuel | 25.-- fl•ha$^{-1}$ |
| Total | 58.-- fl•ha$^{-1}$ |

*Contractor*:

According to Lange (1972) combine harvesters' average operational life is 5 years when they are used by contractors and then harvest approximately 100 ha per year giving a total use of 500 hectares. The situation is *assumed* to be the same at the present time. In the table made out by Lange the total maintenance costs are fl.7500.--, that is fl.1500.-- per year 40% of which are labour costs and 60% costs for materials. The price indexes of 1981 (since 1970) for labour and materials costs are respectively 3.2 and 2.0 (Anonymus, 1981), thus the price index of maintenance costs becomes 2.5. An extra 10% for 1982 gives a price index of 2.75. Thus the maintenance costs per year are fl.4125.-- which, per hectare, is about 41.-- fl•ha$^{-1}$
The costs for fuel are *assumed* to be the same as at the IJ.D.A.: 25.-- fl•ha$^{-1}$
Total 66.-- fl•ha$^{-1}$

*Grain farm*

As a rule 1.5% of the purchase price of fl.210.000.--, which is fl.31.50 per hectare, is considered to be the maintenance cost per hectare.
For the grain farm the fuel costs are 10% less since there is less transportation over large distances, so that we have

| | |
|---|---|
| fuel costs | 22.50 fl•ha$^{-1}$ |
| maintenance costs | 31.50 fl•ha$^{-1}$ |
| Total | 54.-- fl•ha$^{-1}$ |

### A 2.2.2. *Wages per hour (WA)*

*IJ.D.A.*

The IJ.D.A. calculates for this fl.37.50 per hour (including unworkable hours, training and travelling costs) and an allowance of 7.5% for management costs giving a total of 40.-- fl•h$^{-1}$.

*Contractor*

The wages including the costs for unworkable hours, travelling and management are in accordance with the rates of the Association of Contractors 32.60 fl•h$^{-1}$.

*Grain farm*

The usual wages of about 20.-- fl•h$^{-1}$ are *assumed*.

A 2.2.3. *Fixed costs (AFC)*

*IJ.D.A.* These costs have been calculated to cover 250 hours including road time and the time used for the rape-seed harvest. Accounting for winter wheat per hectare (namely 1.21 ha·h$^{-1}$) this gives

| | |
|---|---|
| depreciation | 67.-- fl·ha$^{-1}$ |
| interest | 41.30 fl·ha$^{-1}$ |

together 108.30 fl·ha$^{-1}$ including management allowance of 7.5% giving a total of 116.50 fl·ha$^{-1}$

The total fixed costs for 175 hectare of wheat are then fl.20387.50.

*Grain farm*

In 1982 the purchase price (VAT included) of a new machine was *NV*=fl.210 000.-- and the residual value (*RV*) after 10 years of use is *estimated* as fl.30 000.--. Then the fixed costs are

| | | |
|---|---|---|
| depreciation (*NV* - *RV*)/10 = | fl.18 000.-- | |
| interest: 10% of (*NV* + *RV*)/2 = | fl.12 000.-- | |
| insurance costs 1½% of *NV* = | fl. 3 150.-- | |
| the total fixed costs | fl.33 150.-- | for 100 hectare |

So the fixed costs per hectare are 331.50 fl·ha$^{-1}$.

*Contractor*

He *should* book the same costs as the cereal grower, and in addition, according to the BOVAL (Association of contractors) standards (Anonymus, 1979) the shelter costs (1.75%) and the general costs (3%) we arrive at a total of fl.9975.--. The total costs are thus fl.33150.-- + fl.9975.-- = fl.43125.-- -- per hectare, that is 431.25 fl·ha$^{-1}$.

*Note*: When the costs MVC + HVC + MFC are added, they amount fl.530.-- per hectare at a field capacity of 1 ha·h$^{-1}$. Compared to the tariffs which varied between 350.-- fl·ha$^{-1}$ and 440.-- fl·ha$^{-1}$ in 1982 it becomes apparent that the contractor is not reimbursed for his expenses at 100 ha·year$^{-1}$. Since the estimates for fixed costs are low, the amount of 431.25 fl·ha$^{-1}$ for the fixed costs will be maintained in our study in view of the rather long operational life of 10 years that was included in the calculation of fixed costs.

For the IJ.D.A. the value of *AAN* is *assumed* to be 175 ha, which is the area of wheat per combine harvester to be harvested in 1982. In the years 1977 ... 1981 the average driving speed for machine B was 0.9 m·s$^{-1}$, resulting in *VMN* = 0.9 m·s$^{-1}$. For the contractor, *AAN* is *assumed* to be 100 ha, while *VMN* is *assumed* to be 1.0 m·s$^{-1}$, because the cereal farmer waits for more favourable conditions and then the machine speed can be higher.

A 2.2.4. *Costs of the grain loss*

These are calculated in the model and account for the trading value of approximately fl.0.55 kg$^{-1}$ (Schrier, 1982) minus the transportation, cleaning and drying costs.

At the IJ.D.A. the transportation costs are 100.-- $fl \cdot ha^{-1}$, which gives 0.015 $fl \cdot kg^{-1}$ at an average yield of 6885 $kg \cdot ha^{-1}$ in 1982. In 1982 the processing and drying costs were fl.0.03 $kg^{-1}$, leaving 0.505 $fl \cdot kg^{-1}$ as the costs of grain loss.

For the cereal grower the transportation costs are lower; let us *assume* they are fl.0.01 $kg^{-1}$. The drying costs are also lower, because the farmer uses the machine for fewer hours and is in a position to wait for more favourable moisture contents (see A 2.2.2.6). For instance, at the average reduction of grain moisture content from 21% to 17%, costs of processing included, yields a total of ≈0.0165 $fl \cdot kg^{-1}$. Thus the value of the grain is 0.534 $fl \cdot kg^{-1}$. The decrease in value of damaged grain is, according to the EEC intervention agreement, 0.00027 $fl \cdot kg^{-1}$ per 0.1% exceeding 4%. In the simulation this level will only occur in unfavourable situations in close conformity with reality.

### A 2.2.5. *Costs of extra V-belt wear*

The lifetime of a V-belt mainly depends, according to IJ.D.A. data (Vos, 1982), on the extent to which the operator is able to avoid the formation of wads. If an operator doesn't take the necessary steps, a V-belt can be worn out after 100 hours of use. Normally the operational life of a V-belt is 500-700 hours, the average being 600 hours. The price of a V-belt is ≈ fl.350.--. Since the acceleration and deceleration of the threshing cylinder arising out of speed control is comparable with wad-formation, it *seems to be reasonable to assume* a lifetime of 50 hours for a V-belt at a controlled cylinder. Presumably the construction will be adapted, so that lifetime will increase, but then also the costs will be to the account of the control. Let us *assume* that they will be as estimated, that is 350.--/50 = 7.-- $fl \cdot h^{-1}$ for a controlled machine. This is 0.00194 $fl \cdot s^{-1}$, while per uncontrolled machine it is 350.--/(600·3600) = 0.00016 $fl \cdot s^{-1}$. By means of simulations, the V-belt tension has been ascertained to be 1251 N with manual control and 1866 N with threshing-speed control. We will only take into account the costs of wear that are above those of manual control, so that when $V_3$ is the cost rate per unit of force, we can calculate $V_3$ by the relation (1866-1251) $V_3 = (0.194 - 0.016) \cdot 10^{-2}$. Hence $V_3 = 2.89 \cdot 10^{-6}$ $fl \cdot s^{-1} \cdot N^{-1}$.

When *FOB* is the belt force the costs are $(FOB - 1251) \cdot V_3$. In this case, *FOB* values less than 1251 will give a yield so we had better only take the *FOB* values which are greater than 1251, but in that case the cost rate $V_3$ will be too large. On studying the distribution of values of *FOB*, it was found necessary to reduce $V_3$ to about $1.0 \cdot 10^{-6}$ to get the same costs of wear.

It is not worth while to calculate the cost rate more accurately because the real relation between wear and belt forces is unknown. The used costs are 0.0 $fl \cdot s^{-1} \cdot N^{-1}$ if $FOB \leq 1250$ and $(FOB - 1250) \cdot 1.0\ 10^{-6}$ $fl \cdot s^{-1} \cdot N^{-1}$ if $FOB > 1250$.

### A 2.2.6. *Costs of timeliness losses*

The header and cutting losses (front-end losses), occurring when a just-ripe crop is harvested are not taken into consideration, as such losses cannot be harvested at all and are *assumed* to be independent of the machine speed. Based on an about 10 years of research, the IJ.D.A. has established a model in which the loss is calculated as a function of weather factors like wind, rain, etc. By simulating this model with the weather conditions of the past 40 years, the function (1) of figure A 2.2.6.1 can be found (Fokkens, 1981). The standard deviation for this curve has been indicated by the dotted lines. This means, for instance, that if the harvest is brought in 24 days after ripeness, 2% of the original yield can no longer be collected.

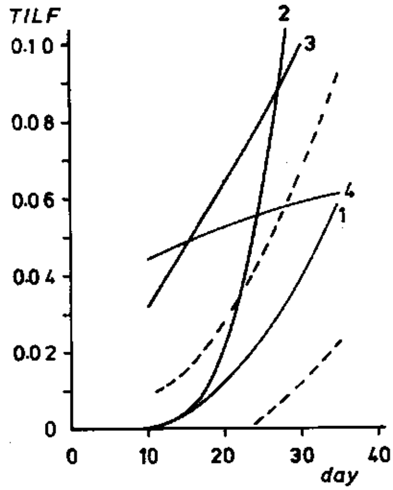



Figure A 2.2.6.1. Functions of timeliness loss related to the number of days after combine ripeness
(1) curve calculated and used by the IJsselmeerpolders Development Authority
(2) curve used in this study based on (1) including the sprouting risk
(3) front-end loss curve of Philips (1974)
(4) front-end loss curve of Audsly (1974)

The sprouting losses are not included in this curve since they are separately calculated as depending on other weather factors. In the event that sprouting occurs, the loss, according to the above-mentioned curve, will be doubled in the IJ.D.A. model because of a higher front-end loss and will be increased by 9% of the percentages so obtained. The chance of sprouting increases rapidly from September 1st. *Assuming* this chance to be 50% on September 15th and also that the crop is worthless on October 1st, then curve (2) in figure A 2.2.6.1 does not seem *unreasonable*. The equation of this curve is $1.3 \cdot 10^{-3}(d - 8)^3$% for $d > 8$ and 0 for $d < 8$ ($d$ = the day of the harvest).

For comparison, the following curves are drawn in the figure: the total front-end loss curve of Philips (1974)(curve 3) and the curve of Audsley (1974)(curve 4). Both curves are taken from McGechan (1982).

The real course of the harvest is determined by the machine speed and the workable hours in the previous period. The distribution of the workable hours varies strongly from year to year, so a choice has to be made for the desired certainties. This will be indicated by the percentages of years in which the in table A 2.2.6.1 indicated number of hours that are used in the calculation, are not available and here a choice has been made for 25% and 16 2/3%. According to Portiek (1975), 87% of the workable hours of a 24-hour day are between 06.40 o'clock M.E.T. and 23.40 o'clock M.E.T.. The figure of 85% of the available, workable hours in 24 hours have been taken for the grain farm. No reduction has been applied for the Sunday as, in unfavourable years, this also will be a workday.

For the IJ.D.A. farm the harvest season is long, so the hired workers just work until about 21.00 o'clock. The workable hours in the period from 09.40 - 23.40 o'clock M.E.T. include about 7% of the total workable hours, according to Portiek, so there remain 80% workable hours per day.

Besides, a choice also has to be made for the moisture content of the grain above which there will be no harvesting. For the farmer and the contractor this value is assumed to be 23% and for the IJ.D.A. 27%. As to the statistics on the moisture standards 21, 19 and 17% (see table A 2.2.6.1) it can be *assumed* there are *about* as many workable hours when the harvest takes place when the moisture content is between 21 and 23% as when it takes place at below 21%. From this it is *assumed* that the average moisture content during the harvest for the grain farm will be about 21%.

Table A 2.2.6.1. The number of the workable hours, without straw-moisture-content limits during a 24-hour day, based on calculated grain moisture contents covering the period 1957 ... 1968

| The number of years in which less than the indicated number of hours are available: | | | 25% | | | | | | 16 2/3% | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Moisture content standard (%) | <17 | <19 | <21 | <23 | <25 | <27 | <17 | <19 | <21 | <23 | <25 | <27 |
| Period: | | | | | | | | | | | | |
| August 2 | 0 | 26 | 55 | 81 | 97 | 110 | 0 | 16 | 25 | 43 | 60 | 78 |
| September 1 | 0 | 0 | 24 | 36 | 58 | 73 | 0 | 0 | 5 | 12 | 32 | 64 |
| September 2 | 0 | 0 | 15 | 49 | 52 | 61 | 0 | 0 | 10 | 21 | 32 | 36 |
| Total 24-hour day | | | | 166 | | 244 | | | | 76 | | 178 |
| Total work hours: farmer | | 85%: | | 141 | | | | 85%: | | 65 | | |
| IJ.D.A. | | | | | 80% | 295 | | | | | 80% | 142 |

The winter wheat harvest could have started at the IJ.D.A. grain farm in the years 1979 ... 1982 in August on resp. 17th, 23rd, 16th, 10th and 4th, according to the standard of ripeness applied. This standard is defined as the date on which the grain moisture content has reached 20% or a lower level. As mean data *we chose* the 15th, the starting date of period August 2 from table A 2.2.6.1.

The calculation of the timeliness loss is then as follows. The 80% or 85% of the available, workable hours are proportionally divided over the 15 days of each period. Each day's harvested area is calculated for a range of machine speeds from 0.0 ... 1.7 $m \cdot s^{-1}$ and the workable hours of that day. Then the timeliness losses of each day are calculated and summed up until the total area is harvested. The percentages are recorded in table A 2.2.6.2 while the costs, converted into $fl \cdot ha^{-1}$ are shown in figure 1.4.1.3. These costs are based on a yield of 6 $tons \cdot ha^{-1}$ and the grain values given in A 2.2.4.

Table A 2.2.6.2. Timeliness loss in % of the total crop

| | *VW* (=*VM*•*CL*) | 2 | 3 | 4 | 5 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|---|---|
| Farm | Weather risk | | | | | | | |
| Cereal farm | 25% | 22.09 | 3.85 | 0.739 | 0.149 | 0.053 | 0.010 | 0.002 |
| IJ.D.A. | 25% | 40.13 | 16.98 | 4.99 | 2.07 | 1.02 | 0.315 | 0.128 |
| Cereal farm | 16 2/3% | 63.90 | 49.05 | 35.85 | 24.07 | 13.48 | 4.39 | 1.56 |
| IJ.D.A. | 16 2/3% | 55.58 | 38.45 | 23.66 | 10.83 | 5.00 | 1.96 | 1.04 |

A 2.3.1. *Header and conveyer*

*Auger transfer*

The transfer of the mass transport to the driving torque of the auger has been estimated by studying the response on a step function. This can be explained as follows: Figure A 2.3.1.1 shows a view, from above, of a header with the dimensions of machine B and between brackets the dimensions of machine A.

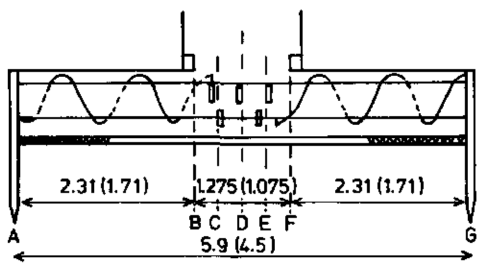



Figure A 2.3.1.1. Dimensions of the header of machine B and (between brackets) machine A

It can be *assumed* there is 0.3 s between the mowing of the crop and the transfer to the auger for machine A, based on a machine speed of 1 $m \cdot s^{-1}$ and the dimensions. The part of mass BF of the total mass is 1.07/(4.5 - 1.07) = 0.31 and is directly taken over by the retractable auger fingers. The mass of AB and GF is transported to B and F at a speed of 1.64 $m \cdot s^{-1}$. This speed is calculated from the slope and dimensions of the auger windings and the rotational speed. After (4.5 - 1.07)/1.64 = 1.05 seconds all the crop has arrived at B and F. The material supply corresponds to the drawn lines in figure A 2.3.1.2. The mass has to be divided over BF, so that the average BC has to be covered, because the auger windings also go further. This line will be more fluent, because of initial processes and skidding.

Initially this process would be considered to be a second-order system in accordance with

$\frac{1}{(1 + 0.27 \cdot s)^2}$ (see the interrupted line), later a first-order process in accordance with $\frac{1}{1 + 0.54 \cdot s}$ has been used (see the line with long interruptions).

A similar reasoning has been applied to the header of machine B, which has a width of 5.9 m. Field measurements indicated a value of 2.0 - 2.4 s for the real transportation time from the far to the take-over by the auger fingers. Figure A 2.3.1.3 shows the result. However, in this case, too, it seemed more correct to approach it by a first-order transfer, namely

$$\frac{1}{1 + \tau s} = \frac{1}{1 + 0.7 \cdot s}$$

Consequently the transfer depends on the working width (*CL*). This relation can be estimated by $\tau = 0.12 \cdot CL$.

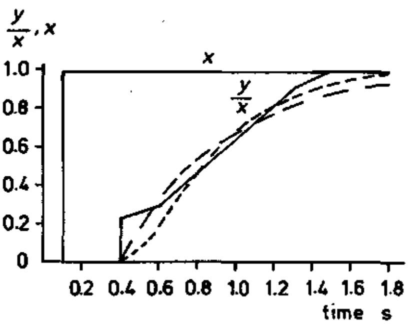



Figure A 2.3.1.2. Theoretical response of straw feed rate at the centre of the auger on a step in straw density parallel to the cutter bar of machine A
(———) calculated crop supply,
(— — —) approximated supply according to first-order transfer and
(-----) second-order supply.

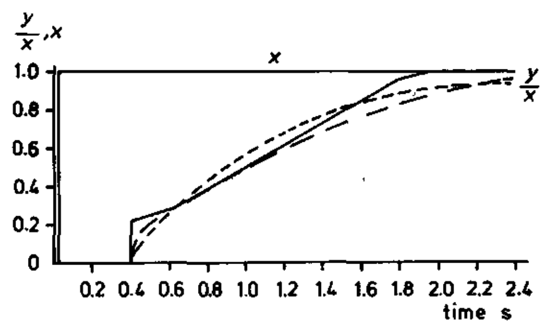



Figure A 2.3.1.3. Same as figure A 2.3.1.2. for machine B
(———) calculated crop supply,
(— — —) smoothed calculated crop supply and
(-----) approximated supply according to first-order transfer 1/1+0.7•s.

*Delays* (see figure A 2.3.1.4)

The quantity of material presented to the elevator is the same as delivered by the auger fingers. Hence the transfer is linear. Nevertheless there is a delay of 0.22 s, which can be derived from the speed of the crop and the dimensions of the machine. This delay was measured, too, by studying the peaks in plotted signals of the auger torque and the elevator displacement of machine A. The average delay of 174 peaks was found to be 0.65 s (Wevers, 1972). This value is rather high compared to the theoretical value of 0.22 s and can be explained by the fact that mainly high peaks have been chosen. The peaks are those of crop accumulations occurring before the arrival of the crop at the auger pins.

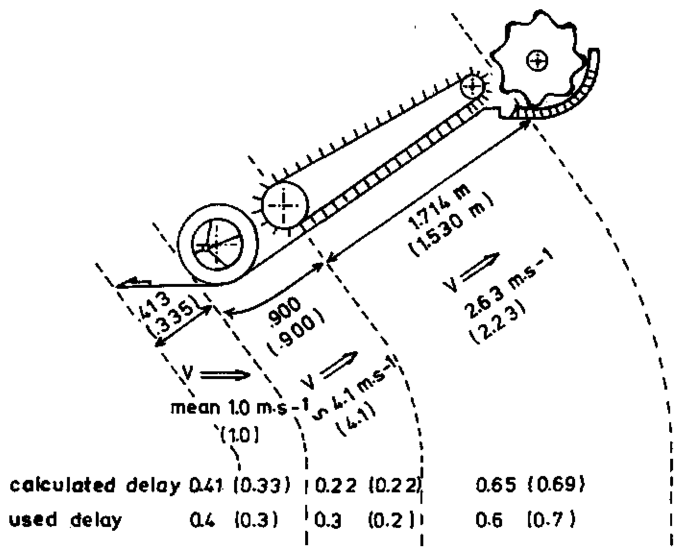



Figure A 2.3.1.4. Delays in header and conveyer, based on dimensions (m) and speeds $m{\cdot}s^{-1}$ for machine B and (between brackets) machine A

By determining cross-correlations between both signals, an average delay of 0.43 s has been found over 12 tests (Theunissen, 1979). Eimer (1973) finds delays of 0.25 - 0.35 s and 0.6 - 0.7 s, depending on the machine. The inertia of the mass-spring system of the elevator axle is also included in this value (for this see 3.1.2). Based on these observations and the imperfections expected at transfer, the value used for the delay is *assumed* to be 0.3 s.
In the simulation model the displacement of the elevatorchain (*DE*) is taken into consideration separately, because the auger torque (*TA*) as well as (*DE*) are used as a measured parameter for the straw feed rate (see 3.1). The delays to the threshing cylinder are calculated as 0.7 s for machine A and 0.6 s for machine B, when the elevator speed and the length of the intake channel are taken into consideration.

A 2.3.2.a *Concave separation model*
From the formula for the concave separation or threshing separation efficiency *TSE* of Caspers (1973) it can be derived that

$$TSE = 1 - \exp(- LA \cdot NU \cdot RPS \cdot (VT-VE)^{BETA})$$

This *experimental model* has been arrived at from research with a rasp bar threshing cylinder of diameter of 0.60 m, width of 0.98 m and concave length 0.68 m. The tests have been performed with rye, spring wheat and sometimes winter wheat. For our model the data of winter wheat and spring wheat have been used.

The threshing separation efficiency *TSE* is described by this model dependent on the threshing speed *VT* minus the intake speed *VE*, the crop property *BETA*, the concave length, the concave adjustment and the straw feed rate. These factors affect the values of *LA*, *NU* and *RPS*.

*LA* is the concave length factor determined by the length of the concave, the feed rate, the concave adjustment and the crop. It is a ratio relating the separation of a certain part of the concave to the total separation in the threshing cylinder as used by Caspers. The influence of the feed rate is small and negligible for our purpose.

A value of 0.9 can be *assumed* for *LA* based on data of spring wheat and a concave length of 610 mm for machine B (see figure A 2.3.2.1). This value approximately accounts for other crops too and doesn't depend on the adjustment at this level.

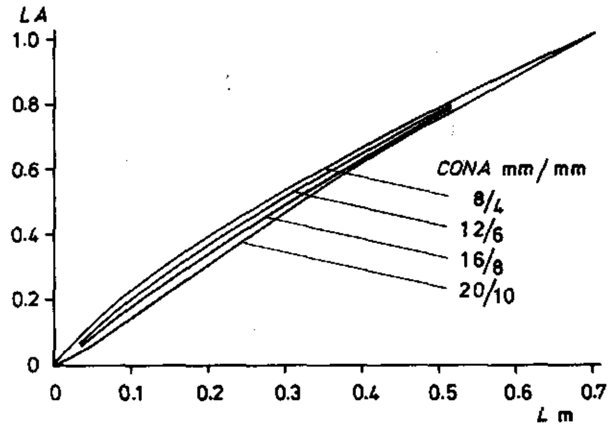



Figure A 2.3.2.1. Concave length factor (*LA*) related to the length of the concave (*L*) for, different concave adjustments (*CONA*) indicating the gap at the front in mm/gap at the end in mm of the concave as given by Caspers (1973) for spring wheat (*MCS* = 13%)

*RPS* is the reciprocal of the so-called charge coëfficient. This value of *RPS* depends on the straw feed rate, and in fact decreases with increasing material supply. See figure A 2.3.2.2 with data of spring wheat.

On our machines the intake speed is fixed (machine A: 2.3 $m \cdot s^{-1}$, machine B: 2.6 $m \cdot s^{-1}$), resulting in *a more simple relation* to the straw feed rate. The table below gives the values fed to a function generator during the simulations. In this table the specific feed rate is introduced. This is the straw feed rate *FS*, per m width of the threshing cylinder *LT*, so *FS/LT*.

Table A 2.3.2.1. The used values of *RPS* dependent of the specific feed rate *AFS* for both studied combine harvesters

| Specific feed rate in $kg \cdot s^{-1} \cdot m^{-1}$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| *RPS* machine A: ($\cdot 10^{-3}$) | 10.2 | 8.5 | 7.0 | 5.7 | 4.8 |
| *RPS* machine B: ($\cdot 10^{-3}$) | 10.5 | 8.8 | 7.3 | 6.0 | 5.0 |

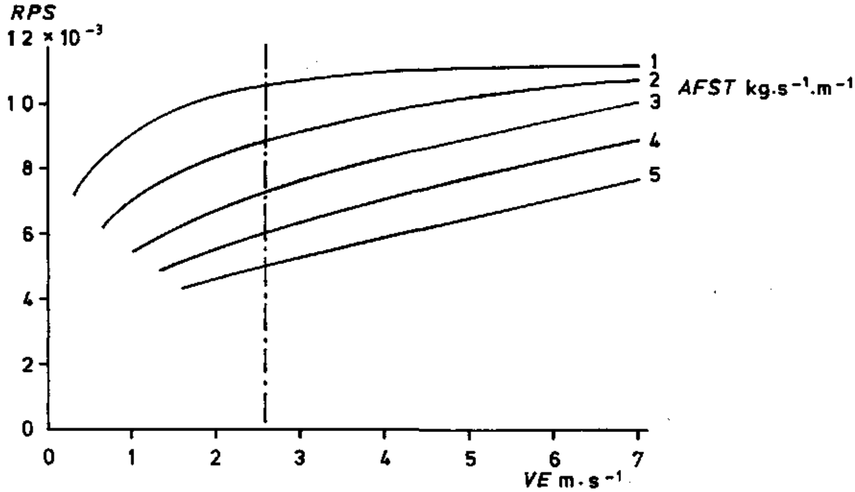



Figure A 2.3.2.2. Reciprocal charge coefficient (*RPS*) related to the crop supply speed (*VE*) for different specific straw feed rate levels (*AFST*) as given by Caspers (1973) for spring wheat (*MCS* = 13%)
(—·—) line corresponding to the elevator speed of machine B

*NU* is the ratio between *RPS* at the standard concave adjustment (20 mm at the front and 10 mm at the back) and *RPS* at the real concave adjustment. Therefore the value of *NU* is determined by the concave adjustment and the straw feed rate according to figure A 2.3.2.3. From these data the relation between *NU* and the feed rate can be derived: see figure A 2.3.2.4.

