Design and Integration of Components for Site Specific Control of Fertilizer Application

J. van Bergeijk

Promotor: prof. dr. ir. L. Speelman
hoogleraar Agrarische Bedrijfstechnologie
Wageningen Universiteit

Co-promotor: dr. ir. D. Goense
afdelingshoofd Precisielandbouw en Management
Instituut voor Milieu- en Agritechniek (IMAG)

Promotie Commissie:

prof. dr. ir. A. Stein, Wageningen Universiteit
prof. dr. ir. G. van Straten, Wageningen Universiteit
prof. ir. A. J. M. Beulens, Wageningen Universiteit
prof. dr. ir. J. de Baerdemaeker, Katholieke Universiteit Leuven

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Abstract

Spatial and temporal variability in soil, crop and climate characteristics results in non optimal use of fertilizers when the application rate is kept constant within agricultural fields. Components to adapt the fertilizer rate to site specific conditions are identified and discussed. One of the basic components is positioning; both for data acquisition and for site specific control, a reliable and accurate positioning device has to be available. For a correct description of the spatial variability of soil properties often many samples are required. The possibility to reduce the number of soil samples by means of correlation with recorded plough draught is presented. Next to data recording, site specific control of a fertilizer spreader is discussed. Not just adaption of fertilizer rate to local requirements but also recording of applied fertilizer amount is important. Calculation of the required amount of fertilizer is based on information from different sources. To accommodate this data exchange, an information model for processing of spatial and temporal data is presented. Field experiments were conducted to evaluate the components and determine the required spatial scale of operation. To describe the soil variability, a grid with a cell size of 5 by 5 meter was necessary. The positioning system was sufficiently accurate but the implements for the application of fertilizer had to be modified to vary application rate that precise.

Cover: soil type map, courtesy to founder and members of the regional research station "prof. dr. J.M. van Bemmelenhoeve", Wieringerwerf.

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Aan mijn ouders,
voor Hanneke, Adam, Marieke en Laura

Voorwoord

De motivatie om als AIO aan dit proefschrift te beginnen bestond uit interesse in de landbouw gecombineerd met een passie voor techniek. Dat dit bij een onderwerp als 'precisie landbouw' past, is na het lezen van dit proefschrift, naar ik hoop, duidelijk. Deze motivatie alleen was echter niet voldoende om dit proefschrift af te ronden. Onderzoek bestaat namelijk naast het opzetten en uitvoeren van experimenten ook uit het opschrijven van de bevindingen en zeker voor dat laatste deel was wel eens wat extra motivatie nodig. Dit proefschrift zou er dan ook niet geweest zijn zonder de hulp van een groot aantal mensen bij zowel de uitvoering van de experimenten als bij het schaven aan de tekst. Een aantal van hen wil ik hier noemen.

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Stellingen

1) Twee of drie dimensionale plaatsbepaling, alleen gebaseerd op satellietsignalen, is niet betrouwbaar genoeg voor het positioneren van landbouwkundige bewerkingen.
dit proefschrift

2) Multidisciplinaire aanpak in onderzoek werkt alleen als vanuit de relevante disciplines kennis en gegevens kunnen worden uitgewisseld. Voor het laatste is tenminste een gemeenschappelijk informatiemodel noodzakelijk.
dit proefschrift

3) De hoeveelheid tijd die een bedrijfsleider nodig heeft voor het opstellen van de specificaties voor uitvoering van het veldwerk wordt in menig onderzoek naar precisie landbouw onderschat.

4) Een simulatie wijkt altijd af van de werkelijkheid.
dit proefschrift, pagina 138

5) In geautomatiseerde systemen dient de datum in de volgorde jaartal/maand/dag ingevuld en opgeslagen te worden. Dit vereenvoudigt sorteren op datum en voorkomt foutieve invoer door automatische keuze van een nationale notatie variant.

6) Een '*firewall*' houdt in de praktijk meer kennis buiten de deur dan binnen de deur.

7) Een systeem zo ontwerpen dat wijzigingen in specificaties eenvoudig door te voeren zijn, is minstens zo belangrijk als het opstellen van de specificaties zelf.

8) Routinematig onderzoek bestaat niet.

9) De term mechatronica is van toepassing op een systeem waarbij een elektronische en een mechanische component elkaar aanvullen. De term mechatronica mag echter niet gebruikt worden wanneer de ene component ingezet wordt om een ontwerpfout in een andere component te compenseren.

10) Het principe om zelfbeschikking voor ieder individu tot beginsel te verheffen strookt niet met de wens tot het definiëren van algemeen geldende normen en waarden.