During the simulations the values of the *concave adjustment 8/4* (8 mm at the front and 4 mm at the back) *have been used throughout.*

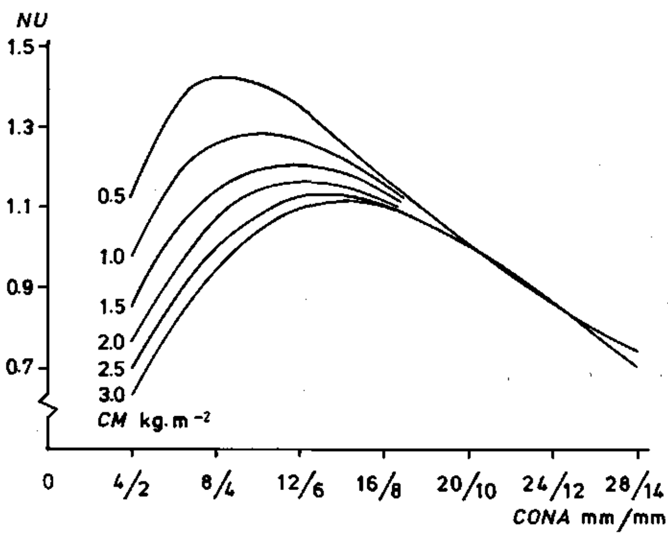



Figure A 2.3.2.3. Compression factor (*NU*) related to the concave adjustment (*CONA*) for different crop mass levels on the conveyer (*CM*) of the test rig of Caspers (1973) for spring wheat (*MCS* = 13%)

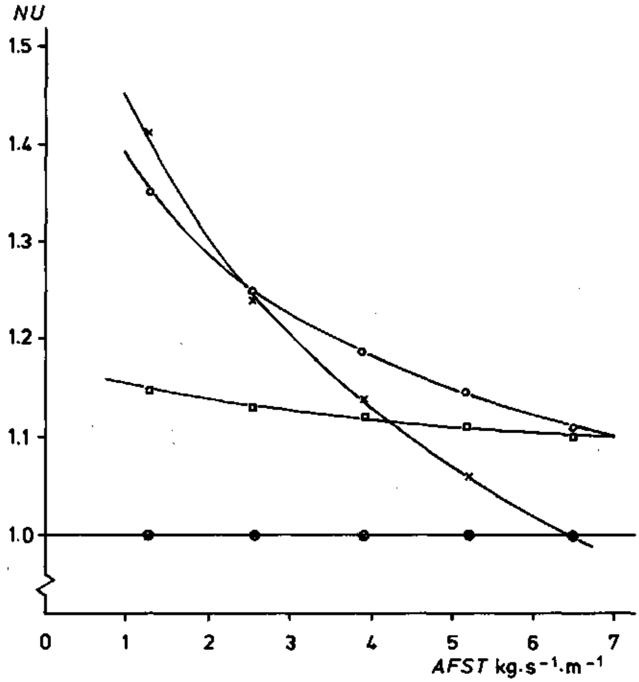



Figure A 2.3.2.4. Compression factor (*NU*) related to specific straw feed rate (*AFST*) for different concave adjustments: × = 8/4, o = 12/6, ◘ = 16/8, ● 20/10 mm/mm as given by Caspers (1973) for spring wheat (*MCS* = 13%)

A 2.3.2.b *Laboratory research*

The process at the threshing cylinder and the walkers has been researched by means of a test rig as shown in figure A 2.3.2.5. This test rig consisted of a threshing cylinder with a diameter of 0.45 m, a width of 0.78 m, a concave length of 0.3 m and 10 trays to collect the separated material.

The chosen variables were the type of crop, the moisture content of the straw, the straw feed rate and the feed rate variations. In figure A 2.3.2.6 the results are given of tests with winter wheat 1, 2, 3 with moisture contents of respectively ≈ 15%, 30% and 45% with stored straw, first unmoistened, then slightly moistened and, last of all, considerably moistened. The feed rate is in kg (dry matter)$\cdot s^{-1} \cdot m^{-1}$. The points in the figure are the averages of 5 test each lasting 12 seconds (Donkersgoed, 1980). The threshing cylinder speed was 30.6 $m \cdot s^{-1}$; the concave adjustment was 8/4 mm and the elevator speed was 3.5 $m \cdot s^{-1}$.

Apart from the observations at the low feed rate, the measurement points of wheat 2 and 3 link up well with the curve which can be obtained with the Caspers model in which *BETA* = 1.55. See models 2 and 3 in figure A 2.3.2.6 (*LA* is 0.53 at this concave length).

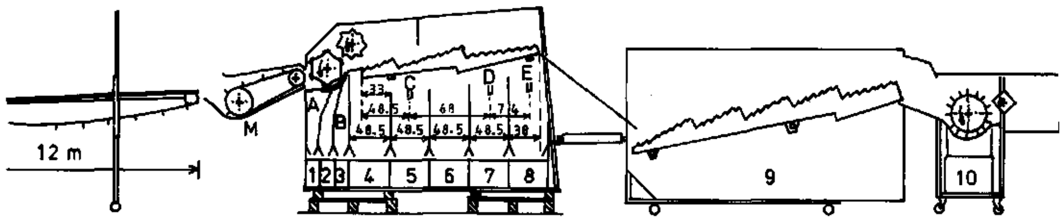



Figure A 2.3.2.5. Test stand for the laboratory tests consisting of conveyer belt, stationary small combine harvester, reshaker and rethresher.
M = measurement of the displacement of the elevator chain, A and B acoustic grain kernel sensors underneath the threshing cylinder, C, D, E acoustic sensors underneath the straw walker placed as indicated by the dimensions, 1 ... 10 trays in which grain was gathered: 1 ... 3 threshing separation, 4 ... 8 walker separation, 9 walker loss, 10 threshing loss

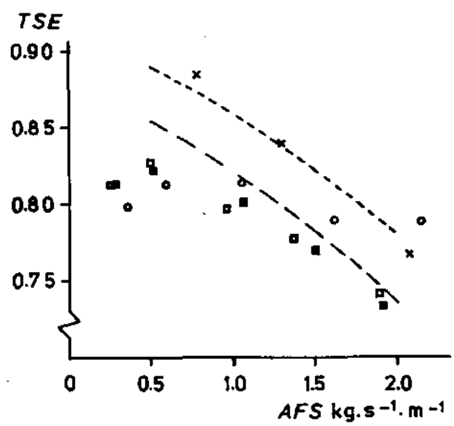



Figure A 2.3.2.6. Threshing separation efficiency (*TSE*) related to specific straw feed rate for variously treated wheat (see text):
wheat 1: *MCS* = 15% (o);
wheat 2: *MCS* = 30% (■);
wheat 3: *MCS* = 43% (□), at conveyer speed of 3.5 $m \cdot s^{-1}$ and
wheat 4: *MCS* = 15% (×) at conveyer speed of 1.2 $m \cdot s^{-1}$
Threshing separation model *BETA* = 1.550(— — —), *BETA* = 1.625(------)

The low feed rates deviate, because the differences in the supply speed of the conveyer (0.75 $m \cdot s^{-1}$) and in the intake speed of the elevator (3.5 $m \cdot s^{-1}$) generate an irregular feed rate. This effect is higher at a low feed rate, because then there is so little coherence of the material on the conveyer that the elevator takes over the material separately.

At tests (Sytsma, 1981) with equal conveyer and elevator speeds of 1.2 $m \cdot s^{-1}$, resulting in a more regular intake, higher threshing separation efficiency values were found. Here the material used was wheat with a straw moisture content of 14.7% and the threshing speed was 30.6 $m \cdot s^{-1}$.

In figure A 2.3.2.6 the averages of 4 tests with wheat 4 are shown. In this case, too, the Caspers model for *BETA* = 1.625 (model 4) is fairly satisfactory although the threshing cylinder diameter of the test (= 0.45 m) differs from that of Caspers (= 0.60 m). The results of tests under the same conditions as before for wheat 1, 2 and 3 are processed in figure A 2.3.2.7. Every point represents the result of one test on one type of spring wheat or oats or winter wheat. With winter wheat there are 6 straw moisture-content variations studied; early (at the time of harvesting), medium (after 1 month of storage) and late (after 2 months of storage) and of each type there is a dry and wettened version. For the illustration, there are two lines of the model for *BETA* = 1.625 and *BETA* = 1.550 in this figure.

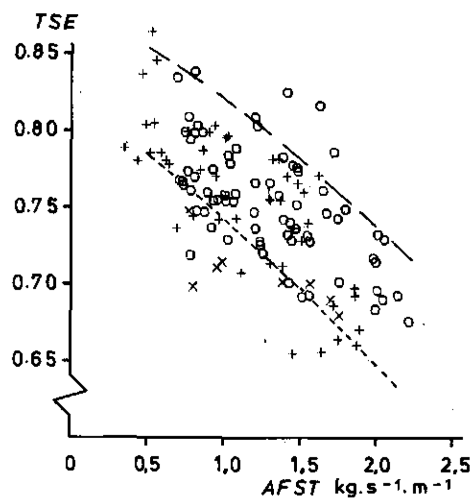



Figure A 2.3.2.7. Threshing separation efficiency (*TSE*) related to specific straw feed rate (*AFST*) of laboratory tests with different crops: × = spring wheat, o = winter wheat, + = oats
Lines are relations calculated by the model for *BETA* = 1.625 (— — —) and *BETA* = 1.55 (------)

A 2.3.2.c *Field tests*

Field measurements have been performed with machine A under different harvest conditions. A walker loss measurement machine was built for this in accordance with figure A 2.3.2.8 and used in the period 1974 ... 1976 (Gelder, 1975). The straw feed rate was found by measuring the auger torque and by relating this to the calibrated real straw feed rate of 15 m tests (see 3). In addition to this the displacement of the elevator chain, driving speed, grain loss monitor signal and in 1976 the content of the grain tank were measured continuously. In 1975 the material falling through the walkers over the part B-C of runs of 120 m was collected (see figure A 2.3.2.8). The walker losses and the total grain feed rate were also measured, so that the total grain separation of the concave finger grate and the first part of the walker could be determined. The total separation

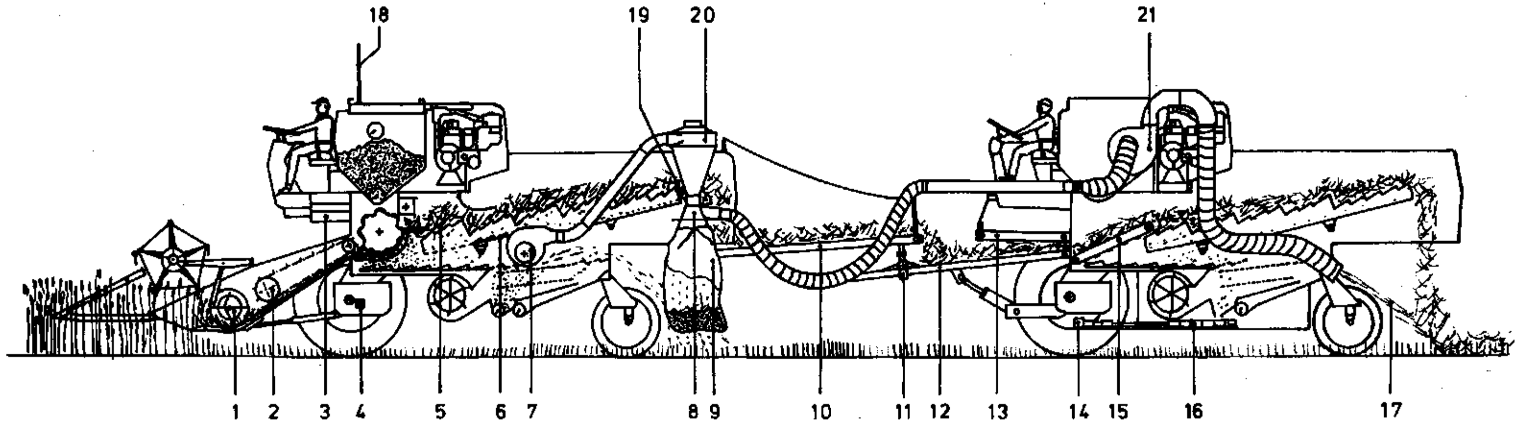



Figure A 2.3.2.8. Function of combine harvester with measurement devices and loss measuring machine
1. measurement of auger torque, 2. measurement of displacement elevator chain, 3. amplifiers and transmitter, 4. measurement of machine speed, 5. covering plate on first walker step, 6. conveyer bottom to: 7. auger and blower for the material separated by the walkers, 8. cleaning compartment, 9. grain and straw sack, 10. conveyer belt capable of moving horizontally and vertically, 11. conveyer (10) guiding parts, 12,13,15. conveyer belts, 14. transporting element moving: 16. walker-loss-gathering trays, 17. chaff separated at (8), 18. transmitting antenna, 19. grain-loss acoustic sensors, 20. cyclone, 21. blower

can be compared to the function of Caspers, because there is a close linear relation between the *concave separation* and *the sum of the separation* by the finger grate and the first walker part (A-B)(see A 2.3.4).

The data of the test with oats (*) and spring wheat are shown in figure A 2.3.2.9. In the tests indicated by (o) the first part of the walkers (A-B) was covered with sheets. From this it is found that it does not matter whether or not this part is covered, so that the separation at the first part of the walkers is small and *can be considered* as a part of the concave separation. The figure also shows the line of the model of Caspers for *BETA* = 1.58 and *VT-VE* = 30.0 $m \cdot s^{-1}$ and concave adjustment 8/4 mm. It is found that this line isn't steep enough. With regard to this it should be realized that the moisture content of the straw of the model of Caspers is 13% while the straw moisture content of the oats in the tests varied from 53% to 62% and of the spring wheat in the tests from 22% to 37% during the field tests. Consequently, one is dealing with quite another crop. An adaption of *NU* and *RPS* is the only solution owing to the difference in crop properties.

The observations on tests carried out in 1976 with winter wheat with straw moisture contents of 15% - 24% are plotted in figure A 2.3.2.10 (Snel, 1977). The tests were performed with the same machine as given in figure 2.3.2.8. However, in this case the measurement stretch of 120 m could be split up into 4 separate parts of ~ 30 m. For this the weight of the grain tank content was measured and the losses and walker separation collected in separate trays and sacks. Therefore the measurement points refer to averages over stretches of 30 m.

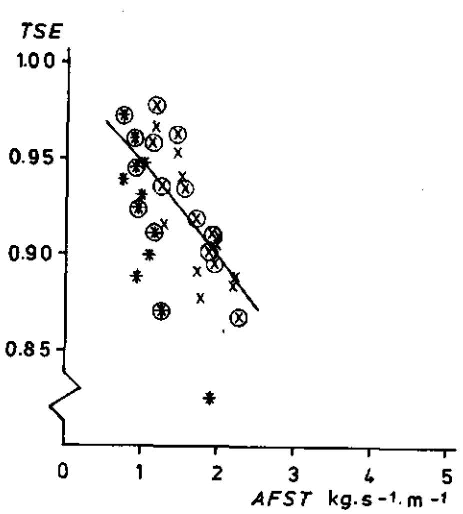



Figure A 2.3.2.9. Threshing separation efficiency (*TSE*) of field tests (1975) in oats: * with walker plates, ⊛ without walker plates in spring wheat × with and ⊗ without walker plates (see text)

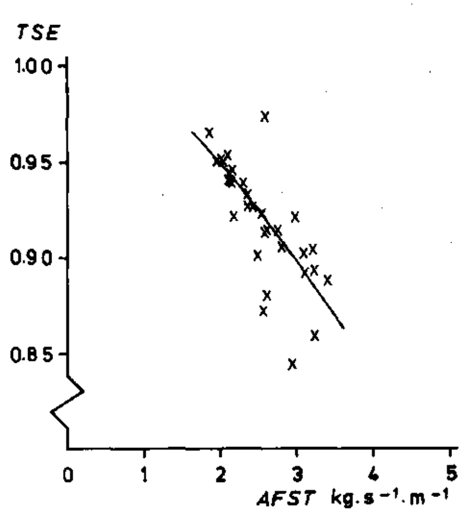



Figure A 2.3.2.10. Separation efficiency of field tests (1976) in winter wheat (———) model with *BETA* = 1.66, *VT-VE*=30.0 $m \cdot s^{-1}$, concave adjustment = 8/4 mm

A well-fitting model for these measurement points can be obtained for *BETA* = 1.66, *VT-VE* = 30.0 $m \cdot s^{-1}$ and a concave adjustment of 8/4 mm. This model fits the model of Caspers well, thanks to a dry crop under dry harvesting conditions. The general conclusion is that the model of Caspers performs well under field conditions and better still if the crop is dryer than in the Caspers tests.

### A 2.3.2.d *The threshing separation efficiency in relation to feed rate variations*

The extent to which the amplitude and frequency of feed rate variations affect the threshing separation efficiency (Smook, 1980) has been investigated. This was achieved in laboratory tests with the test rig shown in figure A 2.3.2.5.

Winter wheat (moisture content 16%) was distributed in piles on the 12 m long horizontal conveyer moving at a speed of 1 $m \cdot s^{-1}$. The piles were 1 m in length and contained equal quantities of material per $m^2$ for each feed rate level, the distances between the piles being equal (see fig. A 2.3.2.11). The greatest distance was 4 m, others being 2, 1 and 0 m (the last mentioned meaning close together, but separate). Tests were also done with piles 0.5 m in length with a distance of 0 metre between them. There were also tests with crop put down regularly with the ears forward and upward (see: even feed in fig. A 2.3.2.11). The speed of the elevator (behind the horizontal conveyer) was 3.5 $m \cdot s^{-1}$.

The piles are all taken up at once resulting in an actual feed rate under the elevator and to the threshing cylinder of 3.5 times the original feed rate (see the dotted line in the top of figure A 2.3.2.11). This momentaneous feed rate is called the cylinder feed rate. In this way, the frequencies of the feed rate variations were 0.2, 0.3, 0.5, 1.0 and 2.0 Hz.

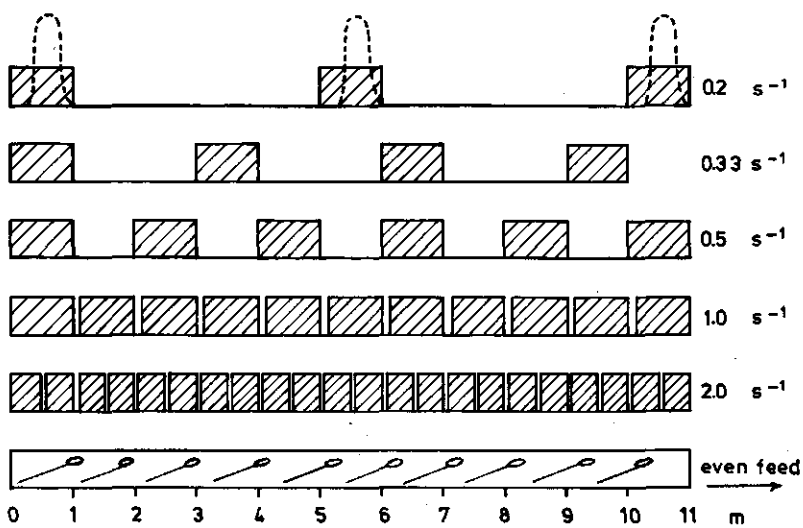



Figure A 2.3.2.11. Deposition of straw at the conveyer belt [hatched] and an example of expected resultant cylinder feed rate (-------)

The regular feed rate or even feed on the conveyer also becomes irregular when it is taken over by the elevator chain. It was found from the registration of the displacement of the lower axis of the elevator chain that the wads at the intake are depending on the feed rate level. It was tried to calculate the cylinder feed rate for the even feed on the conveyer.

It was possible, especially at high feed rates, to ascertain the level of the peaks of the measured feed rate, *FSE*, at even feed (see figure A 2.3.2.12). The average value of the peaks has been calculated (= *TE*) and compared to the peak value of the irregular feed at the same feed rate level (= *TI*) (see figure A 2.3.2.13). This gives a value $A = TE/TI$. The amplitude of the irregular cylinder feed rate in case of even feed at the conveyer can in this way be calculated also, namely

$$\text{cylinder feed rate} = \frac{\text{speed elevator}}{\text{speed conveyer}} \cdot A \cdot \text{conveyer feed rate } (\text{kg}\cdot\text{s}\cdot\text{m}^{-1})$$

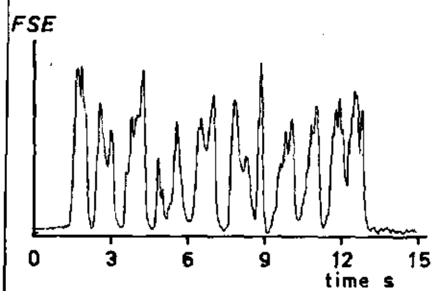



Figure A 2.3.2.12. Measured feed rate at the elevator for an even feed of 4 $\text{kg}\cdot\text{s}^{-1}$

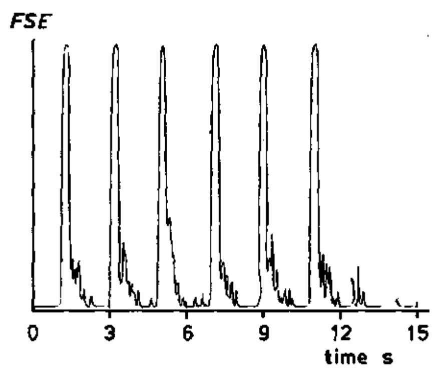



Figure A 2.3.2.13. Measured feed rate at the elevator at an irregular feed of 0.5 $\text{kg}\cdot\text{s}^{-1}$ of mean feed rate 4 $\text{kg}\cdot\text{s}^{-1}$ (same scale as A 2.2.2.12)

Table A 2.3.2.2 shows the values of $A$ and the calculated cylinder feed rate for various feed rate levels at even feed.

Table A 2.3.2.2. The calculated cylinder feed rate for irregular feed and even feed

| | | | | |
|---|---|---|---|---|
| Straw feed rate on the conveyer belt $\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$ (width of cylinder) | 1.28 | 1.71 | 2.13 | 2.50 |
| Cylinder feed rate for irregular feed ($\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$) ($A = 1$) | 4.48 | 6.00 | 7.46 | 8.75 |
| $A$ | 0.19 | 0.31 | 0.42 | 0.50 |
| Cylinder feed rate for even feed ($\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$) | 0.85 | 1.86 | 3.13 | 4.38 |

Now it is found and shown in fig. A 2.3.2.14 that there is no significant difference between the various frequencies when the threshing separation efficiency, *TSE*, and the threshing loss, *TLF*, (the average of 4 repetitions) is regarded as a function of the cylinder feed rate. This means there is no important redistribution in the threshing cylinder because the actually presented cylinder feed rate determines the threshing separation efficiency.

The threshing separation efficiency of the 2.0 Hz and the regular feed rate variants is proportionally too high. This is because there are lower feed rates between the peak feed rates which cause a more favourable concave separation. Consequently there was a redistribution in these tests on taking over from the conveyer. The same conclusion has to be drawn from other tests with a varying feed rate (Sytsma, 1981; Groothuis, 1979), namely that the frequency does not affect threshing separation efficiency.

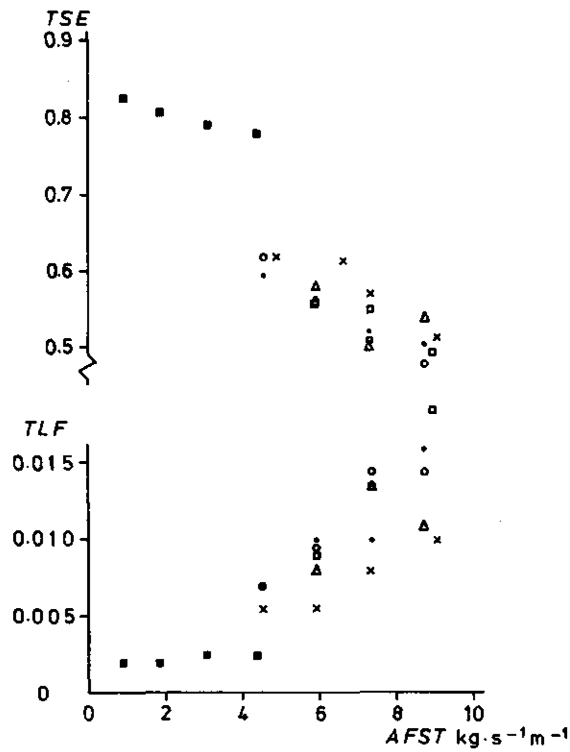



Figure A 2.3.2.14. Threshing separation efficiency *TSE* and threshing loss (fraction) *TLF* related to specific feed rate *AFST* and irregular feed: 0.2 $s^{-1}$(×); 0.33 $s^{-1}$(□); 0.5 $s^{-1}$(o); 1.0 $s^{-1}$(●); 2.0 $s^{-1}$(×) and even feed (■)

A 2.3.4.a *Relation between separation front of walkers and concave separation*

It has been ascertained from other tests with the test rig given in A 2.3.2.5 (Donkersgoed, 1980) that the relation between the content of tray 4 (= separation first walker part and concave grate) and the content of trays 1 + 2 + 3 (= concave separation) is well described for different crops by a linear relation. An exponential or squared relation is better for some types of crop, but the difference is slight when all the crops are taken together. Table A 2.3.4.1 gives a résumé of the results of regression analysis and fig. A 2.3.4.1 shows the observations together with the two regression lines for all the crops taken together.

Table A 2.3.4.1. Results of regression analysis of the separation of the front end of the walkers (tray 4) explained by the concave separation with two models

*n* = number of 12-sec. tests
*MCS* = moisture content of the straw (% w.b.)
*WS4* = separation of tray 4 (grams dry matter)
*CS* = concave separation (grams dry matter)
*b* = regression coëfficient
*MCCS*= multiple correlation coëfficient

| crop | $n$ | $MCS$ | $WS4 = b_0 + b_1 \cdot CS$ | | | $\ln(WS4) = b_2 + b_3 \cdot CS$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | $b_0$ | $b_1$ | $MCCS$ | $b_2$ | $b_3$ | | $MCCS$ |
| oats | 25 | 17 | 15.0 | 0.043 | 0.98 | 3.78 | 3.3 | $10^{-4}$ | 0.94 |
| win- | 25 | 15 | −10.8 | 0.069 | 0.98 | 4.67 | 1.7 | $10^{-4}$ | 0.97 |
| ter | 25 | 30 | −122.0 | 0.094 | 0.92 | 4.30 | 2.3 | $10^{-4}$ | 0.99 |
| wheat | 25 | 43 | −81.8 | 0.071 | 0.91 | 4.19 | 2.2 | $10^{-4}$ | 0.97 |
| all crops | 100 | -- | −66.9 | 0.076 | 0.91 | 4.25 | 2.2 | $10^{-4}$ | 0.93 |

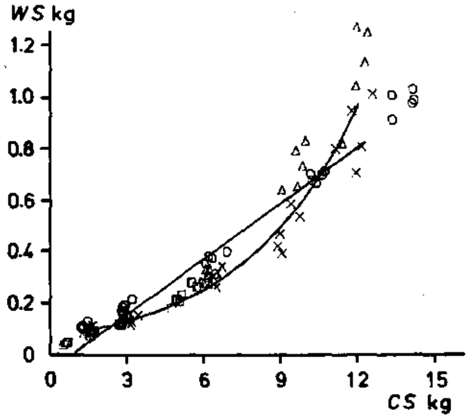



Figure A 2.3.4.1. Relationship between content of tray 4 (*WS*) at the front of the walkers and concave separation (*CS*)
□ = oats, o = wheat 1, Δ = wheat 2, × = wheat 3

A 2.3.4.b *Steady-state model of walker separation*

The grain content in the straw on the walkers $G_x$ at $x$ decreases as a function of the distance $x$ from the point at the walkers where the exponential model starts (at $o$). The unity of $G_x$ is $kg \cdot s^{-1}$ because the mass is moving backwards and $kg \cdot s^{-1} \cdot m^{-1}$ when the content is considered for width of the walkers in metres. At the start the grain content is $G_o$. The decrease at any place behind o is *assumed* to be proportional to $G_x$ itself so that

$$\frac{dG_x}{dx} = - WE \cdot G_x \qquad \text{(a 2.1)}$$

in which $WE$ = the proportional factor, called walker efficiency.
From (a 2.1) it follows that

$$\frac{dG_x}{G_x} = - WE \cdot dx \qquad \text{(a 2.2)}$$

When we want to know the value of $G_w$ at any place $w$ it can be calculated by integrating (a 2.2)
so that

$$\int_o^w \frac{dG_x}{G_x} = -\int_o^w WE \cdot dx \qquad \text{(a 2.3)}$$

Solving (a 2.3) gives

$$\ln G_x \Big|_o^w = - WE \cdot x \Big|_o^w \qquad \text{(a 2.4)}$$

Thus $\ln G_w - \ln G_o = - WE \cdot w + o$ (a 2.5)

or $G_w / G_o = \exp(-WE\ w)$ (a 2.6)

or $G_w = G_o \exp(-WE \cdot w)$ $\quad kg \cdot s^{-1}$ (a 2.7)

In fig. A 2.3.4.2 the curve of the grain content $G_w$ is drawn including the initial process from $b$ to 0. The initial process can be clearly seen in the walker separation curve represented by line $WS$. This function holds

$$WS = \frac{dG_w}{dx}$$

Thus from (a 2.1) and (a 2.7) we have

$$WS = -G_o \cdot WE \cdot \exp(-WE \cdot w)\ kg \cdot s^{-1} \cdot m^{-1} \quad (\text{or } kg \cdot s^{-1} \cdot m^{-2})$$

Now, the *assumption* in the model, $WE$ is constant, can be tested from the measured $WS$! This can be done in two ways:

1) $WS$ measured over a certain distance $\Delta w$, give the calculated $WE$(s) yielding for that distance and that place. In that case $G_o$ has to be known at $w$.
2) A local $WE(\ell)$ can also be calculated by taking $G_o$ at place E and by measuring $WS$ from E to $w$. Both curves of $WE$ are sketched in fig. A 2.3.4.2.

When considering the results of some laboratory tests it becomes clear that the behaviour of $WS$ above tray 4 is an initial process. Therefore this has to be contemplated as in coherence with the concave separation (see Appendix 2.3.4a). This also shows the importance of the baffle curtain, because the separation starts just behind the curtain.

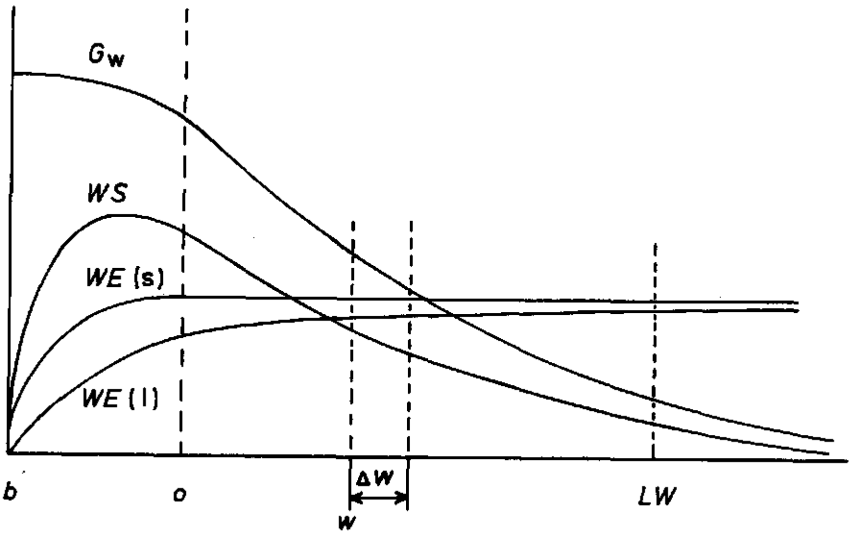



Figure A 2.3.4.2. Sketch of the grain content in the straw ($G_w$), walker separation (*WS*), local walker efficiency (*WE*(*ℓ*) and walker efficiency holding for the distance from *b* to *w*, as a function of the place on the walkers (*w*) measured from the front of the walkers (*b*)

Boyce (1974) reaches the same conclusion that, without the curtain, the major part of the separation starts at the rear of the walkers because there the straw reaches a speed slow enough for separation. A second curtain at the rear of the walkers does not have any function if there is a first curtain.

Reed (1972) obtained a lower walker separation with a light curtain.

Behind the baffle curtain the walker separation coëfficient *WE*(s) has *theoretically* to be independent of its place under the walkers.

Results of laboratory tests with the test rig (explained in paragraph A 2.3.2.b) and three kinds of winter wheat 1 ...3 (Donkersgoed, 1980), show how this conclusion depends on the feed rate level and the crop properties.

Fig. A 2.3.4.3 gives a number of results at a feed rate level of about 2.3 $kg \cdot s^{-1} \cdot m^{-1}$. The level of *WE* decreases slightly, probably because of straw compaction. At lower feed rate levels the separation above tray 6 and 7 is higher (see fig. A 2.3.4.4). The reason can be that there is still irregular feed at lower feed rates at the front of the walkers whereas it has been flattened towards the end of the walkers (see A 2.3.2.4.c).

The crop properties affect the level, as could be expected. The influence of the feed rate level on walker separation is shown in fig. A 2.3.4.5 for wheat 1. For wheat 2 and 3 the same pattern is found at a higher level. The separation is calculated for the position of the different trays. Two conclusions can be drawn: the variance is high at the lower feed rate levels, probably because of the irregular feed. The decrease in *WE*(s) with increasing feed rate is slight, especially when compared with the results of the field tests (paragraph 2.3.4).

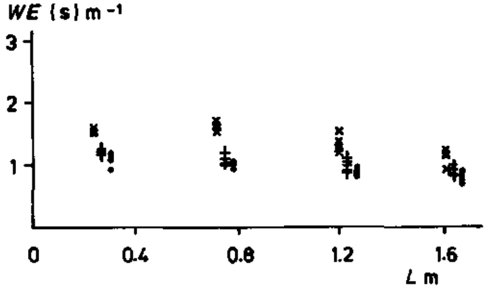



Figure A 2.3.4.3. Walker efficiency *WE*(s) related to the distance from the end of tray 4 (*L*) for different kinds of winter wheat at a straw feed rate level of 2.3 kg $s^{-1} \cdot m^{-1}$
× = wheat 1 (2.8 $kg \cdot s^{-1} \cdot m^{-1}$), + = wheat 2 (2.1 $kg \cdot s^{-1} \cdot m^{-1}$), ● = wheat 3 (1.99 $kg \cdot s^{-1} \cdot m^{-1}$). The points × are plotted in the centre of the tray while + and o are shifted to the right for clear recognition

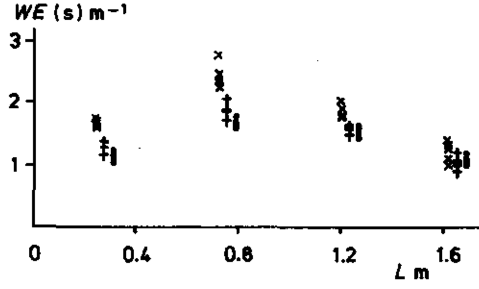



Figure A 2.3.4.4. Same as figure A 2.2.4.3 for straw feed rate levels of about 0.6 $kg \cdot s^{-1} \cdot m^{-1}$
× = wheat 1 (0.63 $kg \cdot s^{-1} \cdot m^{-1}$), + = wheat 2 (0.57 $kg \cdot s^{-1} \cdot m^{-1}$), ● = wheat 3 (0.52 $kg \cdot s^{-1} \cdot m^{-1}$)

The test rig conditions apparently differ a good deal from those of machine A in the field. A probable reason can be found in the short test length of time (10 sec), because it was registered that the period in which the crop left the walkers was longer than the period in which it was fed into the machine, so that feed rate was in fact reduced. Further research on this matter is necessary to make these differences clear.

The research done by Reed (1970, 1972) supports the exponential model and the dependence of our field tests on feed rate. For this reason the use of the exponential model in our model is *thought* to be *justified*.

A 2.3.4.c *Dynamic model of walker separation*

*Pulse type feed rate variations*
The walker separation has also been considered in the work described in A 2.3.2.d, in which the straw feed rate varied considerably at different frequencies. The contents of trays 1 to 10, were weighed and the signals of the displacement of the elevator chain (M), the pulse-type signals of the acoustic sensors at point A, B, C, D and E were recorded. These sensors were placed above the corresponding trays 1, 3, 5, 7 and 8. In a subsequent test with sinusoidal variations (Sytsma, 1981), the positions of C, D and E were shifted to the places indicated by the measures in figure A 2.3.2.5. The signals of sensors A and B (10x20 mm each) were added before recording. Sensors C, D and E were each 50x150 mm and the signals were separately recorded. After the tests it was found, however, that the signal of E was of no effect. Cross-correlations were made of all the remaining combinations and the highest values were averaged over 4 repetitions and the 3 or 4 feed rate levels per frequency (see figure A 2.3.4.6).

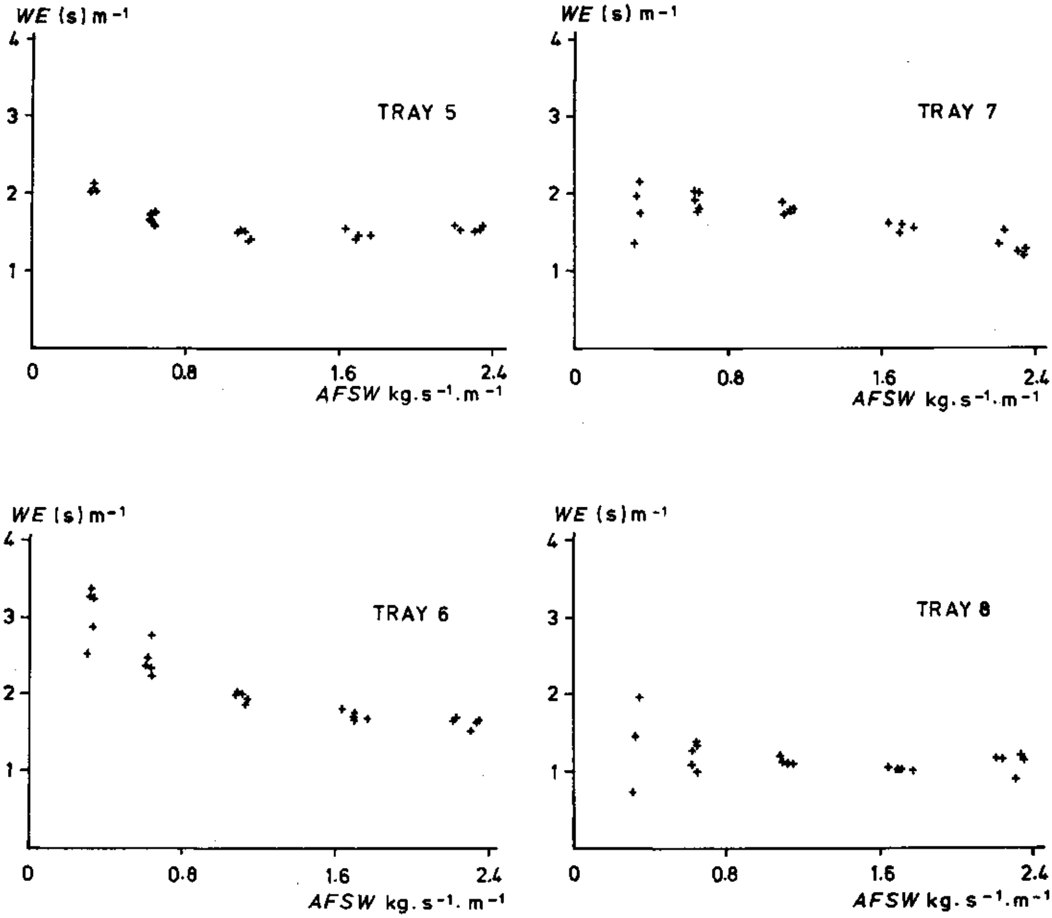



Figure A 2.3.4.5. Walker efficiency *WE*(s) above various trays in the test rig related to specific straw feed rate

From this the following observations can be derived, bearing in mind that the feed rate varies pulse-wise with frequencies indicated by $F_v$. The correlation (r) between M and AB (∗) is rather high and somewhat lower for $F_v = 2\ s^{-1}$, so that the feed rate variations below $2\ s^{-1}$ are evidently transitory, while some suppression of variations of $2\ s^{-1}$ *seems* to occur. The correlation between M and C (o), as well as AB and C (x) are about the same, though lower than between M and AB (∗), because of disturbances in the threshing cylinder. Except for the variation of $0.2\ s^{-1}$ the correlation is not obviously dependent on the variation frequency. This leads to the conclusion that, in front of the walkers, variation is only suppressed slightly.

As regards the correlation between M and D (Δ), AB and D (□), and especially between C and D (•), a decline can be seen at the lower frequencies.

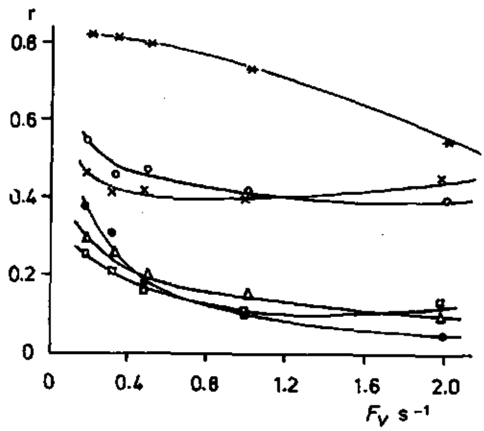



Figure 2.3.4.6. Correlation (r) of feed rate sensor (M) and acoustic grain kernel sensors AB, C and D to variation frequency.
Correlation between AB-C (×), AB-D (□), C-D (●), M-AB (✱), M-C (o) and M-D (▲)

In terms of a decrease in the amplitude of sine-type variations passing through a first-order process, there is a noticeable decrease at 0.33 Hz and higher frequencies which is obvious above D. Although we are, of course, not dealing with sine-type variations at the input to the threshing cylinder, the variations at the walkers have become more or less like sine functions. This is even more the case for longer walkers where the lower frequencies are suppressed somewhat more. *Assuming* that the breakpoint frequency of the variation suppression is at 0.2 Hz, then the time constant is $\underline{\tau} = 1/(0.2 \cdot 2\pi) = 0.8$ s. Although this deduction is not quite watertight, it is, however, an indication in a direction affirmed later on. Additional research is necessary on this point.

Nevertheless, the two following conclusions *can be justified*

1) The correlation is higher at low frequencies because the piles remain more easily identifiable. In those cases the redistribution is slight.
2) Redistribution does occur, especially behind the baffle curtain, because the signals of sensor C, which is positioned under the curtain, show less suppression of variation than those of sensor D.

It is important to realise that, when there is no redistribution, the walkers, too, are dealing with the cylinder feed rate as defined in A 2.3.2.d and then the walker efficiency *WE* will deviate from the *WE* at a regular feed rate. *WE* can be calculated from the tray contents.

If there is in fact a redistribution, the values of *WE* as a function of the position underneath the walkers, will turn out to be like even feed, that is will be shown to be slowly decreasing. Figure A 2.3.4.7 shows *WE*($\ell$) of a regular feed rate at 6 levels and of a varying feed rate at the highest feed rate level of 2.5 kg$\cdot$s$^{-1}\cdot$m$^{-1}$. $G_o$ has been taken from tray 5 and higher.

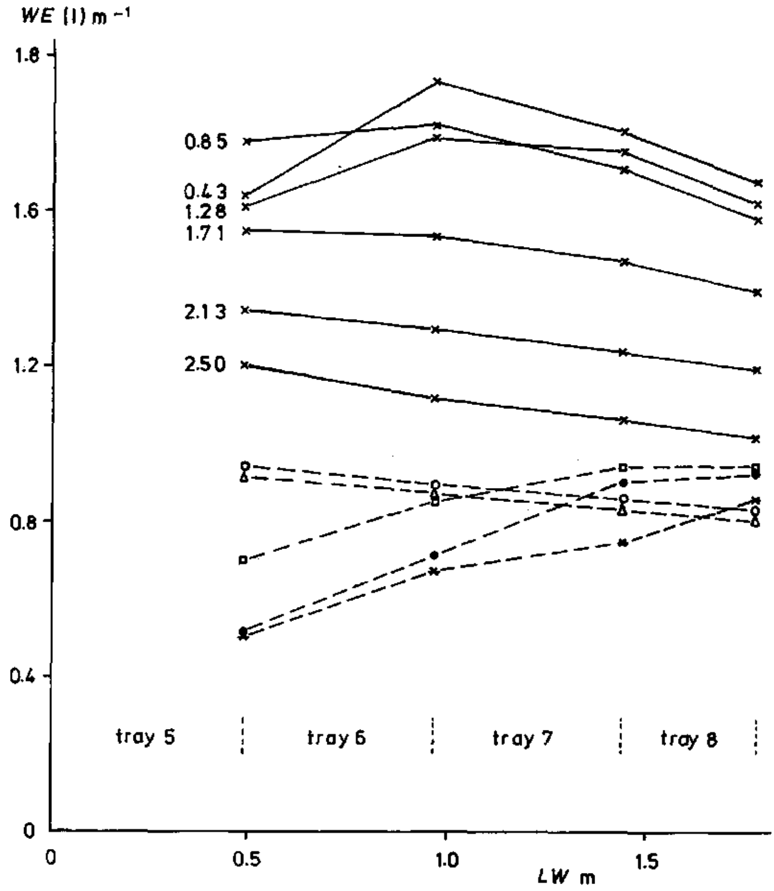



Figure A 2.3.4.7. Walker efficiency ($WE(\ell)$) related to position on walkers ($LW$) of tray 5 for even feed (——) at different levels of mean straw feed rate as indicated in $kg \cdot s^{-1} \cdot m^{-1}$ (see also table A 2.2.2.2) and for irregular feed at mean feed rate level of 2.5 $kg \cdot s^{-1} \cdot m^{-1}$, this being a cylinder feed rate level of 8.75 $kg\ s^{-1} \cdot m^{-1}$ (— —) at different variation frequencies: △ = 2 $s^{-1}$, o = 1 $s^{-1}$, □ = 0.5 $s^{-1}$, ✱ = 0.33 $s^{-1}$, ● = 0.2 $s^{-1}$

The following can be seen in fig. A 2.3.4.7:

A) The variations of 2 $s^{-1}$ and 1 $s^{-1}$ behave like "even feed" at a somewhat lower level. It therefore can be concluded that there is a redistribution at these frequencies because the line is straight just as it is with "even feed". The redistribution already occurs under the curtain. However, the redistribution is incomplete, since $WE(\ell)$ remains lower than at "even feed". This is possibly a consequence of another type of redistribution under the curtain.

B) The variations of 0.5, 0.3 and $0.2 \cdot s^{-1}$ show a lower *WE*(ℓ) at the front and a higher *WE*(ℓ) at the rear of the walkers. It therefore can be concluded that *WE*(ℓ) is low at the front part of the walkers because of the cylinder feed rate, so that there the redistribution is slight. At the rear of the walkers the redistribution transferring the cylinder feed rate into the feed rate is comparable to "even feed". The calculated value of *WE*(ℓ) at the end of the walkers is shown to reach the value of "even feed".

The *conclusion* to be drawn can be that there is also redistribution at the end of the walkers for variations of $0.2\ s^{-1}$ and higher so that the break-point frequency of the *assumed* first-order transfer is at $0.2\ s^{-1}$ or lower, with the result that $\underline{I}$ = 0.8 or larger for the researched type of variations.

In figure A 2.3.4.7 it also appears that the low feed rates initially have a lower *WE*(ℓ) value and also that they don't show the expected increase to the final value of *WE*. Therefore the conclusion is that the irregular part of a low feed rate cannot be corrected by redistribution.

*Sinusoidal feed rate variations*
Conclusions have been drawn from the previous research, expressed in terms of frequencies of pulse like functions. A laboratory test (Sytsma, 1981) was performed to check these conclusions with sinusoidal feed rate variations. In these tests, 3 feed rate levels were used, averaging 0.71, 1.33 and 2.07 $kg \cdot s^{-1} \cdot m^{-1}$, with varying feed rates at amplitudes of 20% and frequencies of 0.2, 0.4, 0.8 and 1.6 Hz. In addition there was a test with even feed and one with an average feed rate of 2.07 $kg \cdot s^{-1} \cdot m^{-1}$ and an amplitude of 40%. Each test was performed with winter wheat *MCS* = 15% with 4 repetitions. The speed of the horizontal conveyer and the elevator chain were both 1.2 $m \cdot s^{-1}$ in order to prevent redistribution at the elevator chain (see A 2.3.2.d).

The results showed no evident effect of the frequency on the concave separation and the total walker separation at 20% amplitude. However, the concave separation was lower at an amplitude of 40% than at 20%. Also, the walker efficiency was lower at an amplitude of 40% and a frequency of 0.2 Hz. The feed rate at "even feed" could be characterized as irregular, too. The frequencies introduced could be visually recognised from the signals of the acoustic sensors A ... E positioned as indicated in figure A 2.3.2.5. From the power-density spectra, made only for the 40% amplitude/0.4 Hz variant, it was apparent that the 0.4 Hz component could be clearly recognised as a peak at M, B and D. Acoustic sensor A didn't work, sensor C showed a peak at 0.2 Hz and at sensor E there was a peak at 0.2 Hz but at a very low level.

The conclusions to be drawn from this are that
1) There is no redistribution at the threshing cylinder.
2) On the walkers there is a redistribution at frequencies above 0.2 Hz according to the walker efficiency and in accordance with the power-density spectra. The higher frequencies are indistinguishable from "even feed", allowing the conclusion $\underline{I}$ = 0.8 to be maintained. It can be expected that a redistribution is intensified by longer walkers. This research has to be continued.

*Field research*

The course of the walker losses as a function of time has been recorded for a large number of field tests with a grain loss monitor at the end of the walkers of machine B. Special attention has been paid to be response of walker loss to a step function on straw feed rate generated by a combine harvester driving into the crop at a given desired speed.

Figure A 2.3.4.8 shows the response of the walker loss values, averaged per 0.25 s.

*Assuming* a first-order transfer on the walkers enables an estimation of $\underline{\tau}$ to be made since 63% of the level of the step function at a first-order process is reached after $\underline{\tau}$ seconds. The 63% level is indicated in the figure by a dotted line giving $\underline{\tau}$ values varying from 0.2 to 0.9 seconds and averaged as 0.6 s. In an empty machine the straw introducing the first losses at low feed rates moves faster backwards under the curtain than a big straw mass in a continuous process. Therefore it is better to derive the $\tau$ for a continuous process from recordings of high losses (high straw feed rates). It is indeed remarkable in the figures that the higher losses are accompanied by the highest time constants 0.6, 0.8 and 0.9. It *would appear* to be justified to prefer the value $\underline{\tau}$ = 0.8.

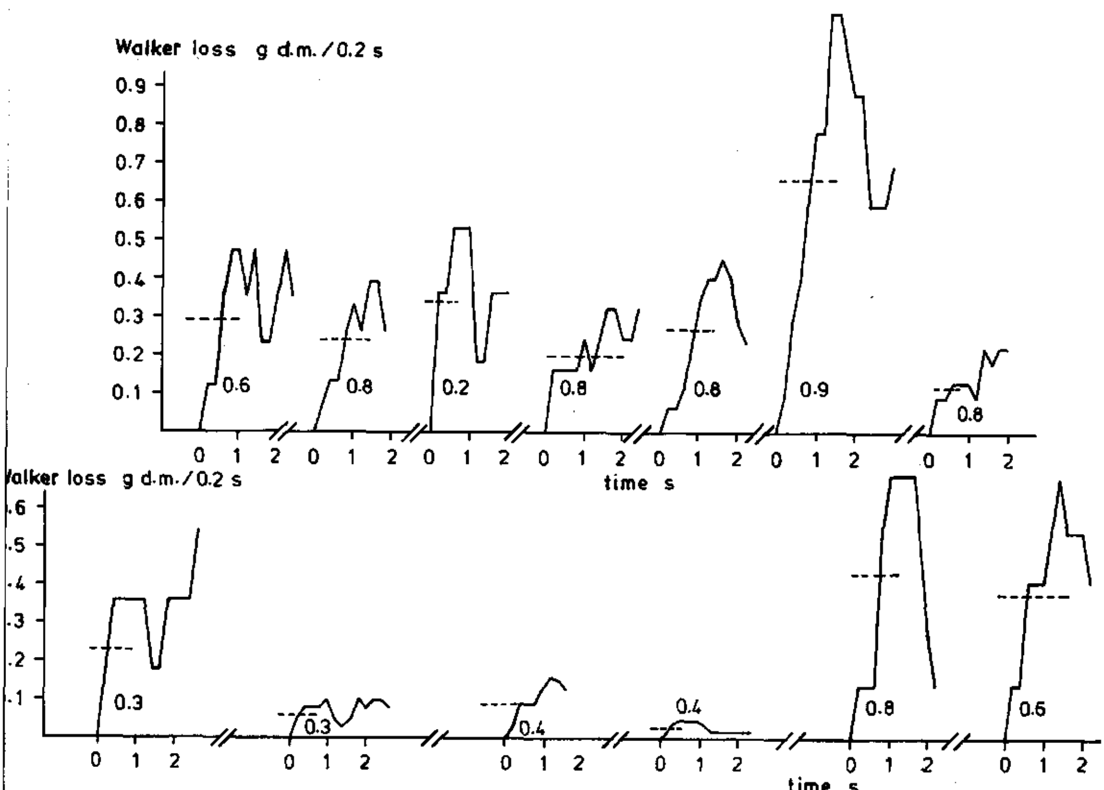



Figure A 2.3.4.8. Walker loss response to straw feed rate step function

A 2.3.4.d *Time delay on walkers*
The straw almost or completely comes to a standstill under the baffle curtain at the front of the walkers. Hence the total delay on the walkers cannot be estimated from the speed of the straw. An accurate estimate is desired, since total delay in the process is a very important determining factor for control. During three years of field research the time that a coloured wad of straw is transported through the combine harvester was traced with machine A.