11) Het feit dat een ligfiets lichter trapt wijzigt niets aan de voor- en nadelen van het fietsen: dat je zelf moet trappen blijft zowel het grootste voordeel als het grootste nadeel.

Stellingen behorende bij het proefschrift:

Design and Integration of Components for Site Specific Control of Fertilizer Application.

J. van Bergeijk
Wageningen, 29 oktober 2001

Contents

Account

The chapters 2, 3 and 4 have been published as articles in the Journal of Agricultural Engineering Research as mentioned on the opening page of these chapters. Reference should be made to the original articles. Except for the different font and for changes necessary to add chapter based numbering, the journal style is maintained throughout this thesis.

Chapter 1

Introduction

Agricultural production has to meet the societal demands for food and other materials such as fibres and energy sources. Society, in turn, is not only consumer but also influences agricultural production methods through economic, ecological and political mechanisms. Currently, agricultural production in the Netherlands not only has to meet criteria such as providing high quality and safe food at low cost, but also has to minimise environmental impact and fulfill obligations with respect to landscape conservation. For arable production, excessive use of fertilizers and agrochemicals that may lead to leaching of nutrients and contamination of groundwater has to be avoided. To be able to do so, the spatial and temporal scales at which these phenomena occur must be known. In legislation, formulated to reduce nutrient losses, it was identified that the criteria should match the scale of the information available on nutrient flows (van Aartsen, 1995). Whereas legislation at individual field level seems the ultimate goal, the optimal use of nutrients might require nutrient management systems that operate at scales smaller than the usual field size.

One approach to maintaining high productivity and increasing nutrient efficiency is known as "precision agriculture". The premises of precision agriculture are to adapt field operations to local variations in crop and soil conditions by the use of state of the art technology, combined with knowledge-intensive field management. The goal of precision agriculture is an economically viable agricultural production process with low environmental impact.

The origin of precision agriculture can be found in soil science where 'farming soils, not fields' expresses the awareness of the need to adjust field operations to local circumstances (Carr *et al.*, 1991). After this spatial aspect, the right timing of field operations is the second essential part of precision agriculture. Both aspects, the spatial and temporal variability present in an agronomic system, will be discussed in the following paragraphs.

1.1. Spatial variability

The relation between soil heterogeneity and variation in crop characteristics within single fields was already a theme in agricultural research at the beginning of the 20th century. For instance, plough draught recording to test soil uniformity was conducted around 1925 (Haines & Keen, 1925). The title of this paper "Studies in soil cultivation. II. A test of soil uniformity by means of dynamometer and plough" reflects the difference in approach with current precision agriculture research. While current research is often focussed on the characterization of variability of an agriculturally significant soil property, research from previous decades tested for uniformity of those properties in order to minimize variation between experimental plots. An example of the variability of the top soil clay content of a field, which will be further explored in this study, is given in *Fig. 1.1 (Perdok et al., 1997)*. The pattern of relatively large variations at short distances is typical for areas reclaimed from sea or tidal zones present at the northern and western parts of the Netherlands.

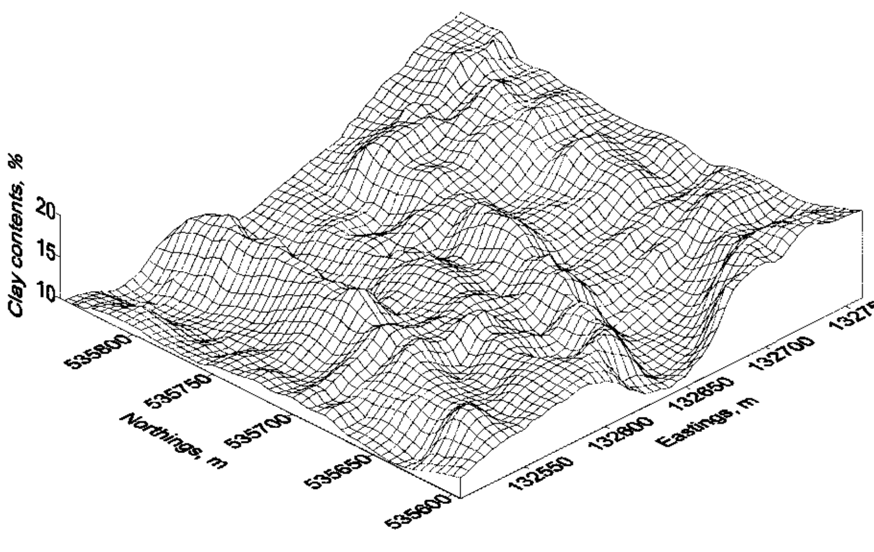

Fig. 1.1. Top soil clay content of a field in the north west part of the Netherlands, after Perdok, 1997

The idea of utilizing knowledge on spatial variability of agronomically important soil properties to optimize crop production is also old. An early example is a detailed spatial analysis of limestone requirement to explain the variation encountered within fields (Linsley & Bauer, 1929).