It was calculated that the delay of straw from the middle of the cutter bar of the machine to the end of the walkers varies between 7 and 13 seconds (Wevers, 1972). The average was 9.75 s over three years. With the same measurement method an average of 7.1 s was later found for machine B.
A disadvantage of this method is that the wad does not behave like loose material. Average values of 7.3 and 10 s for machines A and B, respectively, have been found by means of cross-correlations between the signals of the loss monitor and the auger torque. The last-mentioned measurement results will be used to calculate the delay, because they are the most accurate ones (see paragraph 4). Incidentally, in the case of machine A 7 observations were involved, varying between 8 and 11.8 s. This variation can also be found in the other observations and is presumably due to material standstill under the curtain and variations in speed of the material on the walkers, especially at the sides of the machine.

The delay from the auger to the threshing cylinder is 1.0 s for machine A and to the rotary separator of machine B 1.1 s. The first-order process on the walkers also gives a phase shift representing a time delay of about 0.7 s for the low frequencies. The delay to be applied at the walkers will be therefore 10.0 - (1.1 + 0.7) = 8.2 s.
Although systematic causes for the deviations could not be ascertained, the impression nevertheless exists that crop conditions, feed rate levels and slopes certainly have an impact on this delay.

A 2.4.3. *Dimensions threshing cylinder vari-drive*
The existing vari-drive sizes are indicated in fig. A 2.4.1. The maximum displacement D of the driving variator discs can be derived from

$$dR_{max} = R_{max,eff} - R_{min,eff} = 0.2135 - 0.1225 = 0.091 \text{ m}$$

$$\underline{\beta} = 26^0 \text{ so } \tfrac{1}{2}\underline{\beta} = 13^0 \qquad \text{(a 2.8)}$$

$$x = dR_{max} \cdot \text{tg}\tfrac{1}{2} \qquad \text{(a 2.9)}$$

$$D = 2x = 2 \cdot 0.091 \cdot \text{tg } 13^0 = 0.042 \text{ m} \qquad \text{(a 2.10)}$$

A change in the working radius $dR$ follows from the displacement $dD$.

$$dR = \frac{dD}{2.\tan\frac{1}{2}} = \frac{dD}{0.462} \qquad \text{(a 2.11)}$$

so that the working radius of the driving disc is

$$R_{in} = 0.1225 + \frac{D}{0.462} \text{ when } D \text{ goes from 0 to 0.42 m.} \qquad \text{(a 2.12)}$$

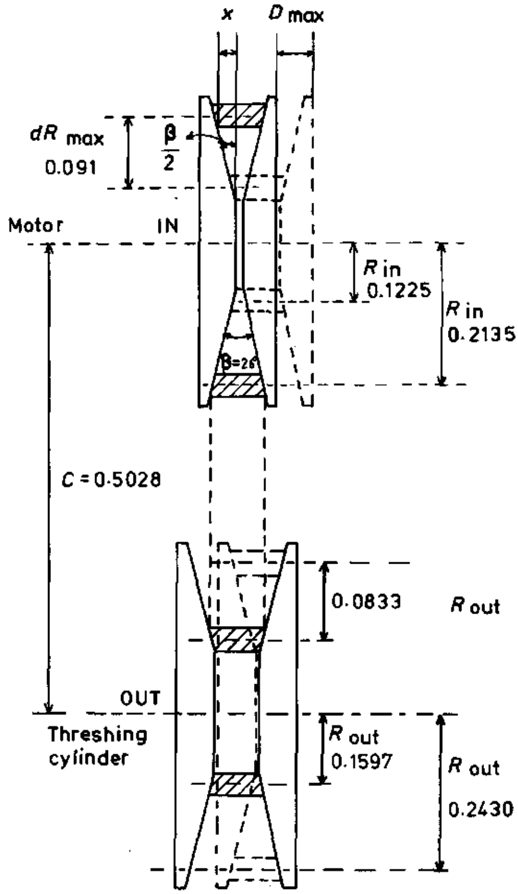



Figure A 2.4.1. Threshing cylinder vari-drive. Dimensions and symbols

The radius of the driven disc can be derived as will be explained below, from

$$R_{out} = R_{in} - \frac{\pi}{2} C + \sqrt{(\frac{\pi^2}{4} - 2) \cdot C^2 + C \cdot L - 2\pi \cdot C \cdot R_{in}} \qquad \text{(a 2.13)}$$

so for $C = 0.5028$
and $L = 2.184$ (the length of the V-belt) we get equation (a 2.14)

Though the manufacturer stated that $L = 2.155$ m, the belt was presumably larger because of elasticity. The value of $L$ used in the equation, is calculated from the average of the extreme positions of the variator discs, indicated in the drawing.

$$R_{out} = R_{in} - 0.7898 + \sqrt{1.216 - 3.159 \cdot R_{in}} \qquad \text{(a 2.14)}$$

$$RT = \frac{R_{in}}{R_{out}} = f\ (D) \qquad \text{(a 2.15)}$$

At $D = 0 \rightarrow R_{in}=0.1225 \rightarrow R_{out}=0.243 \rightarrow RT=0.504$

$D = 0.042 \rightarrow R_{in}=0.2134 \rightarrow R_{out}=0.1597 \rightarrow RT=1.34$

*Derivation V-belt length*

For open, flat belt drives the belt length (see figure A 2.4.2) is accounted for by

$$L = 2 \cdot C \cdot \cos \gamma + \pi(R_1+R_2) + 2\gamma(R_1-R_2) \qquad \text{(a 2.16)}$$

namely BD+AG+EF+AB+(DE+GF)

A more accurate approach is that given in the technical manuals (e.g. Roloff, 1972) in which

$$L = 2 \cdot C + \pi(R_1+R_2) + \gamma(R_1-R_2) \qquad \text{(a 2.17)}$$

namely BS+AT+(EF+AB)+½DE+½GF

For small angles yields

$$\gamma \approx \text{tg } \gamma \approx \frac{R_1 - R_2}{C} \qquad \text{(a 2.18)}$$

and in the figure it is

$$\text{tg } \gamma \approx \frac{R_1 - R_2}{C}$$

Hence $L = 2C + \pi \cdot (R_1 + R_2) + \frac{(R_1 - R_2)^2}{C}$ (a 2.19)

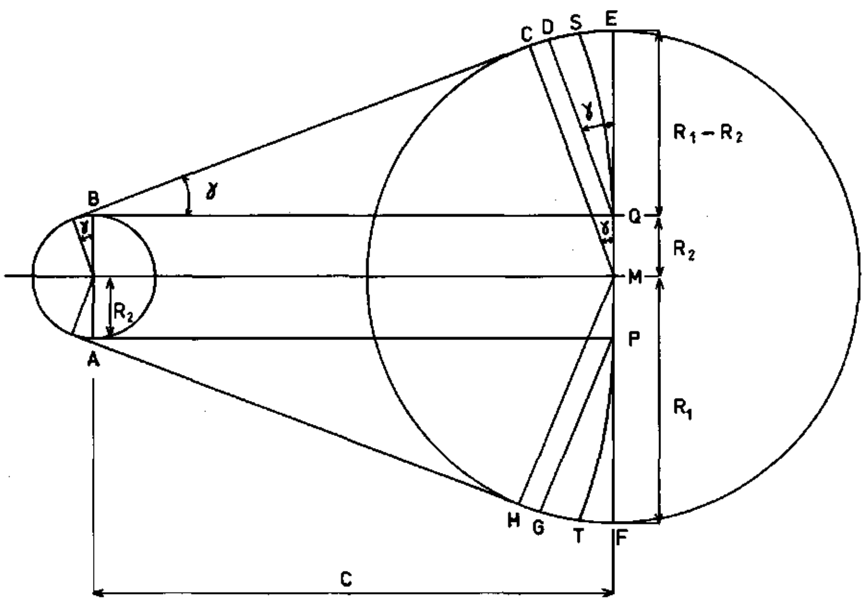



Figure A 2.4.2. Sketch for the calculation of belt length related to the dimensions

Since a relation is needed in which $R_1 = f\ (R_2,\dots.)$, the formula is transformed to read as

$$C{\cdot}L = 2\ C^2 + \pi{\cdot}C{\cdot}R_1 + \pi{\cdot}C{\cdot}R_2 + R_1{}^2 - 2R_1R_2 + R_2{}^2 \qquad \text{(a 2.20)}$$

or

$$C{\cdot}L = R_1{}^2 - 2R_1R_2 + R_2{}^2 + \pi{\cdot}C{\cdot}R_1 - \pi\ C{\cdot}R_2 + \frac{\pi^2}{4}{\cdot}C^2$$

$$C{\cdot}L = \frac{\pi^2}{4}{\cdot}c^2 - 2\pi\ C{\cdot}R^2 - 2C^2 + C{\cdot}L \qquad \text{(a 2.21)}$$

$$C{\cdot}L = (R_1 - R_2 + \frac{\pi}{2}\ C)^2 = (\frac{\pi}{4} - 2)\ C^2 + CL - 2\ \pi CR_2 \qquad \text{(a 2.22)}$$

or, finally, as

$$R_1 = R_2 - \frac{\pi}{2}\,C + \sqrt{(\frac{\pi^2}{4} - 2)C^2 + C{\cdot}L - 2\pi{\cdot}C{\cdot}R_2} \qquad \text{(a 2.23)}$$

When $R$ and $L$ are replaced by $R_e$ and $L_e$ (e stands for effective) then this formula can be *approximatively* applied to V-belts.

A 3.1.1. *Auger torque and elevator chain displacement as feed rate sensor*
During field measurements with machine A the auger torque and the displacement of the elevator chain have been measured and related to the straw collected behind the machine on a sheet after an estimated time delay. This time delay has been estimated as indicated in A 2.3.4-d. The results of these measurements can be found in the figures A 3.1.1.1 ... A 3.1.1.9. Both parameters are collated per measuring year to make it easier to ascertain comparable tendencies. The elevator chain displacement has always been measured by means of an inductive linear displacement to voltage transducer (Bergman, 1976).

From 1969 ... 1971 the auger torque has been measured by means of strain gauges mounted on the driving axle and since 1972 it has been measured by means of a special transducer, as shown in figure A 3.1.1.10, which recorded the driving force in the drive chain. This transducer has been designed especially for this research, but is unsuitable for protracted measurements, as the pivoting point does not rotate enough, dust and moisture causing jamming when the point is not cleaned frequently enough.

Up till 1972 the straw was collected on a sheet consisting of 5 separate parts, and 30 metres in total length. Collecting started after 20 m harvesting. The material on the sheets has also been used to determine the walker loss. After 1972 the straw was collected on a sheet 15 m in length while the machine entered the crop.

A 3.1.3. *Auger torque to elevator displacement relation*
In 1973 the measuring signals of the auger torque and of the elevator displacement were recorded from 14 tests with machine A on winter wheat and spring wheat. The length of the stretch was 240 m, resulting in a recording time of about 200 s. Both signals were filtered first with a low-pass fil-

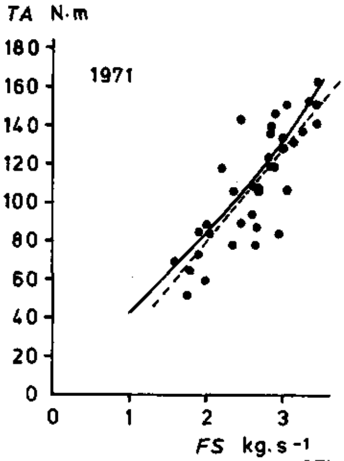



Figure A 3.1.1.1. Auger torque to straw feed rate relationship in field tests of 30-m stretches with winter wheat (Manella) in 1971 $MCS$ = 11.5-28.2% (----): linear equation: $TA$ = - 16.6 + 48.1•$FS$ (r = 0.82) (——): quadratic equation: $TA$ = 13.5 + 23.4•$FS$+5.53•$(FS)^2$ (r=0.82)

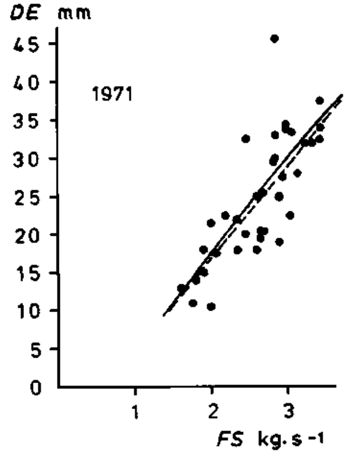



Figure A 3.1.1.2. Displacement elevator to straw feed rate relationship in the same field tests as in figure A 3.1.1.1 (—)$DE$ = -7.7+12.1•$FS$(r=0.78); (---)$DE$ = -11.1+15.2•$FS$-0.56•$(FS)^2$ (r=0.78)

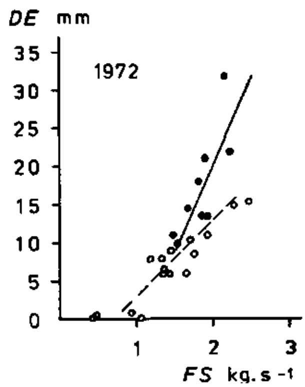



Figure A 3.1.1.4. Relationship of displacement elevator to straw feed rate in same field tests as in figu A 3.1.1.3: winter wheat: (——)$FS$ = 0.041 • $DE$+1.16 (r=0.73) spring whea (----)$FS$ = 0.097$DE$+0.74(r=0.86)

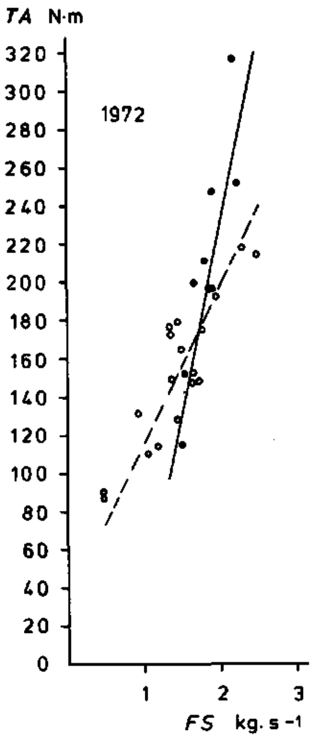



Figure A 3.1.1.3. Auger torque to straw feed rate relationship of field tests in 30-m stretches (drawn points) with winter wheat (Manella) (•); $MCS$ = 21.3-36.3% and spring wheat (Solo) ($o$); $MCS$ = 20.7-55.8% (data of 5-m stretches); (——)winter wheat: $FS$ = 0.0050$TA$+0.83(r=0.79); (------)spring wheat: $FS$ = 0.012$TA$ - 0.39 (r=0.86)

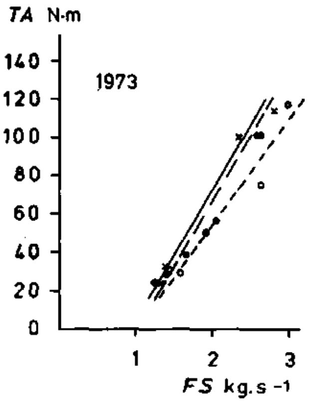



Figure A 3.1.1.5. Auger torque to straw feed rate relationship in field tests of 15-m stretches with winter wheat (Manella) early in the season (•) *MCS* = 22.3-27.3% (— —) *FS*=1.03+0.0146· *TA* (r=0.98) and late (×) *MCS* =12.3% (——) *FS* =0.93+0.0147*TA* (r=0.98) and spring wheat (Fundus) (o): *MCS* =23.5% (-----) *FS* =0.99+0.0184*TA* (r=0.97)

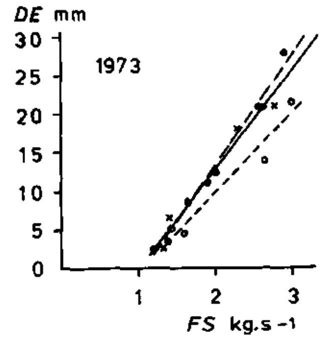



Figure 3.1.1.6. Relationship of displacement elevator to straw feed rate in same field tests as in figure A 3.1.1.5
(— —) *FS*=1.11+0.069*DE* (r=0.99)
(——) *FS*=1.01+0.078*DE* (r=0.98)
(-----) *FS*=1.08+0.096*DE* (r=0.96)

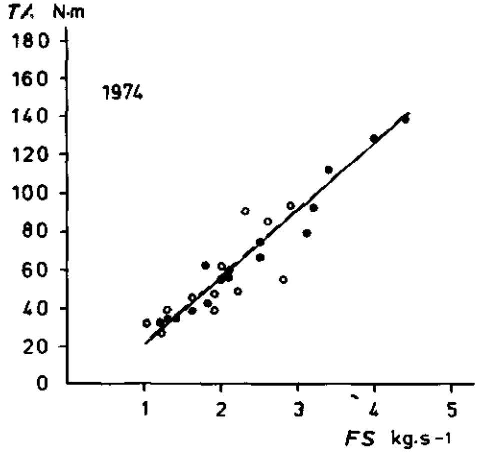



Figure 3.1.1.7. Relationship of auger torque to straw feed rate in 15-m-stretch with winter wheat (Clement) (•) *MCS*=56.3-57.7%, (——) *FS*=0.426+0.0287· *TA* (r=0.98) and spring wheat (Fundus) (o), *MCS* =31.8=42.2% (---) *FS* =0.394+ 0.0283*TA* (r=0.94)

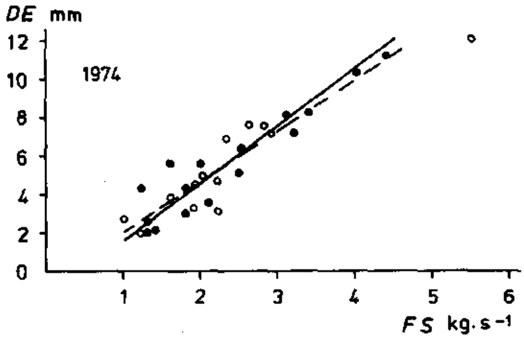



Figure A 3.1.1.8. Relationship of displacement elevator to straw feed rate in same field tests as in figure A 3.1.1.8
(——) (•) *FS*=0.480+0.335 *DE* (r=0.93)
(-----) (o) *FS*=0.236+0.379 *DE* (r=0.94)

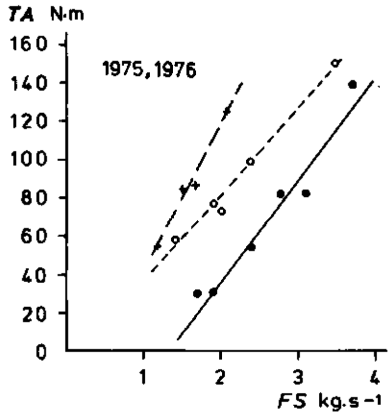



Figure A 3.1.1.9. Relationship of auger torque to straw feed rate; field tests over stretches of 15 m with oats (1975, Astor) (+). *MCS*=58% (--); *FS*=0.491+0.0129• *TA* (r=0.98), spring wheat (1975, Fundus) (o); *MCS* =23% (-----) *FS*=0.229+0.0221• *TA* (r=0.99) and winter wheat (1976, Clement) (•); *MCS*=17.8-18.5; (——) *FS* =1.35+0.0186 *TA* (r=0.97)

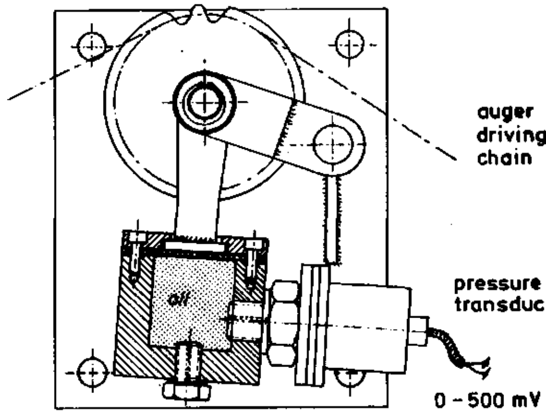



Figure A 3.1.1.10. Torque sensor mea ring the tension in the auger drivin chain.

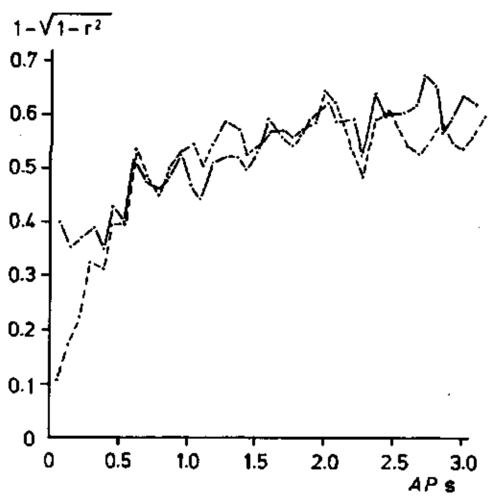


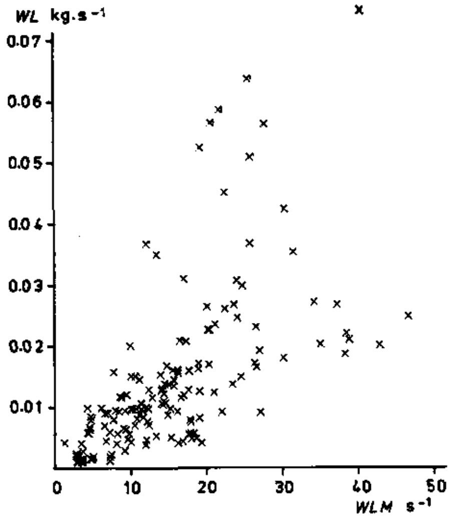

Figure A 3.1.3.1. The value representing the part of the auger torque variation that is explained by the elevator displacement: $1 - \sqrt{1-r^2}$ as a function of the period *AP* over which the signal is averaged for two different tests of about 200 s ter having a break-point frequency of 12.5 $rad \cdot s^{-1}$ and afterwards sampled at a sampling interval of 0.08 s. By shifting the data of both signals and carrying out cross-correlations, the time lag can be determined for each measured stretch. The data of both signals of two tests were then averaged over a period of $AP$ and, the correlation $r$ was determined, the lag being taken into consideration.

In figure A 3.1.3.1 the value of $1 - \sqrt{1 - r^2}$ has been plotted as a function of $AP$. This value represents the part of the auger torque signal explained by the displacement signal.

In addition, the correlation has been calculated for each test at $AP = 2$ for a linear relation $DE = a + b \cdot TA$ and for an exponential relation $DE = a \cdot \exp(b \cdot TA)$. Table A 3.1.3.1 shows the results. Sometimes the relation is rather good, sometimes poor. Both signals seem to include considerable measuring noise.

Table A 3.1.3.1. Coefficients of correlation between elevator displacement and auger torque for averaging periods of 2 s
ww = winter wheat, sw = spring wheat, lin = linear relation, exp = exponential relation, $DE = a \cdot \exp(b \cdot TA)$

| trial | crop | lin | exp |
|---|---|---|---|
| 1 | ww | 0.64 | 0.63 |
| 2 | ww | 0.93 | 0.93 |
| 3 | ww | 0.82 | 0.80 |
| 4 | ww | 0.86 | 0.85 |
| 5 | ww | 0.80 | 0.80 |
| 6 | ww | 0.65 | 0.63 |
| 7 | ww | 0.67 | 0.62 |
| 8 | ww | 0.93 | 0.93 |
| 9 | ww | 0.87 | 0.88 |
| 10 | ww | 0.90 | 0.88 |
| 11 | sw | 0.74 | 0.70 |
| 12 | sw | 0.88 | 0.87 |
| 13 | ww | 0.53 | 0.51 |
| 14 | ww | 0.92 | 0.93 |



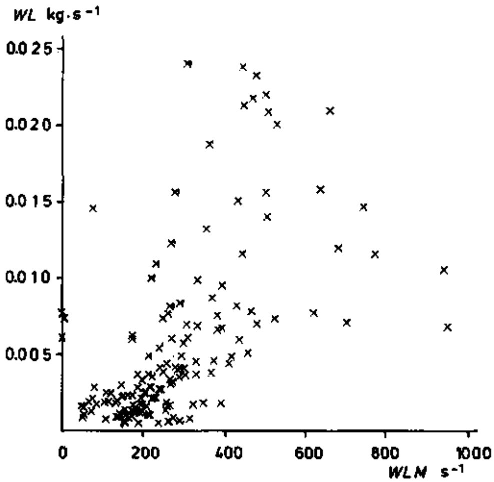
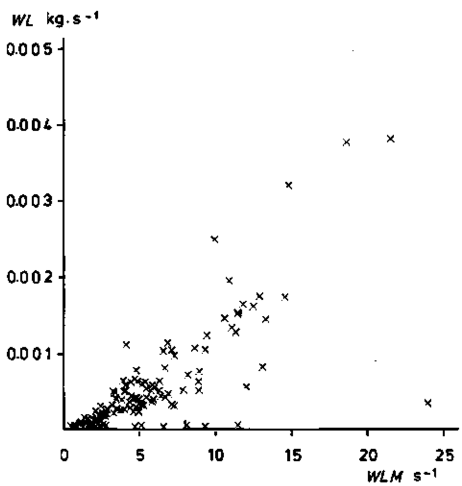




Figure A 3.3.1.1. Relation between measured walker loss by rethreshing of straw, gathered by 6-m sheets. (*WL*) and by counting the number of pulses from the grain loss monitor over the same stretches (*WLM*) Tests in 1972

Figure A 3.3.1.2. Same as figure A 3.3.1.1 for tests during 1973



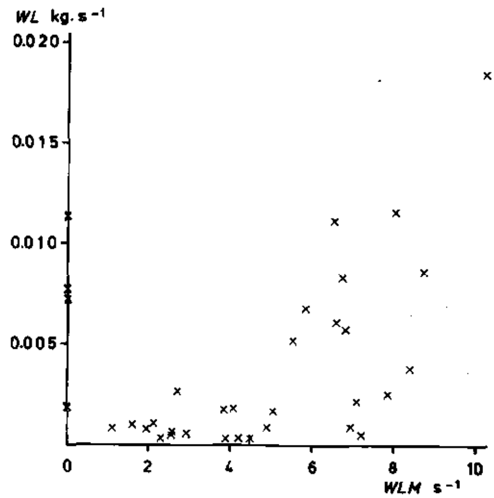




Figure A 3.3.1.3. Relation between measured walker loss by grain loss measuring machine (*WL*) and by counting the number of pulses from the grain loss monitor (*WLM*) over the same stretches of 30-m in length. Tests in 1975

Figure A 3.3.1.4. Same as figure A 3.3.1.3 for the 1976 tests

### A 3.3.1. *Grain-loss monitor*

*Results from literature*
In literature two kinds of test results are reported. Investigators who tested the monitor over a short period, or in a crop, or period with constant crop properties, report on linear relations until pulse saturation occurs. They report also on coëfficients of variation smaller than 10% (Bouman, 1971; Eimer, 1973; Kühn, 1970; Maler, 1974 and Reed, 1968).

The results become worse, especially as regards the variation when tests were done over a longer period with changes in the crop conditions (Anonymus, 1973; Graeber, 1975; Glaser, 1976 and Gullacher, 1979). The reason is the variation in walker separation efficiency over the considered period, which also affects the separation efficiency above the sounding-board of the monitors. Some monitors therefore have a switch for selecting sensitivity. However, there is no point to this since the extent to which the sensitivity has to be altered is not known.

*Results of field tests*
The field-test methods for the years 1971 ... 1973 are explained shortly in A 3.1.2 and, for the years 1974 ... 1976 in A 2.2.2.c. In all these years the added output (pulses) of two grain-loss monitors fixed at two different elements of the walkers was compared to the measured walker loss. In the period 1971 ... 1973 the walker loss of straw was gathered on sheets 6 m in length and measured by rethreshing the content of these sheets in a stationary threshing and separating machine. In the years 1974 ... 1976 the straw and grain from walkers was reshaken in a mobile machine connected to the combine harvester. In this machine the loss over a travelled distance of 4 times 30 metres was gathered (see fig. A 2.3.2.8).

In figures A 3.3.1.1 ... A 3.3.1.4 the data are plotted of walker loss in $kg \cdot s^{-1}$ as a function of the monitor output in pulses per second. The figures for 1971 and 1974 are shown in 3.3.1. The measurements in all these years were done in several crops, winter wheat, spring wheat and oats under a wide range of circumstances, which is the reason for the amount of scatter in the results.

### A 3.3.2. *Principle of an improved loss monitor system*
Figure 3.3.2.1 of 3.3.2 shows the basic idea of improved loss measurement by measuring the separation underneath the walkers. To verify this principle, data of laboratory tests as introduced in A 2.3.2.b were used to calculate loss, based on the walker separation. The separated grain was collected in trays underneath the walkers (Donkersgoed, 1980). The separation was *assumed* to be exponential, starting at tray 5, so that the content of tray 5 was used for the calculation and tray 8 was chosen to be the second, because it is nearest to where the loss occurs. The separation above tray 5 during the test period of 10 s was called $S5$ $kg \cdot m^{-1}$, this being the content of the tray in kg divided by the length of the tray in m. $S8$ was defined in the same way.
The distance $d$ between the centre points of the trays was 1.38 m, the length of tray 5 and tray 8 was 0.48 m and 0.35 m, respectively. As was shown in 3.3.2,

$$S_W = - WE \cdot G_O \cdot \exp(- WE \cdot x) \qquad \text{(a 3.1)}$$

where $S_W$ = the separation of grain at $x$ $kg \cdot s^{-1} \cdot m^{-1}$, $x$ = the distance from the beginning of the correct exponential process m, $WE$ = walker efficiency $m^{-1}$, $G_o$ = amount of grain at the start of the correct separation process. $S_w$ is negative, because it concerns the decrease of grain on the walkers being the grain collected in the tray. For $S5$ $x$ = o, so that $S5 = WE \cdot G_o$ kg·m$^{-1}$ for the test period of 10 s. For $S8$ we have

$$S8 = S5 \cdot \exp(WE \cdot 1.38), \text{ so that } WE = \ln(S8/S5)/1.38 \text{ and}$$
$$G_o = S5 \cdot 1.38/\ln(S8/S5)$$

With known $WE$ and $G_o$ the walker loss $G_\ell$ can be calculated from

$$G_\ell = G_o \cdot \exp(-WE \cdot x) \text{ kg for } x = 1.38 + \tfrac{1}{2} \cdot 0.35 \text{ m}$$

The results of this calculation are shown in figure A 3.3.2.1. Four kinds of crops: oats, wheat 1, 2, 3 (see A 2.3.2.b) are used at different feed rates. $WLM$ represents the measured loss and $WLC$ the calculated loss for a period of 10 s. The full line in the figure represents the relation $WLM = WLC$, while the dotted line is estimated by linear regression, giving

$$WLM = -0.034 + 1.00 \cdot WLC \quad (r = 0.95)$$

We see that the low losses are overestimated and the high losses underestimated, but the principle works. Possibly the position of the trays is not optimal.

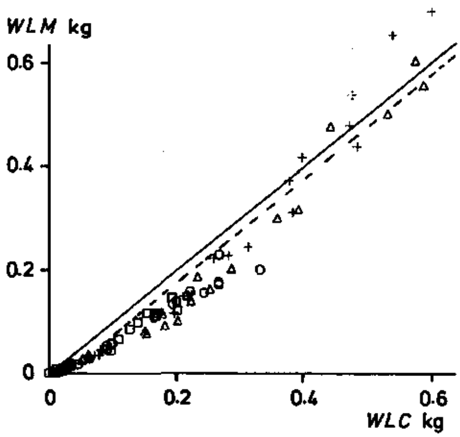



Figure A 3.3.2.1. Walker loss measured in the laboratory test rig ($WLM$) related to walker loss calculated on basis of the contents of tray 5 and tray 8 ($WLC$). The crops were oats (□) and winter wheat, treated in three ways: o=wheat 1, just stored so that $MCS$=15%. Δ =wheat 2, stored and slightly moistened so that $MCS$=30%; + = wheat 3, stored and considerably moistened so that $MCS$=45%.
The lines represent: (——) $WLM$=$WLC$ and (-----) $WLM$=-0.034+1.00·$WLC$ calculated by linear regression (r=0.95)

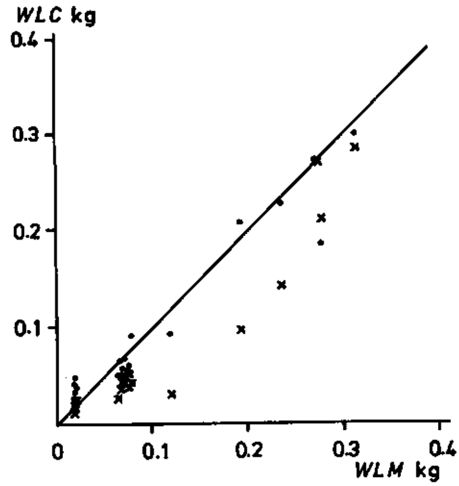



Fig. A 3.3.2.2. Calculated loss ($WLC$) related to measured loss ($WLM$); (×) in the case that the contents of tray 5 and 8 are combined; (•) in the case that trays 5 and 6 are combined, line (——) is for $WLC$ = $WLM$

Glaser (1976) found a linear relation with $r = 0.99$ for the same kind of tests with a shaking conveyer instead of straw walkers.

In other tests (Sterren, 1983), monitors were fitted above trays 5, 7 and 8 (see A 2.3.4.c and figure A 2.3.2.5) and the measured monitor output was used for calculation of loss. In this case monitor calibration is necessary. This is done by comparing each monitor output to the separation given in the separation curve calculated with the content of the trays. The monitor outputs showed pulse saturation, so that an exponential relation was used for the calibration. Losses were then calculated for the three possible pairs of monitors in the same way as already indicated.

The results again showed an overestimation of the low losses. The best results were obtained by combining the monitors above trays 5 and 6 as well as 5 and 8 (see figure A 3.3.2.2). Measuring faults of 40% however still occur. Further research, especially in field studies, is necessary.

A 4.2.1.a *Disturbances in crop density*

Variations in crop density have been measured in field experiments and studied in literature. The crop density is defined as the amount of crop (kg) to be split up into grain and straw (also called: material other than grain) per area ($m^2$). The area considered differs and as this could affect the results, the subject will be treated systematically on the basis of increasing area.

Plots of 0.5 $m^2$, being two rows of winter wheat 1 metre in length were cut on both sides of a 30-m strip harvested by a combine harvester (Hijma, 1970). In each strip, 6 plots at the left-hand side and 6 at the right were selected at random and cut by hand just 0.05 m above the earth. The mean yield of 120 plots was: 0.507 $kg \cdot m^{-2}$ straw (dry matter) and 0.478 $kg \cdot m^{-2}$ grain (dry matter). Straw length was 77 cm and the mean number of ears per $m^2$ was 192. Table A 4.2.1.1 gives the coëfficients of variation of the 12 plots per strip.

Table A 4.2.1.1. Coefficients of variation (*CV* %) of crop measurements of 12 plots of 0.5 $m^2$ at both sides of a strip harvested by a combine harvester

| | YIELD | | | grain | number |
|---|---|---|---|---|---|
| strip | grain | straw | grain + straw | to straw ratio | of ears |
| 1 | 16.6 | 15.2 | 13.7 | 8.2 | 11.7 |
| 2 | 10.8 | 9.1 | 9.6 | 5.0 | 11.7 |
| 3 | 17.0 | 22.6 | 19.0 | 11.5 | 17.9 |
| 4 | 9.1 | 9.2 | 8.7 | 5.5 | 7.0 |
| 5 | 14.3 | 15.4 | 12.4 | 8.6 | 13.1 |
| 6 | 9.7 | 11.7 | 10.4 | 5.9 | 11.8 |
| 7 | 16.1 | 16.7 | 15.7 | 5.9 | 15.4 |
| 8 | 10.5 | 9.9 | 9.2 | 8.8 | 14.0 |
| 9 | 9.2 | 11.1 | 9.7 | 5.9 | 9.7 |
| 10 | 11.1 | 14.7 | 12.8 | 6.4 | 15.0 |
| mean *CV* | 13.0 | 16.0 | 7.6 | 7.2 | 12.7 |

The calculated coëfficients vary considerably. The mean values of the estimated coëfficients show the highest value for the straw yield and a relatively low value for the grain-to-straw ratio. The yields of the left and the right-hand sides of the strip showed no coherence, and neighbouring plots showed great differences in yield though the soil seemed uniform. It was therefore concluded that in short distances the yields show little or no coherence.

Eimer (1973) measured crop densities of plots 6 rows-wide and 0.6-m-long (0.6-0.72 $m^2$). In standing, weedless crop he registered coëfficients of variation in yields of grain and straw: in rye 7.5% in winter wheat 9%, in spring barley 14.5% and in oats 18.2%.

In lodging crop with weeds he found in rye: 15.6%, in wheat 14.6% and in oats 19.6%. A greater variation in straw yield than in grain yield can be concluded from the diagrams in this publication.

Feiffer (1964) published similar results. For winter wheat he registered a variation of 21.4% and in spring wheat,figures between 8% and 64%. He propably calculated the values of the difference between minimum and maximum yields expressed as a percentage of the mean yield. He also shows the variation in crop yield for fields of 3-m-wide and 1-m-long in a sequence up to an area of 3 m by 15 m. He found the greatest variation for intervals of 0.66 m and lower variation for larger intervals.

Heinrich (1968) measured coëfficients of variation of 40 plots measuring 0.5 m by 1.0 m lying adjacent to each other in a direction parallel to the seeded rows as well as perpendicular to the direction for wheat and rye. The mean value was 10% in both cases.

Larger fields, with a width comparable to the cutting width of a combine harvester, were tested to decide on the variation in mass that the machine will usually enter. Some authors expect lower coëfficients of variation because of the effect of taking the mean over a larger area. However, as the variation in the x- and y- directions is the same, this effect will not occur.

Feiffer (1964) indeed registered the same variation in fields measuring 1 m by 3 m.

Eimer (1973) measured the yield of plots 1-m-wide and 0.6-m-long, three next to each other, over the length of 1 m. The yield of the left and right plots deviated 3% of that of the central plot.

Own research (Huisman, 1973) on fields 5-m-wide and 1.5-m-long in a direction parallel to the drainage tubes and perpendicular to that direction showed coëfficients of variation for straw yields of 10.3% and 10.2% respectively and for grain yields 5.2 and 6.7%, respectively. The mean straw yields were 0.56 and 0.76 $kg \cdot m^{-2}$ and the grain yields 0.55 and 0.63 $kg \cdot m^{-2}$, respectively. Fig. 4.2.1 shows the pattern of these yields.

In field tests in which the straw mass out of the combine harvester was gathered on sheets and weighed, the coëfficient of variation of the yields of 5 m x 5 m fields of spring wheat turned out to be 15.9% (of 102 measurements). When the same yield figures are taken, but put together by the 6 sheets forming one single run, the coëfficient of variation becomes 23.1% (Huisman, 1974-b). In 1970 the coëfficients of variation of areas of 154 $m^2$ comprising the same 10 runs mentioned in Table A 4.2.1.1 were found to be 14.3% for the straw yield (plots of 0.5 $m^2$ showed 16.0%) and for the grain yield 3.9% (compare 13.0%) (Klein Hesselink, 1971).

Bogdanova (1960) reports on coëfficients of variation in yields of 50-m runs varying from 7% to 40%.

On the basis of all these results it was concluded that there is no reason to expect a difference in the variation in relation to the area considered. The measured values are estimates of variations that can in fact differ owing to variations in soil and crop properties.

A 4.2.1.b *Disturbances in measured straw feed rate and loss signals*
The measured signals of a number of runs in the field were analysed by means of standard Fast Fourier transform techniques. Without going into detail some of the results will be presented here. The coherence between feed rate signal and loss signal will be studied too, which makes it useful to present the results of feed rate and loss together. Two kinds of data were used

A) Data of mean values of the auger torque signal and grain loss monitor per 0.25-m stretch (≈ 0.25 s at machine speeds of ≈ 1 $m\cdot s^{-1}$). In this case 750 samples were available per run. To these data zeros were added until 1024 data were available.
B) Data of mean values of these signals per period of 0.05 s. In this case 3600 samples were available and zeros were added until 4096 samples were available.

Before zeros were added some corrections were applied. First the mean value and trend were calculated and the data corrected accordingly. Then a taper was applied over 10% of the data at each end and the standard deviation calculated for standardisation. For the plots a Barlett window of 10% of the data was applied. The values used were calculated to unit of feed rate and loss in $kg\cdot s^{-1}$. The data of B were only used for fig. 4.2.3 in the text.

In the figures next in sequence results are shown of run 41, comprising 750 samples of 0.25-m means. Fig. A 4.2.1.1 shows the probability-density function around the mean value. The mean value and standard deviation for the feed rate were 2.25 and 0.0241 $kg\cdot s^{-1}$ respectively, and for loss 0.00844 and 0.0241 $kg\cdot s^{-1}$ respectively. As can be seen, the feed rate

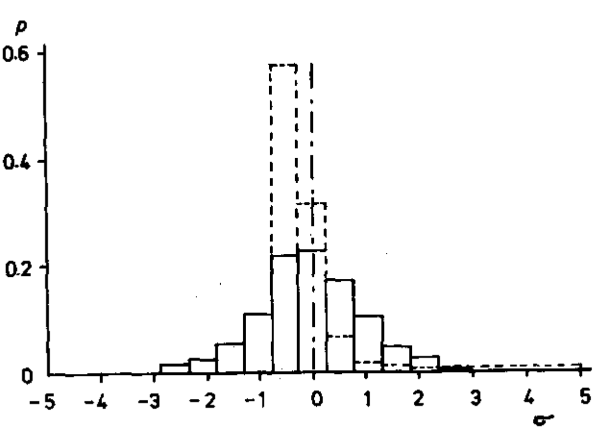



Figure A 4.2.1.1. Probability density (p) function of measured walker loss (-----) and straw feed rate (———) for test run 41 distribution is practically a Gaussian one. The distribution of loss is skew, as could be expected from the exponential relation between feed rate and loss. Other tests show the same pattern.

Fig. A 4.2.1.2 shows the standardised autospectra in linear scale and fig. A 4.2.1.3 does so in double logarithmic scale. The machine speed of this test was constantly 0.84 $m{\cdot}s^{-1}$ so that the scale could be converted to correct frequencies. The peak at 3.15 $rad{\cdot}s^{-1}$ in feed rate is due to the rotational speed of the auger. The power is decreasing with increasing frequency. Above 6 $rad{\cdot}s^{-1}$ the drop is not caused by the averaging per 0.25-m stretch(or 0.3 s in this case) as fig. 4.2.3, with data average over 0.05 s, shows the same pattern, but is caused by the first-order noise character. It is not clear where exactly the breakpoint frequency of the decrease of power lies, possibly a frequency smaller than 0.1 $rad{\cdot}s^{-1}$. In figure 4.2.3 the peaks due to the penetration of the auger fingers are very clear, just as is the peak at the loss lines, owing to the rotational frequency of the walkers. This is because of the extra dropping of seeds on to the sensor boards when the walker moves upwards again.

In the plots now given below the coherence between loss and feed rate of an other test run (52) will be shown. The mean level of the feed rate of this test is 3.07 $kg{\cdot}s^{-1}$ and the standard deviation 0.516 $kg{\cdot}s^{-1}$. The values for the walker loss are 0.027 and $0.19{\cdot}10^{-4}$ $kg{\cdot}s^{-1}$. The average machine speed is 1.02 $m{\cdot}s^{-1}$. Fig. A 4.2.1.4 shows the probability density function and fig. A 4.2.1.5 the autospectra at linear scale. These figures show the same pattern as the others.

The delay between feed rate and walker loss was estimated by means of a phase spectrum. Fig. A 4.2.1.6 shows the phase spectrum calculated after a delay of 9.5 s was applied. (Barlett window 10%) When coherence is good the phase can be calculated correctly. It can be concluded from this phase spectrum (and others) that only a delay occurs.

Fig. A 4.2.1.7 shows the coherence spectrum for three different Barlett windows applied. Other spectra show the same pattern. There is poor coherence in general while the best coherence is mostly found at the low frequencies. This proves that there is a causality between feed rate and loss.

Fig. A 4.2.1.8 shows the cross and autocorrelation functions of loss and feed rate. The autocovariancies decrease very rapidly, so that there is less predictional information in these signals, as can be concluded from the value of $1/e = 0.37$ that is found at a lag of 0.36 s for the feed rate and at 0.21 s for the losses. The cross covariance is always low but is just above the noise level. In this figure it can be seen that the delay was estimated correctly.

The general conclusions to be drawn from this short signal analysis are:
- the signal-noise ratio is low, especially at the loss signal;
- the transform is nonlinear as can be shown in the plots;
- more research has to be done to find the reasons for the poor signal-noise ratio and to explore in detail the coherence of these two signals.

From former tests it is known that the displacement elevator chain shows the same pattern in an autospectrum as the auger torque does. However, it will be worth while studying the coherence of the displacement signal to the loss signal in future too.

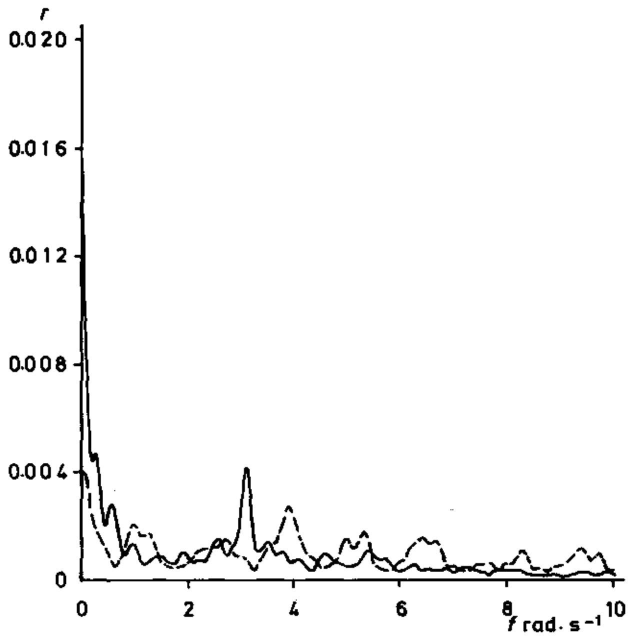



Figure A 4.2.1.2. Autospectra of walker loss (----) and straw feed rate (———) of the same data as figure A 4.2.1.1 (in linear scale)

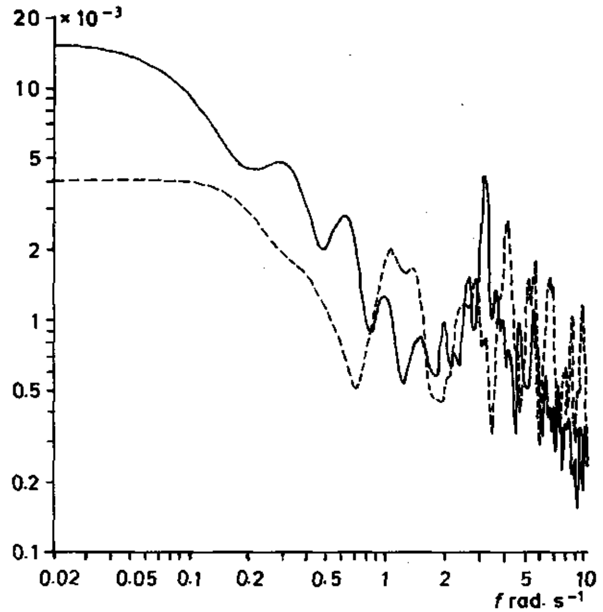



Figure A 4.2.1.3. Autospectra of measured walker loss (-----) and straw feed rate (———) of the same data as figure A 4.2.1.1 and figure A 4.2.1.2, but plotted in double logarithmic scale

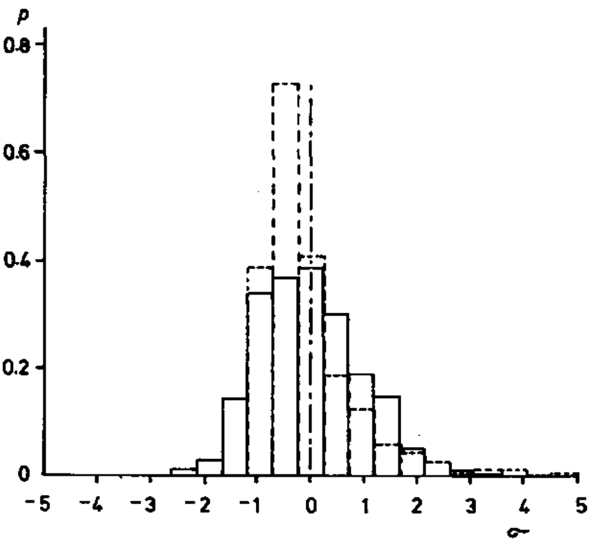



Figure A 4.2.1.4. Probability density function of measured walker loss (------) and feed rate (————) for test run 52

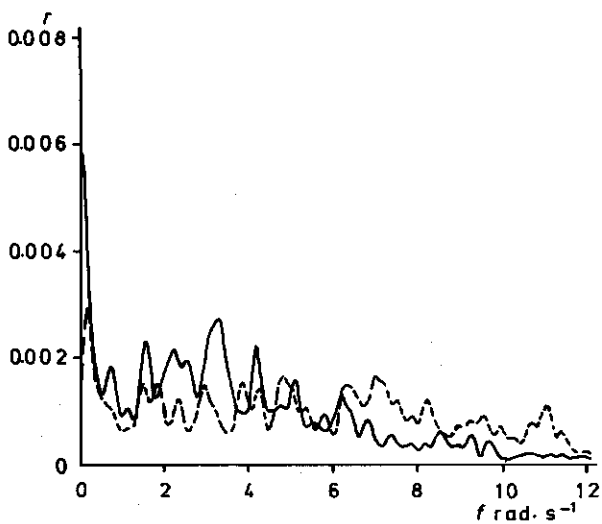



Figure A 4.2.1.5. Autospectra of walker loss (-----) and straw feed rate (————) of test run 52

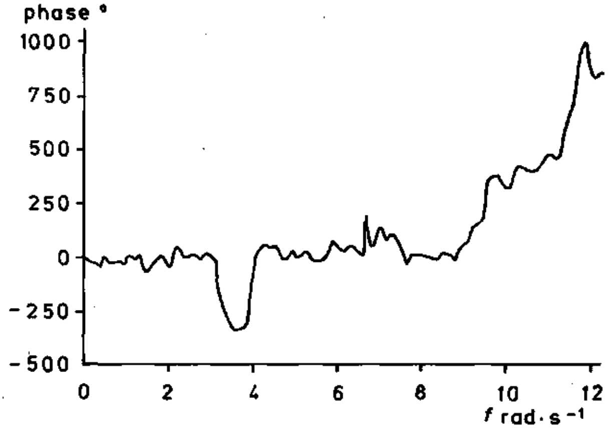



Figure A 4.2.1.6. Phase spectrum of walker loss and straw feed rate signals of test run 52

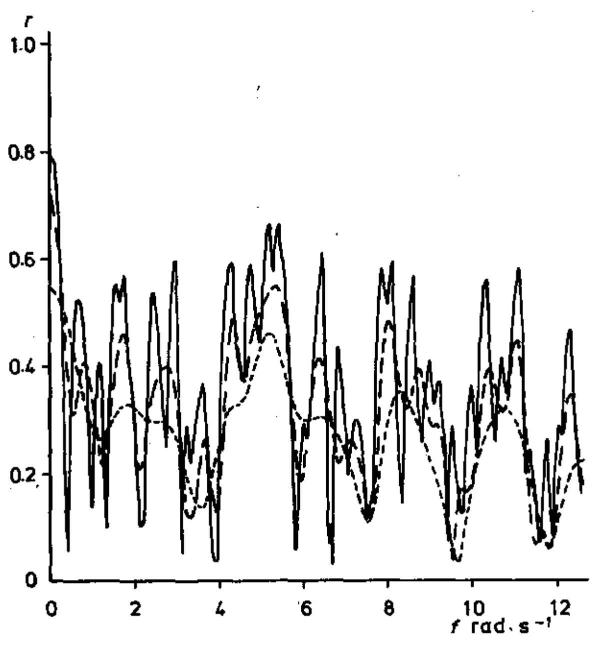



Figure A 4.2.1.7. Coherence spectrum of walker loss and straw feed rate signal for three different Barlett windows (———)=10%, (— —) =5% (--------)=2.5%

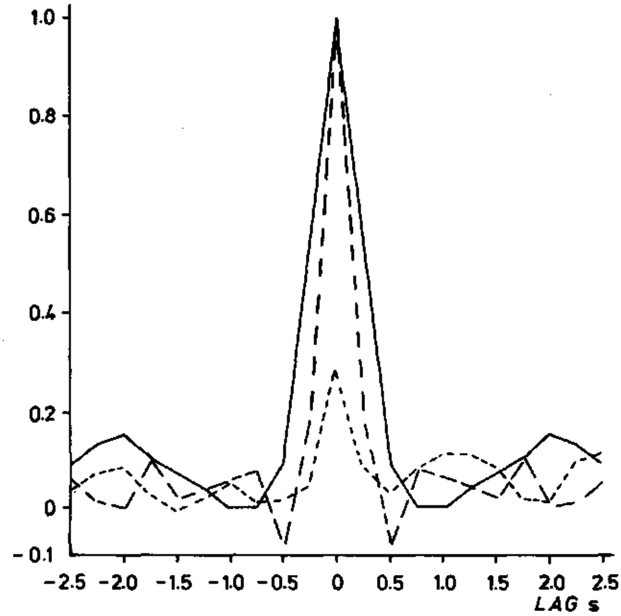



Figure A 4.2.1.8. Autocorrelation function of straw feed rate (———) and walker loss ( — — —) signals as well as crosscorrelation (------) while the delay is corrected succesfully

A 4.2.1.c *Registration of crop variations and machine performance in a practical situation*

Field studies were performed for the purpose of

1) registering realistic variations in crop density and other crop properties affecting losses, and
2) the machine performance of a manually controlled combine harvester for comparison with simulated automatically controlled machines.