Knowledge of spatial variability in soil and crop characteristics is necessary in the development of techniques to optimize agricultural production. Soil scientists initially addressed spatial variability by the identification of different mapping units. Around 1970, another approach evolved, based on statistical analysis (Nielsen *et al.*, 1976). The notion that individual soil samples are often spatially dependent and should be treated as spatially correlated measurements is the basis for a more comprehensive description of soil spatial variability (Buchter *et al.*, 1991). Useful geostatistical techniques were initially designed for the mining industry (Journel & Huijbregts, 1978), and they rapidly found their application in agriculture (Burgess & Webster, 1980; McBratney & Webster, 1981). Pivotal to geostatistics are the use of the semi-variogram to express spatial correlation and interpolation techniques such as kriging to estimate soil properties at non-sampled locations.

Different agronomically significant soil properties have different spatial characteristics. Soil physical properties such as hydraulic conductivity and water retention vary strongly within fields and are often spatially correlated with classical soil types (Nielsen *et al.*, 1995). Soil chemical properties have been explored in many research programs. For example, a large inventory on spatial distribution of soil nitrate on 61 fields in Nebraska showed that despite a large coefficient of variation, 58%, a spatial structure could be formulated for 90% of the field inventories (Hergert *et al.*, 1995). A similar study to explore spatial variability of pH, P, K, Ca, Mg and corn yield in three Michigan fields was reported by (Pierce *et al.*, 1995). Also related to corn was a study to investigate the potential of site specific field management for a relatively homogeneous area near Montreal (Nolin *et al.*, 1996). A large range of soil chemical properties was analysed. The coefficient of variation of most properties was lower than 35% but still the spatial pattern showed a good correlation with the 7 distinguishable soil types, the slight elevation (slopes mostly < 1%), and the corn yield.

Characterization and modelling of the variability of the various soil properties is of little use for site specific management if the information can not be related to phenomena such as soil moisture availability, soil nutrient status and nitrate leaching potential

(Bouma & Finke, 1993). One approach to bridge the gap between classical soil type determination and the information necessary for site specific management, is the concept of functional layers. From a hydrological point of view a functional layer can be defined as a relatively homogeneous layer with significantly different hydrological properties compared to other layers (Wösten *et al.*, 1986; Verhagen *et al.*, 1995). The definition of functional layers reduces complexity and facilitates the computation of soil attributes.

The landscape itself is an important indicator of crop variability. A digital elevation map (DEM) can explain, in some cases, up to 70% of the variability of soil properties such as moisture content (Moore *et al.*, 1993). The use of a DEM also marks a change in landscape modelling. Tools such as geographic information systems (GIS), implemented on powerful computers, enable a more continuous description of the terrain, whereas, previously, distinction was only made between a limited number of mapping units. The result is a better description of the continuously varying nature of agricultural fields.

Information on the variability of crop characteristics is collected in various ways. Initially, manual samples had to be taken and processed. Since approximately 1985, the combination of globally available positioning systems with sensor developments led to the implementation of recording systems for agricultural equipment. Early examples are yield monitors on combine harvesters for grain crops (Searcy *et al.*, 1989). Later on, product mass flow measurement systems for other crops came on the market. The yield maps produced by this equipment greatly contributed to the awareness of the spatial variability present in field crops. Likewise, the development of remote sensing equipment improved regarding spectral range and resolution, spatial resolution and availability. Crop reflectance in specific wave lengths such as the red, green and near infra red bands are used to estimate parameters such as leaf area index and crop stress due to water or nitrogen shortage (Stone *et al.*, 1996).

1.2. The time aspect

Temporal variations can be discussed at different scales. Relevant for the scope of this thesis are the differences between individual growing seasons and the timing of field operations within one season. The seasonal effect on crop growth can be large, depending on the type of climate in a certain region. In a temperate humid climate, variation in early season rainfall was the main cause of large year to year variations in

N-availability for crop growth (van Es *et al.*, 2000). For these regions, the major improvement in nitrate management was to take account of early season weather rather then soil spatial variability. In a Swedish study, net nitrogen mineralization showed both large temporal and spatial variation with a spatial pattern which was consistent over the two years studied (Delin & Linden, 2000). Other nutrients show less temporal variation. For instance, two years after soil sampling, soil nutrient maps for P and K were still usable (Lamb & Rehm, 2000).