A combine harvester of the large-scale grain farm of the IJsselmeerpolders Development Authority was fitted with measurement devices and a four-channel tape recorder. The recorded signals were: the forward speed of the machine, the feed auger torque, the grain loss monitor pulses. Calibration runs were performed every three or four hours to establish the relation between real speed and measured speed, output signal of the feed auger torque measurement and straw feed rate as well as that of the grain loss monitor output and real losses. The speed was measured by a pulse generator,generating about 76 pulses for each traversed metre. The feed-auger torque was measured by a special device shown in fig. A 3.1.1.14 and calibrated by comparing the measurement output to the feed rate. The feed rate was calculated from the speed of the machine and the straw collected over a distance of 12 m on a sheet behind the machine and then weighed.

The results are shown in figure 3.1.1.3. The loss monitor output was compared to the walker loss gathered together with the straw from the walkers on sheets 50 m in length and separated from that straw by a special loss-measuring machine. This machine consisted of a sheet-pick-up device at the front of the loss-measuring machine shown in fig. A 2.3.2.8. The loss pulses were later on converted into an analog signal. Fig. A 4.2.1.9 shows the measuring points of the two curves used for calibration. These data were the basis for exponential curves which were used for calculating losses from the analog signal generated by the test runs of interest.

Eight test runs of two days (August 21st and 23rd) were selected to be used for the calculations. These runs concern tests of two varieties of winter wheat, Nautica and Anouska, harvested under the moisture conditions of the whole day.

The mean values of speed, loss and feed rate were calculated over each 0.25 m distance covered in a total distance of 200 m.

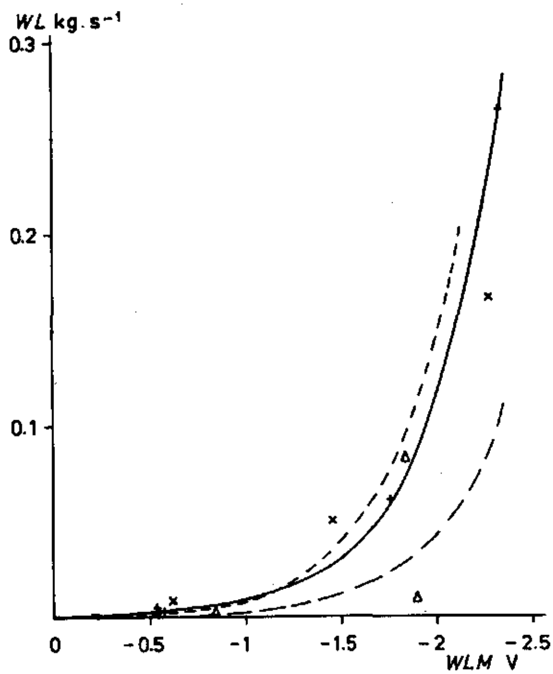



Figure A 4.2.1.9. Calibration curves of walker loss
*WL* = walker loss measured at the sheets, *WLM* = walker loss measured by grain loss monitor, +, × = two different test runs in nautica (———, -----), Δ = test run in anouska (—— ——)

The delay between loss and feed rate was calculated by cross-correlation for each test run. The calculated delays were listed in Table A 4.2.1.3. The delay of speed and its effect on the feed rate was *assumed* to be 0.4 s and converted to the figure appropriate to the distance of 0.5 m. Knowing these delays, it was possible to calculate straw densities and loss - feed rate relations for each test run.

The apparent straw density per distance of 0.25 m was calculated by dividing the delayed straw feed rate value by the product of the machine speed and the constant cutting width of 5.9 m.

The loss - feed rate curves were obtained by calculating the mean values of feed rate and delayed loss over a distance of 8 m and fitting curves by linear correlation of the model

$$\ln WL = D0 + D1 \cdot FS$$

These values of *D0* and *D1* are listed in table A 4.2.1.3.

The distance of 8 m was chosen after comparison of the curves obtained by averaging over 0.25, 0.5, 1, 2, 4, 8, 16 and 32 m. In general the averaging curves over 8, 16 and 32 m were similar, but when the averaging data over shorter distances were correlated the correlation was found to be poor and, as a result, the curves flat. The reason is to be sought in the variation of the delay and other disturbances, which cause poor coherence when the effect of the variation is not filtered out.

The general crop conditions during the tests are shown in table A 4.2.1.2.

Table A 4.2.1.2. General information on crop conditions of the test runs used in the simulations

| Variety of winter wheat | Nautica | Anouska |
|---|---|---|
| Harvest date in August | 21st | 23rd |
| Moisture content grain % | 16 | 17 |
| Moisture content straw % | 31 | 17 |
| Grain yield $kg \cdot ha^{-1}$ | 6200 | 6200 |
| Grain-to-straw ratio | 1.06 | 1.44 |

The *BETA* and *WEP* values of the threshing and walker separation models, calculated by parameter estimation techniques are also listed in table A 4.2.1.3. This will be explained in paragraph 6.2.1.

Table A 4.2.1.3. Data of calculated parameters and mean values of test runs used in the simulations
Var. = variety: N means nautica, A means anouska
Delay = calculated delay between measured auger torque and grain loss monitor signal
*D0*, *D1* = parameters in loss-to-feed rate equation
*BETA1* = threshing coefficient estimated by simulation
*BETA2* = threshing coefficient estimated by correction of *BETA1*
*WEP* = estimated walker efficiency parameter
*SDAV* = average straw density of test run
*VMAV* = average machine speed measured at the field test
*FSAV* = average straw feed rate measured at the field test
*WLAV* = average walker loss measured at the field test

| Test nr. | Var. | Delay | *D0* | *D1* | *BETA1* | *BETA2* | *WEP* | *SDAV* $kg \cdot m^{-1}$ | *VMAV* $m \cdot s^{-1}$ | *FSAV* $kg \cdot s^{-1}$ | *WLAV* $kg \cdot s^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | N | 10.0 | - 8.3 | 1.1 | 1.806 | 1.7569 | 1.747 | 0.66 | 0.98 | 3.80 | 0.0163 |
| 33 | N | 8.5 | - 6.3 | 1.1 | 1.561 | 1.4212 | 1.600 | 0.60 | 0.99 | 3.50 | 0.1105 |
| 37 | N | 9.5 | - 5.7 | 0.9 | 1.451 | 1.3150 | 1.931 | 0.50 | 0.98 | 2.89 | 0.0502 |
| 39 | N | 10.0 | - 6.7 | 0.5 | 1.818 | 1.7539 | 1.789 | 0.62 | 0.90 | 3.29 | 0.0071 |
| 52 | A | 9.0 | - 5.9 | 0.7 | 1.643 | 1.6155 | 1.791 | 0.52 | 1.02 | 3.10 | 0.0263 |
| 55 | A | 10.5 | -10.8 | 3.0 | 1.531 | 1.3620 | 1.896 | 0.42 | 0.94 | 2.29 | 0.0176 |
| 57 | A | 9.5 | -10.1 | 2.6 | 1.546 | 1.4038 | 1.877 | 0.45 | 0.95 | 2.53 | 0.0298 |
| 61 | A | 9.0 | - 8.5 | 1.3 | 1.766 | 1.7125 | 1.692 | 0.49 | 0.96 | 2.01 | 0.0074 |

A 4.6.4. *Measurement of losses on combine harvesters of farmers and contractors in practice*

Machine performance test measurements in practical situations were carried out in 1972 and 1980. Simple measurement techniques were used to be able to research as many machines as possible in each season by one or two men. Farms were selected at random from all over the Netherlands. The operator was asked to do his work as he was in the habit of doing. The measured variables and the used measuring techniques were as follows.

Walker loss. Walker + sieve losses were gathered in 1972 on a sheet 2 m long, while in 1980 just the walker losses were gathered on a 10-m sheet.

Sieve loss. These were collected in both years in a catch net, held behind the sieves by hand over the 10-m stretch.

Straw feed rate. The straw collected on the sheets was weighed and the machine speed was measured over 10 m, so that the feed rate could be calculated.

Moisture content of straw and of grain. Samples were taken immediately after the discharge of straw or grain, and the moisture content (wet base) was measured by the oven method.

Threshing loss. The losses were estimated by taking 50 threshed ears from the straw, rethreshing them by hand and comparing the threshed grains to the number of grains in 50 unthreshed ears.

Adjustments, machine and general crop data were also recorded.

The measurement data of 1972 are listed in Table A 4.6.4.1. The measurement data of 1980 are listed in Table A 4.6.4.2. Two measurements were done then at each machine. For this table the straw feed rate is calculated on a 1-metre standard width of the threshing cylinder. The mass figures are based on the wet weight.

Table A 4.6.4.1. Data of measurements in practical situations of 1972 (see text).
*AFS* = specific straw feed rate, *VM* = machine speed, *MCS* = straw moisture content, *MCG* = grain moisture content, *TL* = threshing loss, *SL* = sieve loss, *WL* = walker loss, *GY* = grain yield

| User | Crop | *AFS* | *VM* | *MCS* | *MCG* | *TL* | *SL* | | *WL* | | *GY* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $kg \cdot s^{-1}$ | $m \cdot s^{-1}$ | % | % | % | $kg \cdot ha^{-1}$ | % | $kg \cdot ha^{-1}$ | % | $kg \cdot ha^{-1}$ |
| C | wb | 1.9 | 0.7 | 55 | 21 | 1.7 | 32.5 | 0.47 | 418.0 | 6.10 | 6860 |
| F | sb | 1.6 | 0.9 | 40 | 25 | 4.5 | 3.8 | 0.01 | 10.0 | 0.25 | 4000 |
| C | wb | 1.7 | 0.6 | 58 | 19 | 1.4 | 55.8 | 0.98 | 123.0 | 2.20 | 5600 |
| C | sb | 1.6 | 1.2 | 13 | 20 | 1.4 | 3.0 | 0.08 | 33.0 | 0.83 | 4000 |
| C | sb | 2.3 | 1.0 | 61 | 26 | 2.9 | 8.8 | 0.20 | 117.0 | 3.75 | 4400 |
| C | sb | 2.3 | 1.2 | 63 | 23 | 0.8 | 192.0 | 4.80 | 280.0 | 7.00 | 4000 |
| C | sb | 0.7 | 1.1 | 33 | 21 | 0.0 | 1.8 | 0.11 | 6.7 | 0.39 | 1700 |
| C | sb | 1.5 | 1.0 | 48 | 18 | 2.5 | 56.3 | 1.33 | 69.0 | 1.64 | 4200 |
| C | wb | 1.6 | 1.2 | 45 | 12 | 0.7 | 15.5 | 0.31 | 17.7 | 0.35 | 5000 |
| C | sb | 1.9 | 1.5 | 17 | 13 | 2.1 | 32.2 | 0.86 | 37.9 | 1.02 | 3730 |
| F | wb | 0.6 | 0.7 | 20 | 15 | 2.0 | 1.4 | 0.03 | 15.5 | 0.30 | 4600 |
| F | ww | 2.3 | 0.7 | 61 | 18 | 1.5 | 8.1 | 0.20 | 30.2 | 0.74 | 4070 |
| C | sw | 2.2 | 1.5 | 12 | 20 | 0.0 | 33.5 | 0.80 | 238.0 | 5.67 | 4200 |
| C | sw | 2.2 | 1.5 | 47 | 18 | 0.0 | 4.0 | 0.10 | 6.5 | 0.17 | 3840 |
| C | ry | 2.3 | 1.6 | 24 | 26 | 0.6 | 4.2 | 0.15 | 43.3 | 1.54 | 2800 |
| F | ry | 1.1 | 0.9 | 30 | 20 | 1.2 | 1.6 | 0.05 | 3.3 | 0.09 | 3500 |
| F | ry | 1.3 | 1.1 | 25 | 20 | 0.5 | 19.5 | 0.53 | 22.2 | 0.60 | 3700 |
| C | ww | 1.8 | 0.9 | 31 | 27 | 1.5 | 4.2 | 0.09 | 8.3 | 0.19 | 4450 |
| C | ww | 2.6 | 1.0 | 31 | 21 | 1.5 | 4.8 | 0.11 | 14.8 | 0.30 | 4450 |
| F | ww | 1.5 | 1.8 | 22 | 20 | 0.7 | 19.3 | 0.37 | 26.4 | 0.50 | 5250 |
| F | ww | 1.7 | 0.6 | 19 | 18 | 0.5 | 4.4 | 0.08 | 6.7 | 0.12 | 5700 |
| F | oa | 1.6 | 1.0 | 48 | 18 | 0.5 | 6.7 | 0.11 | 48.0 | 0.80 | 6000 |
| C | ww | 2.8 | 1.1 | 46 | 20 | 1.0 | 61.4 | 1.23 | 347.0 | 6.94 | 5000 |
| F | oa | 0.8 | 0.6 | 30 | 15 | 1.4 | 12.5 | 0.22 | 181.0 | 3.20 | 5675 |
| C | ww | 2.2 | 1.2 | 42 | 20 | 0.4 | 26.8 | 0.54 | 391.0 | 7.82 | 5000 |
| C | oa | 2.3 | 0.8 | 48 | 20 | 0.1 | 5.7 | 0.10 | 127.0 | 2.23 | 5700 |
| C | oa | 0.9 | 0.6 | 23 | 14 | 0.6 | 5.8 | 0.12 | 184.5 | 3.93 | 4700 |
| C | oa | 1.8 | 1.2 | 7 | 14 | 0.0 | 5.8 | 0.13 | 221.0 | 5.04 | 4400 |
| C | ry | 2.7 | 1.1 | 16 | 20 | 0.7 | 4.4 | 0.11 | 68.7 | 1.73 | 4000 |
| C | ry | 1.9 | 1.0 | 33 | 19 | 0.6 | 4.4 | 0.18 | 158.0 | 6.45 | 2450 |
| C | sw | 2.3 | 1.2 | 21 | 20 | 0.5 | 10.5 | 0.23 | 28.7 | 0.62 | 4630 |
| F | oa | 1.3 | 0.6 | 20 | 19 | 1.0 | 20.8 | 0.50 | 111.5 | 2.79 | 4000 |
| F | sw | 1.5 | 0.9 | 27 | 19 | 1.5 | 5.7 | 0.16 | 6.7 | 0.19 | 3600 |
| F | sw | 3.0 | 1.6 | 24 | 20 | 2.2 | 65.5 | 2.43 | 75.4 | 2.80 | 2700 |
| C | oa | 1.9 | 0.8 | 65 | 21 | 0.4 | 9.2 | 0.20 | 129.0 | 2.76 | 4700 |
| C | sw | 3.6 | 0.8 | 54 | 20 | - | 8.7 | 0.26 | 97.0 | 2.94 | 3300 |

Table A 4.6.4.2. Data of measurements in practical situations in 1980 (see text). Crop is winter wheat only.
*FS* = straw feed rate, *VM* = machine speed, *MCS* = straw moisture content, *MCG* = grain moisture content, *TL* = threshing loss, *SL* = sieve loss, *WL* = walker loss, *GY* = grain yield.

| User | *FS* | *VM* | *MCS* | *MCG* | *TL* | *SL* | *WL* | *GY* |
|---|---|---|---|---|---|---|---|---|
| | $kg \cdot s^{-1}\ m^{-1}$ | $m \cdot s^{-1}$ | % | % | $kg \cdot ha^{-1}$ | $kg \cdot ha^{-1}$ | $kg \cdot ha^{-1}$ | $kg \cdot ha^{-1}$ |
| C | 1.27 | 1.15 | 26 | 17 | 14.9 | 0.3 | 0.8 | 6700 |
| | 1.42 | 1.14 | | | 35.6 | 0.5 | 1.9 | |
| C | 1.40 | 1.05 | 30 | 18 | 6.7 | 3.9 | 13.8 | 7500 |
| | 1.43 | 1.09 | | | 10.0 | 2.8 | 10.0 | |
| C | 1.21 | 0.74 | 62 | 20 | 52.0 | 1.9 | 232.0 | 7500 |
| | 1.01 | 0.70 | | | 87.9 | 1.6 | 137.2 | |
| F | 1.16 | 0.82 | 45 | 17 | 60.8 | 33.2 | 14.0 | 6800 |
| | 1.20 | 0.83 | | | 12.4 | 11.2 | 14.2 | |
| F | 1.44 | 0.96 | 37 | 19 | 10.1 | 3.1 | 14.7 | 8000 |
| | 1.31 | 0.97 | | | 31.2 | 2.4 | 19.0 | |
| C | 1.17 | 0.82 | 27 | 19 | 9.7 | 10.1 | 2.3 | 6700 |
| | 1.24 | 0.80 | | | 5.5 | 7.3 | 2.5 | |
| F | 0.88 | 0.50 | 53 | 18 | 17.8 | 9.8 | 16.1 | 7500 |
| | 0.95 | 0.79 | | | 10.6 | 13.0 | 10.6 | |
| F | 0.69 | 1.02 | 50 | 17 | 6.2 | 3.4 | 1.9 | 7000 |
| | 1.14 | 1.06 | | | 9.2 | 3.7 | 7.2 | |
| C | 0.68 | 0.80 | 58 | 21 | 8.8 | 3.8 | 14.4 | 6500 |
| | 0.88 | 0.89 | | | 6.8 | 1.0 | 19.1 | |
| F | 0.84 | 0.98 | 28 | 16 | 7.7 | 0.9 | 2.3 | 6000 |
| | 0.88 | 1.00 | | | 6.2 | 1.0 | 6.2 | |
| F | 0.49 | 0.81 | 54 | 17 | 0 | 2.5 | 3.6 | 7000 |
| | 0.75 | 1.08 | | | 0 | 1.1 | 7.6 | |
| F | 0.81 | 1.08 | 29 | 15 | 3.4 | 2.9 | 1.7 | 6000 |
| | 1.14 | 1.06 | | | 6.9 | 3.0 | 7.8 | |
| C | 1.38 | 0.75 | 34 | 16 | 26.9 | 3.3 | 8.9 | 7500 |
| | 1.42 | 0.69 | | | 64.2 | 3.6 | 19.6 | |
| C | 1.53 | 1.00 | 46 | 20 | 80.9 | 2.5 | 74.7 | 6500 |
| | 1.86 | 0.98 | | | 53.8 | 2.5 | 118.0 | |
| C | 1.87 | 1.09 | 24 | 18 | 3.3 | 6.8 | 11.1 | 6500 |
| | 1.53 | 1.08 | | | 0 | 9.3 | 8.3 | |
| C | 1.78 | 0.70 | 38 | 18 | 3.0 | 6.9 | 30.3 | 7200 |
| | 1.25 | 0.62 | | | 4.5 | 4.4 | 25.6 | |

A 6.1.2. *Short description of C.S.M.P.*

The simulation language Continuous System Modeling Program III which was used allows the digital simulation of continuous processes on large-scale digital machines. The details of this program are comprehensively described in the manual (Anonymus, 1975) from which the following general descriptions are taken to give an impression of the possibilities and structure for the convenience of readers unfamiliar with this aspect of the problem.

"The program provides an application-oriented language that allows models to be prepared directly and simply from either a block diagram representation or a set of ordinary differential equations. It includes a basic set of functional blocks which can represent the components of a continuous system and accepts application-oriented statements defining the connections between these functional blocks. CSMP III accepts FORTRAN statements, allowing the user to readily handle nonlinear and time-variant problems of considerable complexity.

Input and output are simplified by means of user-oriented control statements. Format options are provided for print-plotting in graphic form, scaled plotting in contoured and shaded form, and printing in tabular form. These features permit the user to concentrate upon the phenomenon being simulated, and not the mechanism for implementing the simulation. The program provides both a basic set of functional blocks (also called functions) and the means for defining functions especially suited to the user's particular simulation requirements. Included in the basic set are such conventional analog computer components as integrators and relays, plus many special-purpose functions like delay time, zero-order hold, dead space, limiter functions, variable-flow transport delay, generalized Laplace transform, and the arbitrary function of two variables. This complement is augmented by the FORTRAN library, which includes subprograms for logarithmic, exponential, trigonometric, and other mathematical functions.

Special functions can be defined either through FORTRAN programming or, more simply, through a macro capability that permits individual existing functions to be combined into a larger functional block. The user is thereby given a high degree of flexibility for different application areas. For example, by properly preparing a set of special blocks, he can restructure CSMP III into an application-oriented language for chemical kinetics, control system analysis, or biochemistry for any particular special-purpose field in continuous system simulation.

CSMP III also provides the CSMP III Language Translator. It accepts a model (or batches of several models) composed of many different types of statements classified as follows:

1. Structure statements, used to describe the structure and properties of the system to be simulated.
2. Data statements, used to give values to parameters, constants, initial conditions, tables, and other data characterizing the specific situation to be simulated.
3. Execution control statements, used to request particular simulation runs and specify, in particular, their integration stepping and conditions of termination.
4. Output control statements, used to request particular printed and machine-readable documents.
5. Translation control statements, used to impose structure on the models, to extend modeling facilities, to separate models, and to provide additional capacity in the simulation vehicles produced.
6. FORTRAN statements (in certain contexts), used to supplement any of the above types of statements.

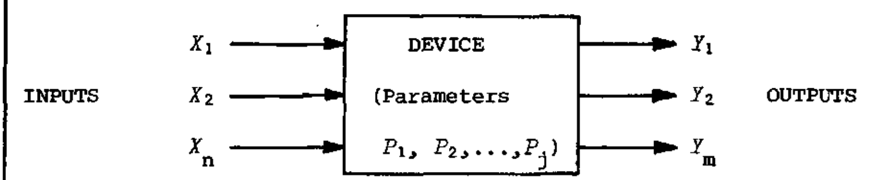
The Translator analyzes each model and produces from it two files and a Translation Output listing. One file contains all of the data, Execution control, and Output control statements for conducting a particular simulation session. It is called the Execution Input file. The second file contains FORTRAN language subprograms of which the ones of most interest here are the BLOCK DATA subprogram and subroutine UPDATE.

These are produced by the Translator from the structure, translation control, and FORTRAN statements included in the model. UPDATE is the subroutine executed in the CSMP III Execution phase in computing model dynamics during a simulation run. UPDATE and the other routines in the second file are compiled under FORTRAN to become the model-specific portion of a simulation vehicle. The Execution phase then uses the simulation vehicle to perform the simulations requested by the statements saved in the Execution Input file and generates any documents requested there.

A simulation vehicle produced from a particular model may be saved and used repeatedly in separate Execution phases as long as no changes need to be made in the structure, translation control, or FORTRAN language portions of the model. The user simply prepares a new execution input deck (set of data, Execution control, and Output control statements) according to the further simulations he wishes performed and supplies them to a different CSMP III procedure."

Figure A 6.1.2.1 shows how blocks in a block diagram or mathematical functions are represented by CSMP III language statements called structure statements.

*BLOCK REPRESENTATION*




*MATHEMATICAL EXPRESSION*

$Y_1, Y_2, \ldots, Y_m = f(P_1, P_2, \ldots, P_j, X_1, X_2, \ldots, X_n)$

*EQUIVALENT CSMP III STATEMENT*

Y1, Y2,..., YM = DEVICE (P1, P2,..., PJ, X1, X2,..., XN)

Figure A 6.1.2.1. The various representations of a relation

In table A 6.1.2.1 the CSMP statements used in this study are listed.

The structure statements that we developed for our program were a "corrector" and the cost minimisation algorithm for control system 1 and control system 2. The "corrector" was required for simulating the behaviour of the hydraulic cylinder. The translation of the ram of a hydraulic cylinder was simulated by an integrator and a limiter. The output of the integrator, however, can still increase when the upper bound of the limiter is reached. The output of the limiter will only decrease when the input of the limiter, the output of the integrator undershoots the upper bound of the limiter, the opposite taken place in the case of the lower limit. The corrector therefore behaves like the oil input or output of the hydraulic cylinder. If the cylinder is at its maximum or minimum the oil stream will be zero and the output of the integrator likewise. In Fortran language:

```
Y=X
IF(OINT.LE.LMIN.AND X.LE.0.0) Y=0.0
IF(OINT.GE.LMAX.AND X.GE.0.0) Y=0.0
```

In the CSMP statement

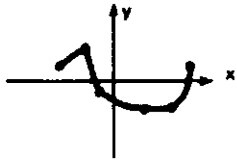
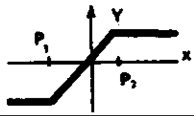
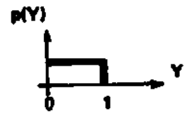
```
Y=CORR (LMIN, LMAX, OINT, X)
```

```
Where Y    = output of the corrector
      X    = input of the corrector
      OINT = output integrator
      LMIN = minimum of limiter
      LMAX = maximum of limiter
```

Table A 6.1.2.1-a. Library of used CSMP III function blocks

| CSMP III Statement | Equivalent Mathematical Expression |
|---|---|
| **INTEGRATOR**<br>Y = INTGRL (IC, X)<br>where: $IC = y\|_{t=t_s}$<br>Alternative 'Specification' Form:<br>Y = INTGRL (IC, X, N)<br>where: Y = output array<br>IC = initial condition array<br>X = integrand array<br>N = number of elements in the integrator array<br>(N must be coded as a literal integer constant) | $y(t) = \int_{t_s}^{t} x\,dt + y(t_s)$<br>where: $t_s$ = start time<br>t = time<br>$\dot{y} = \int_{t_s}^{t} \dot{x}\,dt + \dot{y}(t_s)$<br>Equivalent Laplace Transfer Function:<br>$\frac{Y(s)}{X(s)} = \frac{1}{s}$ |
| **DERIVATIVE**<br>Y = DERIV (IC, X)<br>where: $IC = \frac{dx}{dt}\Big\|_{t=t_s}$ | $y = \frac{dx}{dt}$<br>Equivalent Laplace Transfer Function:<br>$\frac{Y(s)}{X(s)} = s$ |
| **1ST ORDER LAG (REAL POLE)**<br>Y = REALPL (IC, P, X)<br>where: $IC = y\|_{t=t_s}$ | $p\frac{dy}{dt} + y = x$<br>Equivalent Laplace Transfer Function:<br>$\frac{Y(s)}{X(s)} = \frac{1}{ps+1}$ |
| **DEAD TIME (DELAY)**<br>Y = DELAY (N, P, X)<br>where: P = delay time<br>N = number of points sampled in interval p (integer constant) and must be $\geq$ 3, and $\leq$ 16,378 | $y = x(t-p) \; ; \; t \geq p$<br>$y = 0 \; ; \; t < p$<br>Equivalent Laplace Transfer Function:<br>$\frac{Y(s)}{X(s)} = e^{-ps}$ |
| **MODE-CONTROLLED INTEGRATOR**<br>Y = MODINT (IC, X1, X2, X3) | $y = \int_{t_s}^{t_f} x_2\,dt + ic \; ; \; x_1 > 0, \text{any } x_3$<br>$y = ic \; ; \; x_1 \leq 0, x_3 > 0$<br>$y = \text{last output} \; ; \; x_1 \leq 0, x_3 \leq 0$ |
| **IMPLICIT FUNCTION**<br>Y = IMPL (IC, P, FOFY)<br>where: IC = first guess<br>P = error bound<br>FOFY = output name from final statement in algebraic loop definition | $y = f(y)$<br>$\|y - f(y)\| \leq p\,\|y\|$ |
| **STEP FUNCTION**<br>Y = STEP (P) | $y = 0 \; ; \; t < p$<br>$y = 1 \; ; \; t \geq p$<br><br> |

Table A 6.1.2.1-b. Library of used CSMP III function blocks

| **CSMP III Statement** | **Equivalent Mathematical Expression** |
|---|---|
| **ARBITRARY FUNCTION GENERATOR (LINEAR INTERPOLATION)**<br>Y = AFGEN (FUNCT, X) | <br>$y = f(x)$ |
| **ARBITRARY FUNCTION GENERATOR (QUADRATIC INTERPOLATION)**<br>Y = NLFGEN (FUNCT, X) | <br>$y = f(x)$ |
| **LIMITER**<br>Y = LIMIT (P1, P2, X) | $y = p_1 ; x < p_1$<br>$y = p_2 ; x > p_2$<br>$y = x ; p_1 < x < p_2$<br> |
| **NOISE (RANDOM NUMBER) GENERATOR WITH UNIFORM DISTRIBUTION**<br>Y = RNDGEN (S)<br>where: S = seed (S is first truncated to an integer if real valued, then its absolute value is used once to initialize the generator) | Uniform Distribution of Variable y<br><br>$p(y)$ = probability density function |
| **INPUT SWITCH RELAY**<br>Y = INSW (X1, X2, X3) | $y = x_2 ;$ $x_1 < 0$<br>$y = x_3 ;$ $x_1 \geq 0$ |
| **OUTPUT SWITCH**<br>Y1, Y2 = OUTSW (X1, X2) | $y_1 = x_2 , y_2 = 0 ;$ $x_1 < 0$<br>$y_1 = 0 , y_2 = x_2 ;$ $x_1 \geq 0$ |
| **FUNCTION SWITCH**<br>Y = FCNSW (X1, X2, X3, X4) | $y = x_2 ;$ $x_1 < 0$<br>$y = x_3 ;$ $x_1 = 0$<br>$y = x_4 ;$ $x_1 > 0$ |

The cost minimisation algorithm calculates the optimum machine speed as is explained in 5.  using the implicit function statement of CSMP.

### A 6.2.4.1. *The subroutine MECEF for filter and discrete time simulation*

The program of the subroutine in FORTRAN is

```
        SUBROUTINE MECEF1 (GF,INITI,MEAN,WHAT,TINTLO,DELT,TDT,TIME
        REAL INITI,MEAN
        TYD= TYD+DELT
        WHATSC= WHATSC+WHAT
        ITEL  =ITEL+1
        IF (TIME .LT. TDT) MEAN= INITI
        IF (TYD .LT. TINTLO) GOTO 9999
           MEAN= ((1-GF)*MEAN)+(GF*(WHATSC/ITEL))
           IF (TIME .LT. TDT) MEAN= INITI
           WHATSC= 0.0
           ITEL  = 0
           TYD   = 0.0
9999    RETURN
        END
```

In this program

- GF     is the proportional factor of the smoothing filter
- INITI  is the initial value of the input WHAT
- MEAN   is the output of the filter
- WHAT   is the input given for each simulation step
- TINTLO is the sample interval (TD)
- DELT   is the time interval (=simulation step) of CSMP
- TDT    is the initial period
- TIME   is the current simulation time

The output is in this way INITI for the first TDT seconds and after that MEAN, a value constant for each TINTLO interval.

# Summary

The design of agricultural machines is determined by the requirements of the user and the techniques available at the time. The user requires systems which enable him to earn a reasonable income. A contribution to this can be made by maximising the difference between the returns and the costs incurred in obtaining these returns. The technical skills are continually being improved on, and offer new possibilities for optimisation of methods of production so that the last-named are constantly being modified.

The new possibilities thus offered by electronics and automation should also be exploited by the agricultural industry. The aim of the present study is to indicate the method for the development and application of automation of agricultural machinery.

The method is worked out in detail for the automatic control of the forward speed and threshing cylinder rotation speed of a combine harvester, a highly complex piece of machinery that cuts, threshes, separates the threshed grain from the straw and then stores and transports them.

The accent of the study is laid on the method for developing automation systems which implicitly calculate the economic benefits expected from the said systems. The method used will be worked out stepwise below.

I Study of literature showed that various automatic control systems for combine harvesters have been developed and tested, with the aim of keeping the grain loss and/or the straw feed rate (the amount of crops going into the machine per unit time) constant in view of the varying crop density on the field and differing crop properties. The level at which feed rate or loss has to be set was considered as arising from harvest optimisation studies. In these studies, models are used in which just one equation is used for the relationship between loss and feed rate. Automatic loss control, however, is capable of adapting to the change in this relationship so that this has to be taken into consideration in the control system.

In not more than 2 cases was the cost benefit calculated that arises out of the automation of combine harvesters. In these calculations, however, the assumption of one loss-to-feed rate relationship, referred to above was incorporated. Moreover, the calculations were based on control systems in which the loss measuring systems were inaccurate all, of which makes it difficult to assess the results at their true value.

II Whether it is worthwhile developing and applying more accurate loss measuring devices or other control systems will depend on the economic benefit, which makes it necessary to find out what these benefits are likely to be. It was therefore decided to design other control systems than those in the literature with the aim of obtaining the maximum economic benefit and adapting to the varying relationship between loss and straw feed rate.

The calculation of the benefit accuring from these systems was carried out by means of computer simulation, that is to say, copying the real course of the combine in the field with the aid of the computer. This enabled us to proceed as if good loss measuring systems were to hand and to compare control systems which have not even been made yet. In addition, every system can be tested under the same variations in conditions and thus the benefits correctly compared.

III The next phase was the development of a criterion to serve as a guideline or as a target for control of the forward speed and threshing cylinder rotation speed. By assuming that the maximum harvestable amount of grain is known when the crop is ripe enough for combine harvester operation, the losses incurred as the result of making changes in machine (forward) speed and threshing cylinder rotation speed, could be taken as costs and the maximisation of returns converted into terms of cost minimisation. Then the main cost factors of the grain harvest were expressed as functions of machine speed and threshing cylinder speed.

The cost factors were:

1) machine costs proportional to the harvested area;
2) machine and labour costs proportional to time;
3) fixed machine costs for the harvest season;
4) the grain losses incurred in the combine harvester;
5) the timeliness losses arising out of the inability to harvest in one operation at the best time, and

6) the extra wear of the threshing cylinder drive caused by the automatic control.

By putting the cost factors together it could be shown that there are optimum values for machine and threshing cylinder speeds. Moreover, the way in which these values are dependent on the crop properties became evident, in particular crop density in the field and other crop properties affecting the threshing and separation processes in the machine.

In order to describe the cost functions accurately, the subconditions had to be defined with respect to the specific conditions under which the machine is used. The number of possibilities were bundled together so as to result in a number determined by the following choices:

1) *Choice of the fixed area to be harvested per season per machine*
   The choice fell on 100 ha of grain per combine harvester per year in the case of a single farmer or small group of farmers and on 175 ha per machine on the large-scale farm specialised in grain harvesting, such as the IJsselmeerpolders Development Authority (IJ.D.A.)
2) *Weather risk choice*
   If the area to be harvested is fixed, the costs are mainly determined by the timeliness losses which differ greatly from year to year. In the present study these losses are calculated on the basis of data, taken from the literature, on workable hours in grain harvesting over a large number of years. When we consider the workable hours in 9 out of the 12 years available, they will be found to be more than in 10 out of the 12. However, there is a smaller chance that such a number will in fact be available. In such a case we speak of a greater weather risk. With these data and a developed formula which indicates the increase in loss the later the harvest takes place, the timeliness losses can be calculated as a function of the machine speed. For the present study there are two curves which have been calculated as stated above.
3) *Planning terms*
   On the assumption of a fixed harvesting period, a higher machine speed means that a larger area can be harvested per season. Machine costs per hectare are thus reduced. There is also a saving if more can be harvested per season per machine. This must therefore be planned on the long term. The short term planning has been discussed in 1) and 2) above.

IV As has become evident from the foregoing, a large number of simplifications have to be carried out in order to make the complex problem capable of solution. The following ones have been made for simulation purposes.

As regards the control systems we took as our starting point the assumption that the main disturbances that affect the process are variations in the average values and that, to begin with, the systems can be considered as quasi static. Moreover, the process parameters during control of the machine in the field are unknown and therefore have to be estimated. That is done in the simulation using simple models and simplified methods of estimation.

We have restricted the large number of possible control systems to 5, one or other of which uses more measuring signals or controls more variables. The controlled systems are:

System 0: Manual control: the speeds are chosen by the driver on the basis of his experience and customary observation in the field.

System 1: Loss control: machine speed is controlled on the basis of measured loss; threshing cylinder speed is controlled by the driver.

System 2: Loss-feed rate control: machine speed is controlled on the basis of measured loss and straw feed rate. Threshing cylinder speed is controlled by the driver.

System 3: Loss-feed rate-threshing cylinder speed control: a threshing cylinder speed control is added to system 2, which controls the speed on the basis of the measured straw feed rate.

System 4: Loss-feed rate-threshing efficiency control. A control is added to system 3 which sets the average threshing cylinder speed of rotation on the basis of information on the measured grain separation efficiency in the threshing cylinder.

V The development of the above stated control systems has been based on a large number of tests and measurements carried out in the field, in which the crop properties, or the process disturbances as they are called in control terminology, are established. The purpose of the control systems is, of course, that the reaction to the disturbances is such that the costs are reduced to a minimum. This comes about because the optimum speed is calculated anew every time and is adjusted to that value by a feedback control system. The opportunities are restricted because the disturbances cannot be measured accurately while the combine harvester is working (signal-noise ratio is poor) and also because the effect of the control on the process can only be measured after a certain delay.

The effect of the control system on the costs will depend on the nature and volume of the disturbances to which the system reacts. A random sample of crop property variation was taken and recorded during practical tests with a combine harvester. At the same time the machine speed chosen by the driver was also recorded, thus providing a record of the manually controlled situation. These data were used as input data for the simulations.

VI Comparison of the contributions of the various control systems to the minimisation of the costs was then calculated by computer simulation. The following steps were taken for simulation purposes:

1) The system boundary was defined on the basis of the purpose of the model.
2) Then a model was made of the combine harvester process on the basis of physical laws and measurements. Use was made of data given in literature, laboratory research and extensive measurements in the field. Detailed information on these measurements is available in the appendix.
3) Models were also made for control of the machine speed and threshing cylinder rotation speed as well as for the measuring systems needed in the control systems.
4) A computer program written in CSMP III, a simulation language for dynamic processes on digital computer, was made of these models and the control systems.
5) Simulations were then carried out to check the models and to ensure that the control systems were correctly set.
6) Finally the combine harvesting costs were calculated depending on the various controls and cost situations.

VII The simulations have led to the following conclusions:

1) The chosen speeds of the manually controlled IJ.D.A. machine were very close to those at which minimum costs were found. The minimum cost area is, moreover, very wide.
2) The reduction in costs by means of automatic control is slight and, under the above mentioned conditions, less than the cost reduction arising out of a machine design improvement leading to a 5% increase in speed at the same loss level.

   The benefit is greater if the curve of the timeliness losses at lower weather risk is applied in the control. The speed at which minimum costs occur is then much higher namely, than that in the manually controlled situation. Moreover, the range of speeds at which low costs are obtained, is much narrower. This means that the timeliness losses play an important part and that the adjustment of machine speeds to the expected timeliness losses, for instance as the result of changes in the weather during the harvesting process is important for minimisation of costs.

3) Controlling to meet rapidly varying crop density values has not been found to lead to cost reductions. The main savings in costs are obtained by adjusting to the slowly varying crop property and crop density levels, which is very evident from the fact that control system 4 (loss feed rate threshing efficiency control) and control system 1 (loss control) give the greatest reduction in costs. Control system 2 (feed rate-loss control) brings no reduction in costs, partly as the result of the assumptions in the simulation. Control system 3 (loss-feed rate-cylinder speed control) even leads to a rise in costs. Here, in particular, it is made clear how important the part is of the threshing cylinder speed in limiting machine losses and how vital a part is played by timeliness losses in optimisation of the grain harvest.
4) A reliable loss measuring system is a necessary condition in minimising costs. Present day measuring systems are not accurate enough, which means that the development of better systems is a pressing need.
5) Follow up research is also required to find out whether speed optimisation could be carried out with the help of computers not incorporated in the combine harvester but installed elsewhere. The programs in those computers can then include optimisation models in which the accent lies on adjustment of the timeliness curve to the actual weather variations during the harvest period.

It is expected that such systems will be introduced in the immediate future. Later on, systems can be introduced into the machine, comprising a loss feed rate control system (system 2) in which the loss to feed rate relationship is continuously estimated. Only when more measuring devices are available will automatic threshing speed control be developed.

# Samenvatting

Optimalisering van het gebruik van maaidorsers door automatische regeling van rijsnelheid en dorstrommelomtreksnelheid.

Het ontwerp van landbouwmachines wordt bepaald door hetgeen de gebruiker nodig heeft en de mogelijkheden die de techniek op dat moment biedt. De gebruiker heeft systemen nodig die hem in staat stellen een redelijk inkomen te verwerven. Een bijdrage hiertoe is het maximaliseren van het verschil tussen de opbrengst en de kosten die gemaakt moeten worden voor het realiseren van de opbrengst. De technische mogelijkheden worden voortdurend verruimd en bieden daardoor nieuwe kansen tot optimalisatie van de productiemethoden die daarom steeds worden gewijzigd.

De mogelijkheden die de electronica en de automatisering thans bieden, dienen ook voor de landbouw te worden benut. In dit kader heeft deze studie ten doel de methodiek aan te geven voor de ontwikkeling en de toepassing van automatisering bij landbouwwerktuigen.

De methodiek is in detail uitgewerkt voor de automatische regeling van de rijsnelheid en de dorstrommelomtreksnelheid van een maaidorser. Dit is een complex werktuig dat het rijpe graan maait, dorst en het gedorste graan scheidt van het stro, tijdelijk opslaat en transporteert.

De nadruk van de studie ligt op de methodiek van de ontwikkeling van automatiseringssystemen, waarbij impliciet de te verwachten economische voordelen van de ontwikkelde systemen zullen worden berekend. De toegepaste methode zal hieronder stapsgewijs worden beschreven.

I) Uit bestudering van de literatuur bleek dat er diverse automatische regelsystemen voor maaidorsers zijn ontwikkeld en beproefd die de hoeveelheid per tijdseenheid ingevoerd gewas (de voeding) constant proberen te houden. Dit wordt gedaan door de rijsnelheid aan te passen aan de variaties in de gewasdichtheid op het veld, die echter zelf niet gemeten kunnen worden maar herleid worden uit de meting van de voeding ergens voorin de machine. Ook zijn systemen ontwikkeld die meten hoeveel graankorrels niet van het gedorste stro gescheiden zijn en als z.g. schudderverlies met het stro de machine verlaten. In dit geval wordt de rijsnelheid geregeld met het doel het schudderverlies niet te groot te laten worden omdat het verliespercentage meer dan evenredig toeneemt met toenemende strovoeding en zeer sterk afhangt van variërende gewaseigenschappen zoals bijvoorbeeld vochtgehalte, rijpheid en gewassoort.

Met behulp van economische modellen is door diverse onderzoekers berekend wat het optimale verliesniveau is. Dit is niet bij geen verlies, want dat kan alleen worden bereikt door heel langzaam te rijden. Dit is niet gewenst omdat dan teveel machines nodig zijn of de oogst te laat klaarkomt,waardoor de zogenaamde tijdigheidsverliezen te zeer toenemen. Bij al deze studies gaat men uit van één relatie tussen de strovoeding en het verlies terwijl deze nu juist steeds varieert. Hierdoor kan voor systemen,waarbij de rijsnelheid continu wordt aangepast aan de omstandigheden, van deze optimalisatie modellen geen gebruik worden gemaakt.

In twee publicaties is een berekening gegeven van het kostenvoordeel dat bereikt kan worden met automatische snelheidsregeling op een maaidorser. Bij deze berekeningen waren echter regelaars gebruikt waarbij de verliesmeetsystemen niet nauwkeurig waren zodat het moeilijk is de resultaten op hun juiste waarde te schatten.

II) Het zal van de economische voordelen afhangen of het de moeite loont nauwkeurige meetsystemen en andere regelsystemen te gaan ontwikkelen en toepassen. Er moet dus worden nagegaan wat de hiermee te verwachten voordelen zullen zijn. Daarom werd besloten andere dan in de literatuur genoemde automatische regelsystemen te ontwerpen en hiermee de berekeningen uit te voeren. De regelsystemen dienen te worden ontworpen vanuit de doelstelling van economische opbrengst maximalisatie en er dient daarbij wel rekening te worden gehouden met de steeds veranderende relatie tussen verlies en strovoeding.

De berekening van het voordeel van deze systemen is uitgevoerd door middel van computer simulatie, d.w.z. nabootsen van het echte verloop van het maaidorsen op het veld in berekeningen met een computer. Op deze manier kan worden gedaan alsof er goede verliesmeetsystemen zijn en kunnen regelsystemen worden vergeleken die nog niet gemaakt zijn. Bovendien kan elk systeem onder dezelfde variatie in omstandigheden worden beproefd en kunnen de voordelen goed worden vergeleken.

III) De volgende fase was het uitwerken van een criterium als leidraad of wel als doelstelling voor de regeling van de rijsnelheid en de dorstrommelomtreksnelheid kon fungeren. Door ervan uit te gaan dat ten tijde van "maaidorsrijpheid" van het gewas de maximaal oogstbare hoeveelheid graan vastligt, konden de verliezen, ontstaan als gevolg van het ingrijpen in de rijsnelheid en dorstrommelomtreksnelheid, worden aangemerkt als kosten. Hierdoor kon de opbrengst maximalisatie worden omgevormd naar kosten minimalisatie. Vervolgens zijn de belangrijkste kostenfactoren van de graanoogst uitgedrukt als functie van de rijsnelheid en dorstrommelsnelheid. Deze kostenfactoren waren:

1. machinekosten die evenredig zijn met de geoogste oppervlakte,
2. machine- en loonkosten die evenredig zijn met de tijd,
3. machinekosten die vast zijn voor het oogstseizoen,
4. de graanverliezen die ontstaan in de maaidorser,
5. de tijdigheidsverliezen die ontstaan doordat de oogst niet in één keer op het optimale tijdstip kan worden uitgevoerd en
6. de extra slijtage in de aandrijving van de dorstrommel door de automatische regeling.

Door deze kostenfactoren op te tellen kon worden aangetoond dat er optimale waarden voor de rijsnelheid en de dorstrommelomtreksnelheid bestaan. Bovendien werd duidelijk hoe deze waarden afhankelijk zijn van de gewaseigenschappen. Vooral de gewasdichtheid op het veld en die gewaseigenschappen die het dors- en scheidingsproces in de machine beinvloeden zijn daarbij van belang.

Om de kostenfuncties nauwkeurig te beschrijven was het noodzakelijk nevenvoorwaarden te definiëren met betrekking tot de specifieke omstandigheden waaronder een machine wordt gebruikt. De veelheid van mogelijkheden werd gebundeld tot een aantal dat bepaald wordt door de volgende keuzes:

1) *De keuze van de vaste oppervlakte die per seizoen per machine wordt geoogst.* Gekozen is voor 100 ha graan per maaidorser per jaar bij een akkerbouwer of een groepje akkerbouwers en voor 175 ha per jaar voor een maaidorser van het grootlandbouwbedrijf dat gespecialiseerd is in de graanoogst zoals de Rijksdienst voor de IJsselmeerpolders (RIJP).

2) *De keuze van het weerrisico*
Indien de te oogsten oppervlakte vast is worden de kosten vooral bepaald door de tijdigheidsverliezen. Deze verschillen,als gevolg van het weersverloop, sterk van jaar tot jaar. Voor deze studie zijn deze verliezen berekend op basis van gegevens uit de literatuur over werkbare uren in de graanoogst van een groot aantal jaren. Wanneer we kijken naar de werkbare uren die in 9 van de 12 jaar beschikbaar zijn dan zullen dat er meer zijn dan in 10 van de 12 jaar. Er is echter een kleinere kans dat die uren ook beschikbaar zullen komen. We spreken dan van een groter weerrisico. Met deze gegevens en een ontwikkelde formule die de toename van het verlies aangeeft naarmate de oogst later plaatsvindt,kunnen de tijdigheidsverliezen worden berekend als functie van de gekozen rijsnelheid. Voor deze studie zijn twee curves gebruikt die berekend zijn op basis van de beschikbare uren zoals hierboven is aangegeven.

3) *De planningstermijn*
Als men uitgaat van een vaste oogstperiode dan betekent een grotere rijsnelheid dat er per seizoen een grotere oppervlakte geoogst kan worden. De machinekosten per hectare worden dan lager. Dit levert ook een besparing op indien per seizoen meer per machine geoogst gaat worden. Dit moet dan op langere termijn zo gepland worden. De korte termijnplanning is onder punt 1 en 2 beschreven.

IV) Zoals uit het voorgaande reeds blijkt moet een groot aantal vereenvoudigingen worden doorgevoerd om het complexe probleem oplosbaar te maken. Ten behoeve van de simulatie zijn de volgende vereenvoudigingen doorgevoerd.

Ten aanzien van de regelsystemen werd ervan uitgegaan dat de belangrijkste storingen die op het proces inwerken variaties in gemiddelde waarden zijn en dat de systemen vooreerst quasi-statisch mogen worden benaderd. Verder zijn de procesparameters tijdens het regelen op de machine in het veld onbekend en zij moeten dus geschat worden. In de simulatie is dat gedaan met eenvoudige modellen en vereenvoudigde schattingsmethoden.

Het grote aantal mogelijke regelsystemen is door ons beperkt tot 5, waarvan elk ofwel meer meetsignalen gebruikt of wel meer variabelen regelt. De bestudeerde systemen zijn:

Systeem 0: Hand regeling: de snelheden zijn gekozen door de chauffeur op grond van zijn ervaring en gebruikelijke waarnemingen in het veld.

Systeem 1: Verlies regeling: de rijsnelheid wordt geregeld op basis van het gemeten verlies; de dorstrommelsnelheid wordt geregeld door de chauffeur.

Systeem 2: Verlies-voedings regeling: de rijsnelheid wordt geregeld op basis van het gemeten verlies en de strovoeding. De dorstrommelsnelheid wordt geregeld door de chauffeur.

Systeem 3: Verlies-voedings-dorstrommelsnelheids regeling: aan systeem 2 is een dorstrommelsnelheidsregeling toegevoegd die de snelheid regelt op basis van de gemeten strovoeding.

Systeem 4: Verlies-voedings-mantelafscheidingsefficientie regeling: aan systeem 3 is een regeling toegevoegd waarbij de gemiddelde dorstrommelomtreksnelheid wordt ingesteld aan de hand van informatie over de gemeten graanafscheidingsefficientie in de dorstrommel.

V) De ontwikkeling van bovengenoemde regelsystemen is uitgevoerd mede op basis van een groot aantal veldmetingen waarin de variaties in de gewaseigenschappen, in regeltechnische termen de storingen op het proces genoemd, zijn vastgelegd. Het doel van de regelsystemen is immers dat zo op de storingen wordt gereageerd dat de kosten worden geminimaliseerd. Dit wordt gerealiseerd doordat de optimale snelheid telkens opnieuw wordt berekend en zo goed mogelijk wordt ingesteld. De mogelijkheden daartoe zijn echter beperkt omdat tijdens het maaidorsen de storingen niet nauwkeurig kunnen worden gemeten (de signaal-ruis verhouding is slecht) maar ook omdat pas met enige vertraging het effect van de ingreep van de regeling op het proces gemeten kan worden.