The influence of field operation timing on crop growth has been studied extensively. Many of these studies focussed on one or more of the following aspects:

(1) effect of timing of sowing, for instance in sugarbeet crops (Zachariasse, 1974);
(2) effect of fertilizer application timing on crop yield and nutrient losses (van Burg *et al.*, 1984; Bock & Hergert, 1991; James, 1978);
(3) timing of weed control operations (Curfs, 1976);
(4) yield losses due to harvest timeliness (Portiek, 1977; Goense, 1987); and
(5) timing of soil tillage operations (Hokke & Tanis, 1978).

For different crops, nitrogen applications, in particular, have to match crop growth stages closely, in order to obtain maximum yield and avoid negative side effects such as lodging in grain crops or a decrease in sugar extract ability in sugar beet (van Burg *et al.*, 1984). Other research investigated the use of 'controlled release' fertilizers to improve nutrient efficiency (Zangh *et al.*, 1996). In laboratory experiments, nitrate supply matched crop demand better when compared to conventional fertilizers. In practice, the use of these fertilizers requires prediction of soil moisture status and of crop development stage several weeks in advance.

Integration of timeliness information on the various operations in a farm system model has enabled an evaluation of the effects of different mechanization options and can be used to optimize against certain criteria (Goense, 1987). A method to address the stochastic nature of climatic conditions is to use crop growth and soil moisture and nutrient status simulation models. Dynamic simulation studies that utilize multi season weather data provide information on the probability of a certain crop yield and risk of a certain degree of nutrient leaching (Booltink & Verhagen, 1997; Verhagen, 1997). *Figure 1.2* gives the time scale for the field operations within a four year crop rotation.

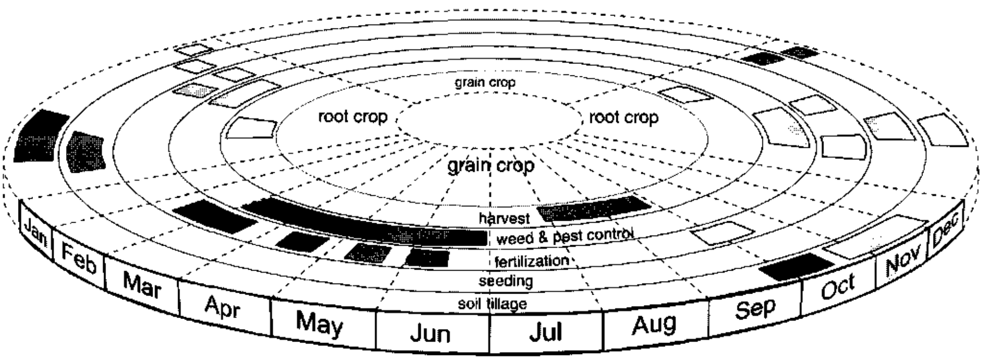

Fig. 1.2. Time scale of field operations within a four year crop rotation

The field operations are depicted as bars representing the time period in which the operation can be executed. The actual execution of an operation on a single field for most operations requires just part of a day. Exceptions are the harvesting of root crops and the main soil tillage operation where the implement capacity can be lower than 1.0 ha/h. The different colours of these bars are used to group operations that belong to the same growing season. Due to field management interactions between successive crops, temporal variations in, for instance, soil nutrient status should be analysed not just for one year or just for a single crop but for the cropping plan over multiple years.

1.3. Control of agricultural production

The basic operational control of crop production to take spatial variation into account is depicted in *Fig. 1.3 (Haapala, 1995)*. In this figure, the smallest controllable unit in a production system is called a production location. What the size of a production location will be, depends on the variation and scale present in the environment and the operational possibilities of the implements.

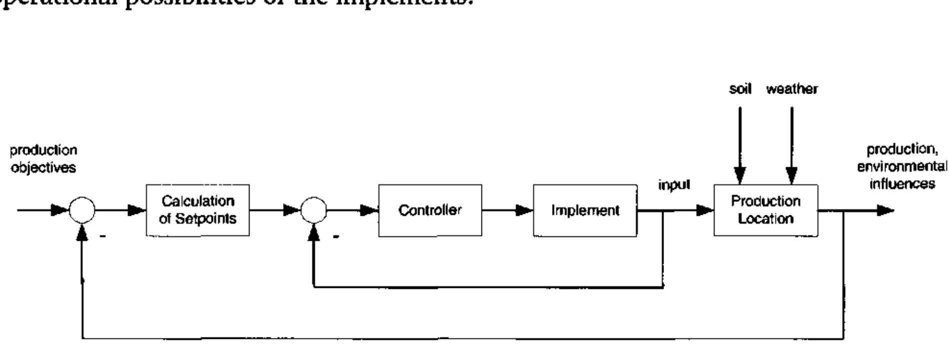

Fig. 1.3. Control loops for crop production control (Haapala, 1995)

In this control model, the feedback loop from a production location is implemented by measurements on the status of a production location. A better response to disturbances from weather, for instance, can be obtained when the control model is extended with a simulation model which predicts the effect of an input for each production location (*Fig. 1.4*). Prediction of the effect of any input on the status of a production location is in practice limited by a number of uncertainties.

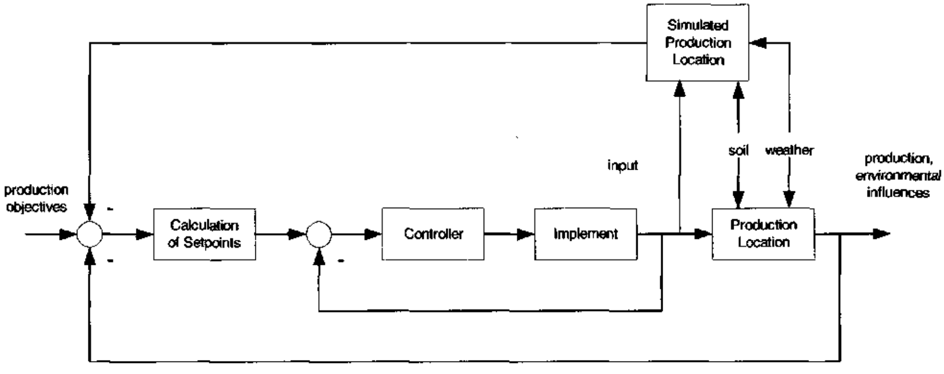

Fig. 1.4. Control loops for crop production control extended with a simulation model

A few to mention are:

(1) unknown long term and inaccurate short term weather forecasts;
(2) unknown or un-modelled causes of crop status change;
(3) unknown or un-modelled interactions between production locations, e.g. run-off;
(4) measurement errors and unknown measurement accuracies; and
(5) unknown or unwanted side effects of operations.

Optimization of agricultural production at a certain location requires knowledge from several research disciplines. Relevant, in the context of this thesis, are agronomy, soil science, farm economics and agricultural engineering. The agronomy discipline comprises plant breeding, crop protection and crop production knowledge. Of the different soil science aspects, the interaction between soils and crops and the effects on describing and modelling, soil nutrient dynamics and soil strength or tractability, for instance, are important. Farm economics, or in a broader sense, farm management is concerned about the viability of a farming system. Agricultural engineering focuses on development and evaluation of equipment for farm systems. Some of the interactions between the agronomy, soil science, farm economics and agricultural engineering disciplines are depicted in *Fig. 1.5.*

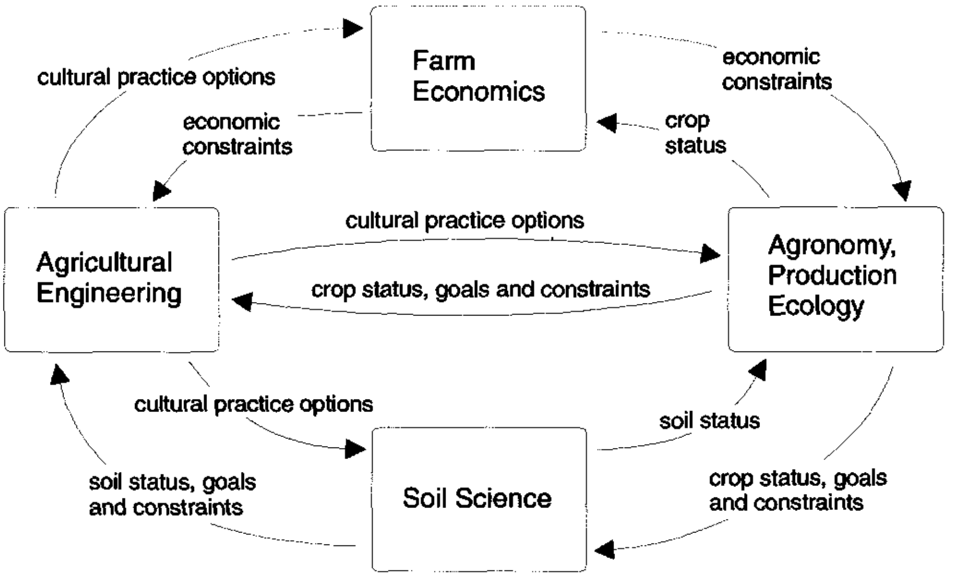

Fig. 1.5. Knowledge exchange between various research disciplines in precision agriculture