De invloed van de regelsystemen op de kosten zal van de aard en omvang van de storingen waarop het systeem reageert afhangen. Een steekproef van variatie in gewaseigenschappen is genomen en vastgelegd tijdens metingen aan een maaidorser in de praktijk. Tegelijkertijd is geregistreerd hoe groot de door de chauffeur gekozen rijsnelheid was, zodat is vastgelegd wat de "handgeregelde" situatie was. Deze gegevens zijn gebruikt als ingangsgegevens voor de simulaties.

VI) De vergelijking van de bijdrage van de verschillende regelsystemen tot kostenminimalisatie is vervolgens door computer simulatie berekend. Ten behoeve van de simulatie zijn de volgende stappen uitgevoerd:

1) Uitgaande van het doel van het model is de systeemgrens gedefinieerd.
2) Vervolgens is van het proces in de maaidorser een model gemaakt, gebaseerd op natuurwetten en metingen. Hierbij is gebruik gemaakt van gegevens uit de literatuur, van laboratorium onderzoek en uitvoerige metingen in het veld. Het proefschrift geeft in bijlagen uitvoerige informatie over deze metingen.
3) Ook werden modellen gemaakt voor de besturing van de rijsnelheid en de dorstrommelomtreksnelheid, alsmede van de meetsystemen nodig voor de regelsystemen.
4) Van deze modellen en de regelsystemen werd een computerprogramma geschreven in CSMP, een simulatietaal voor dynamische processen op een digitale computer.
5) Vervolgens werden simulaties uitgevoerd om de modellen te controleren en een goede instelling van de regelsystemen te verkrijgen.
6) Tenslotte werden de kosten van het maaidorsen berekend in afhankelijkheid van de verschillende regelsystemen en de verschillende kostensituaties.

VII) De simulaties hebben geleid tot de volgende conclusies:

1) De gekozen snelheden van de hand-geregelde machine van de RIJP lagen zeer dicht bij de snelheden waarbij minimum kosten optreden. Het gebied van de rijsnelheden waar de kosten dicht bij het minimum liggen is overigens zeer breed.
2) De kostendaling door automatische regeling is onder de hierbovengenoemde omstandigheden gering en kleiner dan een kostendaling die ter vergelijking bijvoorbeeld te bereiken zou zijn door een verbetering van de machine constructie die resulteert in een hogere rijsnelheid van ongeveer 5% bij hetzelfde verliesniveau.

   Het voordeel wordt groter indien de curve van de tijdigheidsverliezen bij kleiner weerrisico wordt toegepast in de regeling. De snelheid waarbij minimum kosten optreden is dan namelijk veel hoger dan de snelheid bij de hand geregelde situatie. Bovendien is het gebied van snelheden met lage kosten veel smaller. Dit betekent dat de tijdigheidsverliezen een belangrijke rol spelen en dat aanpassing van rijsnelheden aan een verandering in de verwachte tijdigheidsverliezen, bijvoorbeeld ten gevolge van weersveranderingen tijdens de oogst, belangrijk is.

3) Het regelen op snel variërende gewasstanddichtheidswaarden blijkt geen kostendaling te geven. De belangrijkste kostenbesparing wordt verkregen door aanpassing aan de langzaam veranderende gewaseigenschappen en standdichtheidsniveaus. Dit blijkt duidelijk uit het feit dat regelsysteem 4 (verlies-voedings-mantelafscheidingsefficientie regeling) en regelsysteem 1 (verliesregeling) de grootste kostendaling geven. Regelsysteem 2 (verlies voedingsregeling) geeft geen kostendaling en systeem 3 (verlies-voedings-trommelsnelheids regeling) geeft zelfs een kostenstijging.

   Hierbij is het vooral duidelijk geworden welke belangrijke rol het niveau van de dorstrommelsnelheid speelt in de beperking van de machineverliezen en welke belangrijke rol de tijdigheidsverliezen spelen in de optimalisatie van de graanoogst.

4) Een betrouwbaar verliesmeetsysteem is een noodzakelijke voorwaarde voor kosten minimalisatie. De huidige meetsystemen zijn niet voldoende nauwkeurig zodat de ontwikkeling naar betere systemen dringend gewenst is.

5) Vervolgonderzoek is tevens gewenst om te onderzoeken of snelheidsoptimalisatie zou kunnen plaats vinden met behulp van computers, die zich niet op de maaidorser bevinden maar waarbij gebruik wordt gemaakt van elders opgestelde computers b.v. personal computers met optimalisatie programma's. Hierin kan dan de tijdigheidscurve worden aangepast aan het actuele weersverloop tijdens de oogstperiode.

   Te verwachten valt dat een dergelijk systeem het eerst zal kunnen worden toegepast en pas later een systeem op de machine. Het systeem op de machine zal dan moeten bestaan uit een verlies-voedings regeling (systeem 2) met continue schatting van de relatie tussen verlies en strovoeding. Pas later zal een dorstrommeltoerentalregeling kunnen worden geautomatiseerd omdat de benodigde meetapparatuur nog veel onderzoek zal vereisen.

# References


Anonymus, 1967. Groepsbeproeving maaidorsers. ILR publikatie 110, Wageningen.

Anonymus, 1969. The utilization and performance of combine harvesters. Farm mechanization studies No. 18, Min. of Agr. Fish. and Food; NAAS, Silsoe, U.K.

Anonymus, 1973. The utilization and performance of combine grain loss monitors. 1971-2 Farm mechanization studies No. 25, ADAS Liaison Unit.

Anonymus, 1975. Continuous System Modelling Program III (CSMP III) Program reference manual, Program number 5734-XS9. International Business Machines Corporation.

Anonymus, 1976. Merkenonderzoek maaidorsers. IMAG publikatie 64, Wageningen.

Anonymus, 1979. Leidraad kostprijsberekeningen 1979/1980, Stichting Bovalpers, Utrecht.

Anonymus, 1981. Kwantitatieve informatie 1981/1982. PAGV publikatie nummer 12, Lelystad.

Audsley, E. & D.S. Boyce, 1974. A method of minimising the cost of harvesting and high temperature grain drying. J. Agric. Engng Res. 19, p. 173-189.

Arnold, R.E., 1964. Experiments with rasp bar threshing drums. J. Agr. Engng Res. 9, p. 99-131.

Artner, H., 1971. Zur Durchsatzregelung des Mähdreschers. D. Agrartechnik. 21, p. 172-173.

Baader, W., 1966. Durchsatz- und Verlustmessung im Rahmen der Gebrauchswertprüfung von Mähdreschern. Landbauforschung Völkenrode 16, H 2 p. 93-98.

Baader, W. et al. 1969. Die Entmischung eines Korngut-Fasergut-Haufwerkes auf einer vertikal schwingenden horizontalen Unterlage. Grundl. der Landtechnik 5, p. 149-157.

Baumgartner, G., 1969. Anpassung des Mähdreschereinsatzes an Klimaverhältnisse und Ernterisiko. KTBL-Berichte über Landtechnik. Heft 125.

Bergman, O.C., 1976. De meettechnische aspecten van het maaidorsveldonderzoek. Intern rapport, vakgroep Landbouwtechniek, Landbouwhogeschool, Wageningen.

Bogdanova, L.I., 1960. Automation of SK-3 self propelled combine harvester. NIAE Translation 262 of Vestnik. selsk. nauki (5) p. 104-113.

Bouman, A. & A. Cappon, 1971. Verliesindicator op maaidorsers. Landbouwmechanisatie. p. 217-219.

Boyce, D.S. & I. Rutherford, 1972. A deterministic combine harvester cost model. J. Agric. Engng. Res. 17, p. 261-270.

Boyce, B.H. et al., 1974. The separation characteristics of a combine harvester and a comparison of straw walker performance. J. Agric. Engng. Res. p. 77-84

Brizgis, L.J. et al., 1980. Automatic cylinder speed control for combines. Trans. ASAE, p. 1066-1071, 1075.

Brouër, B.P. & J.R. Goss, 1970. Some approaches to automatic feedrate control for self-propelled combine harvesters. ASAE paper, 70-632.

Brown, W.T. & G.H. Vasey, 1967. Wheat harvester survey. Dept. Agr. Engng. W.R.I.C. Rpt. University Melbourne, Australia.

Bruyn, C.P.M. de, 1979. Simulatie van enkele regeltechnische mogelijkheden ter verbetering van het maaidorsproces. Doctoraalscriptie meet-, regel- en systeemtechniek en landbouwwerktuigkunde, Landbouwhogeschool Wageningen.

Caspers, L., 1966. Einfluss von Spaltweite, Spalt- und Korbform auf den Dreschvorgang. Grundl. Landtechnik. 16 p. 220-228..

Caspers, L., 1973. Die Abscheidungsfunktion als Beitrag zur Theorie des Schlagleistendreschwerks. Landbauforschung Völkenrode. Sonderheft 19.

Claesson, S. et al., Skördetröskning. Meddelande nr. 344. Jordbrukstekniska institutet, Sweden.

Cool, J.C. et al., 1979. Regeltechniek. Elsevier, Amsterdam/Brussel.

Cooper, G.F., 1971. Cylinder/concave performance from laboratory tests. ASAE paper, 71-625.

Dongen, H.A.J.M. van, 1981a. Verliesmonitoren in de praktijk. Praktijkverslag, vakgroep Landbouwtechniek, Landbouwhogeschool, Wageningen.

Dongen, H.A.J.M. van, 1981b. Schatting van parameters in het CSMP model van een maaidorser met veldgegevens. Doctoraalscriptie, vakgroep Landbouwtechniek, Landbouwhogeschool, Wageningen

Donkersgoed, K. van, 1980. Een laboratoriumonderzoek naar de relatie van voedingsniveau, gewas en vochtgehalte op mantelafscheiding, schudderafscheiding en schudderverliezen. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool, Wageningen.

Dymnich, V.G., 1956. Automatic control of grain combine harvesters. NIAE Translation 137 of Mekh. Elektrif. Sots. sel. Khoz., (4), p. 23-26.

Eimer, M., 1966. Stand der Regelungstechnik beim Mähdrescher. Grundl. Landtechnik 16, p. 41-50.

Eimer, M., 1970. Entwicklungen von Regelungseinrichtungen am Mähdrescher. Grundl. Landtechnik 20, p. 137-140.

Eimer, M. 1973a. Untersuchungen zur Durchsatzregelung am Mähdrescher. Habilitationsschrift der Georg-August-Universität, Göttingen.

Eimer, M., 1973b. Funktion und Arbeitsqualität der drehzahlgeregelten Dreschtrommel. Grundl. Landtechnik 23, p. 158-163.

Eimer, M., 1973c. Monitore zur Überwachung der Funktion und Arbeitsqualität von Mähdreschern. Landtechnik, p. 215.

Eimer, M., 1974a. Automatic control of combine threshing process. Paper F-5, IFAC Symp. Aut. control for Agr. Saskatoon, Canada.

Eimer, M., 1974b. Untersuchungen zur steigerung der Productivität von Mähdreschern durch den einsatz von Steuer und Regelungseinrichtungen. Paper 74-III-105. CIGR Symposium 1974. Holland.

Eimer, M., 1977. Optimierung der Arbeitsqualität des Schlagleistendreschwerks. Grundlagen der Landtechnik, p. 12-17.

Eykhoff, O., 1977. System identification. John Wiley & Sons, London.

Fedosejev, P.N. et al., 1969. Relation between grain moisture content and quality of the work of the SK4 combine harvester. Tractory. i selchosmasiny 9, p. 27-29.

Feiffer, R. et al., 1964. Die Impulssteuerung des Vorschubes - eine Möglichkeit durchgreifender Verlustsenkung an Trommel und Schüttler. Deutsche Agrartechnik 14 p.257-261.

Feiffer, R., 1967. Elektronische Verlustkontrolle am Mähdrescher Deutsche Agrartechnik p.296-298.

Fekete, A. et al.,1981. Development and test of combine feedrate control unit. Mezőgazdasági gépesitési tanulmányok, Gödöllő.
Feltz, G.C. van der, 1979. Een laboratoriumonderzoek naar de invloed van vochtgehalte, voeding, rijpheid en gewas op mantel- en schudderafscheiding. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool, Wageningen.
Filatov, N.V., 1967. Verstärkung der Körnerabscheidung auf Horden-Strohschüttlern. Landtechnische Forschung 6, p. 196-200.
Fokkens, B. & M. Puylaert, 1981. A linear programming model for daily harvesting operations at the large-scale grain farm of the IJsselmeerpolders development authority. J. Opl. Res. Soc. V 32, p. 535-547.
Fokkens, B., K. v.d. Linden & G. Velthuis, 1983. Personal communication.
Friesen, O.H. et al.,1965. Automatic feedrate control of combines. ASAE Paper 65-167.
Gasparetto, E. et al.,1977. Ultra high speed movie observation of a conventional threshing mechanism (cylinder-concave-rear beater) working on wheat. Proceedings grain and forage harvesting conference. Ames, Iowa, USA, ASAE Publication 1- 78, p. 104-111.
Gelder, J. van, 1975. Schudderafscheiding en verliezen in een maaidorser. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Glaser, F., 1976. Korn-Stroh-Trennung unter besonderer Berücksichtigung eines umlaufenden Siebbandschüttlers. Forschungsbericht Agrartechnik der Max Eyth-Gesellschaft 13, München.
Goss, J.R. et al., 1958. Performance characteristics of the grain-combine in barley. Agr. Engng. 11, p. 697-702.
Goss, J.R. et al, 1965. Automatic feed control for a self propelled combine. ASAE paper, 65-168.
Graeber, E., 1974. Wirtschaftliche und technische Aspekte der Kornverlusterfassung am Mähdrescher. Grundl. Landtechnik (1), p. 15-17.
Groothuis, A., 1979. Invloed van voeding en voedingsschommeling op de korrelafscheiding en de schudderverliezen bij wintertarwe. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Gubsch, M., 1969. Der Einflusz der Längsneigung des Mähdreschers auf das Abschiedungs- und Förderverhalten des Strohschüttlers. Arch. Landtechn. Bd 8. H2/3, p. 127-139.
Gullacher, D.E. & L.G. Smith, 1979. Grain loss monitor performance. ASAE Paper, p. 79-1579.
Gulyaev, G.A., 1960. Investigation of an automatic system for the control of drum loading of tractor drawn combine harvesters. NIAE Translation 263 of Trudy VIM, 1960, p. 189-213.
Gurarii, I.M., 1964. Investigating the automatic control system of combine harvester loading by analog computation. Problemy Avtomatvzatsii S-Kh. Proizvodstva Kolos 287-304.
Hagting, A., 1976. Managing large-scale harvesting operations on a grain farm by means of computerized optimisation models. Paper XVIII th. International Congress of Scientific Workorganisation in Agriculture (Hungary).
Harriott, P., 1964. Process control. McGraw-Hill Book Company,New York.
Heinrich, J., 1968. Gleichmässige Druschgutzuführung zum Dreschwerk als Voraussetzung für eine Automatisierung der Mähdrescherarbeit. Wiss. Zeitschrift der Humboldt-Universität zu Berlin, Math-Nat. R. XVII.
Hijma, P., 1970. Een analyse van tarwe ten behoeve van het maaidorsproces. Doctoraalscriptie Landbouwplantenteelt, Landbouwhogeschool Wageningen.

Himmelblau, D.M., 1972. Applied Non-linear Programming. Mc-Graw Hill.
Hooper, A.W. & B. Ambler, 1979. A combine harvester discharge meter. J. Agric. Engng. Res. 24, p. 1-10.
Huisman, W. et al.,1974a. Automatic feedrate control of a combine harvester in wheat. Paper IFAC Symposium on Automatic control for Agriculture, Saskatoon, Canada.
Huisman, W. et al.,1974b. Automatic feedrate control on a combine harvester. Paper 74-III-106, VII CIGR Conference, Holland, 1974.
Huisman, W., 1977. Berekening van de invloed van de variatie in de voeding op de capaciteit van het maaidorsen. Interne notitie, Vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Huisman, W., 1978. Moisture content, coefficient of friction and modulus of elasticity of straw in relation to walker losses in a combine harvester. Proceedings of the First international grain- and forage-conference. Ames, Iowa, USA, ASAE Publication 1-78, p. 49-54.
Huynh, V.M. et al.,1982. Threshing and separating process - a mathematical model. Trans. of the ASAE, p. 65-72.
Jansen, C.H.A., 1972. Maaidorsverliezen in de praktijk. Praktijkverslag, Vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Jofinov, S.A. & V.U. Miroschnitschenko, 1967. Der abgedrosselte Verdichtungsdruck des Motors als Regelgrösse der Beschickung eines Getreidemähdreschers. Landtechnische Forschung 1, p. 24-25.
Kampen, J.H. van, 1969. Optimizing harvesting operations on a large-scale grain farm. Rijksdienst voor de IJsselmeerpolders, Zwolle, Holland.
Kawamura, N. et al.,1972a. Automatic feedrate control for hydrostatic drive combine of head feeding type (1). Research report on Agricultural Machinery. LAM Kyoto Univ. Japan, No. 4, p. 55-70.
Kawamura, N. & M. Umeda, 1972b. Automatic feedrate control for hydrostatic drive combine of head feeding type (2). Research report on Agricultural Machinery, LAM Kyoto Univ., Japan, No. 5, p. 1-10.
Kawamura, N. & K. Namikawa, 1974. Automatic feedrate control of hydrostatic drive combine of head feeding type - two inputs control system. Paper F-4, IFAC Symposium on automatic Control for Agriculture, Saskatoon, Canada.
Kawamura, N. et al., 1975. Automatic feedrate control of combine in two inputs system and its adaptive control. Memoirs of the college of agriculture. Kyoto Univ., Japan, No. 107, 1975.
Kawamura, T. et al., 1978. Adaptive feedrate control of head feeding type combine. Digital sampled adaptive control system. Research report on agricultural machinery, 1978. Lab. of Agr. Machinery, Kyoto Univ., Japan, p. 68-96.
King, D.L. & A.W. Riddolls, 1960. Damage to wheat seed and pea seed in threshing. J. Agric. Engng. Res., p. 387-398.
Kirk, T.G. et al, 1977. Evaluation of a simulation model of the combine harvester. Proceedings Grain and Forage Harvesting Conference, Ames, Iowa, USA, ASAE Publication 1-78. p. 134-138.
Klein Hesselink, J., 1971. Een onderzoek naar meetgrootheden voor de voeding van een maaidorser. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Klinner, W.E., 1979. Reducing field losses in grain harvesting operations. The Agricultural Engineer 34, p. 23-27.
Kroeze, G.H., 1970. Capaciteiten en verliezen bij maaidorsen. ILR Rapport 173, Wageningen.
Kruse, J. et al., 1982. Microprocessor-based combine ground speed controller. ASAE report 83-3040.

Kühn, G., 1970. Zur Messung der Körnerverluste am Dreschwerk von Mähdreschern. Deutsche Agrartechnik, 6, p. 253-256.
Lange, J.M., 1972. Exploitatiekosten van enkele landbouwwerktuigen. ILR Publikatie 164.
Lint, M.M. de, 1974. Glossary of terms used in the ILR Papers. Papers on Th. 2, Section V, presented by IMAG, Wageningen at CIGR-Congress 23-27 sept. 1974.
Lint, M.M. de, 1968. De capaciteit van maaidorsers in tarwe. Landbouwmechanisatie, p. 537-542.
Loo, J. van, 1977. An automatic feedrate control system for a combine harvester. Internal Publ. Dept. of Agr. Engineering, Agr. Univ. Wageningen.
Loorbach, G. & P.M. Rijk, 1972. Een onderzoek van voeding en verliezen tijdens maaidorsen. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool, Wageningen.
Mailander, M.P. et al.,1979. Computer controlled hydraulics. A combine application. ASAE Paper, 79-1615.
Maler, J., 1974. Regulation of the operation speed of the harvester-thresher according to indicated grain losses. Zemed. Techn. 20 (6), p. 343-354.
McGechan, M.B. & C.A. Glasbey, 1982. Benefits of different forward speed control systems for combine harvesters. J. Agric. Engng. Res. 27, p. 537-552.
Michajlov, M.W., 1962. Automatic control of grain feed in the threshing mechanism of a combine harvester (Russ.). Westnyik Selchos. Nauki, 7 (3), p. 117-125.
Naaktgeboren, A., 1976. Landbouwkundige, Regeltechnische en Ergonomische aspekten van een voedingsregeling voor een maaidorser, werkend onder praktijkomstandigheden. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Nakhamkin, G.G. & M.V. Michajlov, 1960. Automatic controller of loading for a combine harvester. NIAE Transl. 186 of Trakt. Sel'khozmash., 30 (12), p. 19-20.
Nakhamkin, G.G. & M.V. Michajlov, 1972. Developing automatic ground speed control for self propelled combines. Trakt. Sel'khozmash. (6), p. 23-24.
Nakonetschny, I.I. & W.D. Schepowalow, 1967. Automatisches Regeln des Durchsatzes bei Erntemachinen. Deutsche Agrartechnik 17, Heft 11, p. 522-524.
Nastenko, N.N. & I.M. Gurarii, 1959. Automatic control of the drum feed of the SK-3 combine harvester. NIAE Translation 163 of Mekh. Elektrif. Sel. Khoz. (3), p. 45-49.
Nyborg, E.O. et al.,1968. Grain combine loss characteristics. ASAE Paper 68-609.
Oorschot, J.W.M. van, 1979. Technisch en economisch voordeel van voeding/verlies regelsystemen. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Oosten, J.A. van, 1970. Een man-machine systeem in de graanoogst. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Oving, R.K. et al.,1980. Overmechanisatie of slagvaardigheid bij de graanoogst in Nederland. IMAG publ. 143, Wageningen, The Netherlands.
Philips, P.R. & J.R. O'Callaghan, 1974. Cereal Harvesting - A mathematical model. J. Agric. Engng. Res.19, p.415-433.
Pickering, W.D., 1974. Computer modelling of combine harvester separation dynamics. Internal report Division of control engineering Univ. of Saskatoon, Canada.

Portiek, J.H., 1975. Werkbare uren voor de graanoogst, IMAG Publikatie 34.
Portiek, J.H., 1977. Workable time and the weather. IMAG Research Report 77-6.
Reed, W.B. et al.,1968. Combine harvester grain loss monitor. ASAE Paper 68-607.
Reed, W.B. & M.A. Grovum, 1969. Automatic forward speed control of combines for optimum separation efficiency. Proc. of the Nat. Conf. on automatic control, 1969. Nat. Research council, Univ. of Alberta, Edmonton, Canada.
Reed, W.B. et al. 1970. A laboratory study of grain-straw separation. ASAE Paper no. 70-604.
Reichel, H., 1969. Eine Möglichkeit zur automatischen Regelung der Fahrgeschwindigkeit von selbstfahrenden Landmachinen. Archiv. für Landtechnik 2/3, p. 171-177.
Reumkens. F.J.H.A., 1983. Vergelijking van veld- en modelgedrag van een maaidorser met strovoedingsregeling. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Rookmaker, D.P. & H.P. Kaper, 1967. Enkele metingen ter bepaling van comfortwaardering in reizigersmateriaal. Rapport 067/02, Nederlandse Spoorwegen, MW 4.
Roloff, H. & W. Matek, 1972. Machinenelemente. Braunschweig, W.-Germany.
Rumjantsev, J.K., 1964. Automation of the process of control and regulation of drum loading of the SK-4 combine harvester. Problemy Automatcii sel'kh. proisvodstra, Moskou, Kolos 305-312.
Schneller, J. et al.,1982. Combine feed rate sensors. ASAE Paper 82-1577.
Schrier, A.P., 1982. Alco, Personal communication.
Smook, R., 1980. Een laboratoriumonderzoek naar de invloed van frequentie en niveau van de voedingsvariaties op mantelafscheiding, schudderafscheiding en verliezen. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Snel, L., 1977. Maaidorsveldonderzoek 1976. Intern verslag vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Sonnenberg, H., 1970. Korn-Stroh-Trennung mit Doppelkurbel-Horden schuttlern. Grundlagen der Landtechnik 6, p. 161-166.
Souter, W.D., 1967. Separation and conveying on the straw walkers of the combine harvester. M.Sc. Thesis, Univ. of Melbourne, Australia.
Sterren, J.J.E.M. van de, 1983. Schudderverliesschatting met behulp van monitoren onder de schudders van een maaidorser. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Sytsma, H.D., 1981. Dynamisch gedrag van de zaadafscheiding van een stroschudder in een maaidorser. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Takahashi, Y. et al.,1972. Control and dynamic systems. Addison-Wesley publ. comp. Reading, Massachussets.
Theunissen, J.C.J., 1979. Enige dynamische aspecten van een voedingsverliesregeling op een maaidorser. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Trollope, J.R., 1982. A mathematical model of the threshing process in a conventional combine thresher. J. Agr. Engng. Res., p. 119-130.
Verbruggen, H.B., 1975. Digitale regelsystemen, deel 4. Delftse Universitaire Pers 1975.
Vos, J. de, 1982. Personal communication.
Werkman, IJ., 1972. Regeltechnische en landbouwkundige aspecten van een voedingsregeling voor een maaidorser. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.

Wevers, J., 1972. Een onderzoek naar verliesmodellen bij het maaidorsen. Doctoraalscriptie Landbouwwerktuigkunde, vakgroep Landbouwtechniek, Landbouwhogeschool Wageningen.
Wieneke, F., 1964. Das Arbeitskennfeld des Schlagleistendreschers. Grundlagen der Landtechnik, 21, p. 33-34.

# Curriculum vitae

Willem Huisman werd geboren op 23 juni 1944 te Nieuw Buinen.
Na het behalen van het diploma HBS-B in 1962 aan het Ubbo Emmius Lyceum te Stadskanaal begon hij aan de studie in de Elektrotechniek aan de Technische Hogeschool te Eindhoven. In 1963 verwisselde hij deze studie voor die aan de Landbouwhogeschool. In januari 1969 werd aldaar het ingenieursdiploma in de Landbouwwerktuigkunde behaald. Naast het hoofdvak landbouwwerktuigkunde omvatte de ingenieursstudie de vakken werktuigkunde en de industriële bedrijfskunde.
Per 1 februari 1969 trad hij in dienst van de Landbouwhogeschool bij de vakgroep Landbouwtechniek, waar hij is belast met het onderwijs in de oogsttechniek en de producttechniek. Daarnaast werd onderzoek verricht aan maaidorsers, waarvan een deel is verwerkt in dit proefschrift.