Precision agriculture or site specific crop management relies on an increased amount of knowledge and information provided by these research disciplines. How to implement the knowledge exchange in an farming system, is almost a question on its own. The use of simulation models as a way to package knowledge into computer code is one possibility (Rawlins, 1996). Crop growth simulation models can incorporate knowledge provided by several disciplines to evaluate farming systems or field management scenarios. In this way, knowledge on crop systems may be formalised and can be made available to farm practice. It is also a way to facilitate communication and co-operation between research disciplines. Whether this approach will be able to translate fundamental knowledge of crop growth to farm practice is questionable, but the use of computer simulation techniques is already a common way of formalizing knowledge in the various disciplines of agricultural research. An example of the translation of knowledge contained in simulation models to farm practice is the development of decision support systems. For site specific nitrate fertilization, several of these systems are in development and preliminary results show that an improved nitrate efficiency is feasible (McCown *et al.*, 1994; Booltink *et al.*, 1999).

1.4. Agricultural engineering and precision agriculture

Over almost two centuries of farm mechanization, labour productivity has increased significantly. Currently, on a typical arable farm in the Netherlands, one farmer maintains 50 ha whereas half a century ago the same area was farmed by 10 to 20 people. The extensive use of large machinery combined with an increased field size made this possible. In parallel to this mechanization, agronomical research resulted in improved crop varieties and cultivation practices. The agricultural production per hectare increased but the use of large implements with fixed operation parameters could not cope with spatial variability within single fields. Field management aims at maximising production, based on soil and crop conditions which a farmer considered to be representative of the entire field. Less or more productive areas could not be treated accordingly.

Developments in sensor technology and electronic control are now changing agriculture as mechanization did a century ago. Electrically controlled actuators on implements allow adjustment of operating parameters 'on the go'. The use of a positioning system is crucial in adapting field operations to local soil and crop demands (Stafford & Ambler, 1994). Sensor technology, systems control and information technology are three research areas becoming more important in agricultural engineering, although they should not be treated as mere technical solutions. Particularly within agricultural engineering, technology facilitates agricultural production. Close cooperation with disciplines such as agronomy, soil science and farm economics is essential in order to improve farm technology in such a way that farm production will remain economically viable and will operate within boundaries set by society.

The availability of a global position system (GPS) became the key technology to enable precision agriculture. The initial implementations of precision agriculture equipment used satellite based positioning systems together with grain yield sensors and variable rate technology (VRT). With regard to yield maps, three basic questions arose, which are still under discussion:

(1) What is the spatial resolution?
(2) What is the accuracy?
(3) From where do the differences originate?

Traditionally, the engineer would focus on the resolution and accuracy whilst the agronomist would discuss the resulting yield levels. It is clear, however, that there must be a strong interaction between engineering and agronomy in order to provide useful answers. Yield measurement resolution and accuracy certainly limits or sets the scale at which a crop response can be evaluated. On the other hand, agronomy might define operating criteria that a yield sensor has to meet to be able to produce valuable information. A similar interdisciplinary approach is required for variable rate technology; that will be discussed in more detail in the chapters on the design of a robust positioning system and on the determination of required fertilizer spreading accuracy.

The increased use of sensors to quantify soil and crop properties in detail requires a robust information system design to optimise use of data. Standard geographic information systems (GIS) can be tailored to store information about farm specific operations. Not only the storage but also the automated use of spatial data in variable rate technology requires standardisation of data exchange in agricultural systems. Over the last decade, standards for data exchange between farm management and mobile computers and for data exchange between electronic control units on agricultural equipment are being developed (ISO, 1994). Although standardisation progresses, the lack of a globally accepted standard for data exchange at farm operational level is still one of the limiting factors in the adoption of precision agriculture techniques by farmers today.

1.5. Research scope

The previous section showed that contributions from agricultural engineering to precision agriculture are likely to come under one of the following themes:

(1) development of sensors and measurement techniques to quantify crop and soil status;
(2) development of implements suitable for site specific field management;
(3) determination and improvement of accuracy and reliability of sensing systems and implements both spatially and temporally; and
(4) design and implementation of field management systems that incorporate or facilitate knowledge and information exchange with the farm environment, i.e. farm suppliers, consultants, research, etc.

This thesis focuses on developments regarding improvement of N-fertilizer application by means of site specific technology. The research was conducted within the framework of a European Union AIR project 92 1204 'Reduced fertilizer input by an integrated location specific support, monitoring and application system'. The general objective of this project was the development of a support system for efficient and reduced utilisation of N-fertilizer. The reason for restricting the project to nitrogen was the mobile characteristic of nitrate in soils, the related risk of leaching and the economic value or possible profits when compared to other fertilizers. With regard to the previously mentioned agricultural engineering and precision agriculture themes, a number of work packages were defined in the project:

(1) Development of sensors and measurement techniques:
  (a) development of a positioning system;
  (b) development of sensors to monitor crop development; and
  (c) development of yield mapping systems.

(2) Development of implements suitable for site specific field management
  (a) development of a site specific fertilizer application technique.

(3) Determination and improvement of accuracy and reliability
  (a) evaluation of a robust positioning system;
  (b) investigations of the accuracy of yield mapping; and
  (c) evaluation of fertilizer application accuracy.

(4) Design and implementation of field management systems
  (a) information model to construct a fertilizer management support system.

1.6. Research objectives

Based on the interactions depicted in *Fig. 1.5* and restricted to the scope formulated in the previous paragraph, the general objectives for this thesis are:

(1) development of the essential components for a site specific N-fertilizer system;
(2) evaluation of the accuracy of the measurement systems and application components;
(3) determination of the required spatial resolution of the components.

The development of many new techniques and components is often accompanied by the question: "how does this technique or component contribute to the agricultural system". To answer this question for an individual component is often not possible: sometimes a new technique will cause a chain of reactions resulting in major changes to an agricultural system as is happening to positioning components. For other techniques such as individual sensors, however, it is possible to evaluate whether the generated information is worthwhile for farm management. A more specific objective of this thesis is to discuss the components developed and their value for a precision agriculture farming system.

1.7. Thesis outline

Three chapters in this thesis will discuss subjects mentioned in the work packages of the EC-AIR project. Chapter 2 starts with a basic technique, positioning, and is dedicated to improve reliability and accuracy of positioning systems for precision agriculture. This project was carried out in cooperation with EC-AIR project participants in the United Kingdom (Stafford & Bolam, 1996) and in France. Chapter 3 will discuss a technique to support soil type mapping by means of plough draught measurement. Although this is not directly an EC-AIR project work package it fits nicely within this thesis as a precision agriculture technique integrating and supporting data from soil science and agricultural engineering. Chapter 4 continues with the development of a site specific fertilizer application and monitoring technique. Required enhancements to a standard pneumatic fertilizer spreader for site specific field operations are discussed. After implementation, the spreader has been used in field trials which were part of the EC-AIR project. Chapter 5 moves from farm machinery to farm management systems as it focuses on an information system for site specific field operations. Based on an information model (Goense *et al.*, 1996), a database was implemented to facilitate information exchange from sensor systems to field management. The scope of the information model also comprised the use of crop simulation models. Data generated by sensor systems and soil monitoring had to be stored safely while fertilizer management required the possibility to simulate fertilizer application scenarios. Chapter 6, Discussion and Conclusions reflects on the research objectives and discusses the contribution of work presented in chapters 2 to 5 to precision agriculture.

References

Bock B R; Hergert G W (1991). Fertilizer nitrogen management. Managing nitrogen for groundwater quality and farm profitability, Madison, WI, USA, pp 139-164, Soil science society of america

Booltink H W G; van Alphen B J; Finke P A; van Kraalingen D W G; van Persie M; van Bergeijk J (1999). Remote sensing for precision agriculture. NRSP report 98-13. Netherlands Remote Sensing Board (BCRS), Delft

Booltink H W G; Verhagen A (1997). Using decision support systems to optimise barley management on spatial variable soil. In: Applications of systems approaches at the field level (Kropff M J; Teng P S; Aggarwal P K; Bouma J; Bouman B A M; Jones J W; van Laar H H eds), pp 219-233, Kluwer, Dordrecht, The Netherlands

Bouma J; Finke P A (1993). Origin and nature of soil resource variability. Proceedings of the First Workshop Soil-Specific Crop Management. A Workshop on Research and Development Issues., Minneapolis, MN, USA, pp 3-14, ASA, CSSA, SSSA, Madison, WI, USA

Buchter B; Aina P O; Azari A S; Nielsen D R (1991). Soil spatial variability along transects. Soil Technology, 4, 297-314

Burgess T M; Webster R (1980). Optimal interpolation and isarithmic mapping of soil properties, 1, the semivariogram and punctual kriging. Journal of Soil Science, 31, 315-331

Carr P M; Carlson G R; Jacobson J S; Nielsen G A; Skogley E O (1991). Farming soils, not fields: a strategy for increasing fertilizer profitability. J. Prod. Agric., (4), 57-61

Curfs H P F (1976).Systems development in agricultural mechanization with special reference to soil tillage and weed control : a case study for West Africa. PhD thesis, Landbouwhogeschool, Wageningen

Delin S; Linden B (2000). Within-field variations in plant-available soil nitrogen - possibilities to predict and relevance for optimal nitrogen fertilization. Proceedings (CD) of the Fifth International Conference on Precision Agriculture, Minneapolis, MN, USA, ASA, CSSA, SSSA, Madison, WI, USA

Goense D (1987).Mechanized farming in the humid tropics with special reference to soil tillage, workability and timeliness of farm operations. PhD thesis, Landbouwhogeschool, Wageningen

Goense D; Hofstee J W; van Bergeijk J (1996). An information model to describe systems for spatially variable field operations. Computers and Electronics in

Agriculture, 14, 197-214

Haapala H E S (1995).Position Dependent Control (PDC) of plant production. PhD thesis, University of Helsinki, Helsinki, Finland

Haines W B; Keen B A (1925). Studies in soil cultivation. II. A test of soil uniformity by means of dynamometer and plough. Journal of Agricultural Science, 15, 387-394

Hergert G W; Ferguson R B; Shapiro C A; Penas E J; Anderson F B (1995). Classical statistical and geostatistical analysis of soil nitrate-N spatial variability. Proceedings of the Second International Conference on Site-Specific Management for Agricultural Systems, Minneapolis, MN, USA, pp 175-186, ASA, CSSA, SSSA, Madison, WI, USA

Hokke G; Tanis T (1978). Workable days for field operations on arable farms. report 109. Institute of Agricultural Engineering, Wageningen, The Netherlands

ISO (1994). ISO/TC23/SC19/WG1 working document ISO 11783. International Organization for Standardization, Geneva

James D W (1978). Diagnostic soil testing for nitrogen availability : the effects of nitrogen fertilizer rate, time, method of application, and cropping pattern on residual soil nitrogen. Bulletin / Utah agricultural experiment station ; no. 497. Utah state university, Logan, USA

Journel A G; Huijbregts C J (1978). Mining geostatistics. Academic Press. New York.

Lamb J A; Rehm G W (2000). Spatial and temporal stability of pH, soil test phosphorous and soil test potassium. Proceedings (CD) of the Fifth International Conference on Precision Agriculture, Minneapolis, MN, USA, SSA, CSSA, SSSA, Madison, WI, USA

Linsley C M; Bauer F C (1929). Illinois agriculture experiment station. Circular 346

McBratney A B; Webster R (1981). Spatial dependence and classification of soil along a transect in northeast Scotland. Geoderma, 26, 63-82

McCown R L; Hammer G L; Hargreaves J N G; Holzworth D P; Freebairn D M (1994). APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agricultural Systems, 50, 255-271

Moore I D; Gessler P E; Nielsen G A; Peterson G A (1993). Soil attribute prediction using terrain analysis. Soil Science Society of America Journal, 57, 443-452

Nielsen D R; Biggar J W; Erh K T (1976). Spatial variability of field measured soil water properties. Hilgardia, 42, 215-259

Nielsen D R; Wendroth O; Parlange M B (1995). Opportunities for examining on-farm soil variability. Proceedings of the Second International Conference on Site-Specific Management for Agricultural Systems, Minneapolis, MN, USA, pp 95-132, ASA, CSSA, SSSA, Madison, WI, USA

Nolin M C; Guertin S P; Wang C (1996). Within field spatial variability of soil nutrients and corn yield in a montreal lowlands clay soil. Proceedings of the Third International Conference on Precision Agriculture, Minneapolis, MN, USA, pp 257-270, ASA, CSSA, SSSA, Madison, WI, USA

Perdok U D; Kroesbergen B; Kurstjens D A G (1997). Soil mapping at field level by air-dry moisture detection. Proceedings of the 14th Conference of ISTRO, Pulawny, Poland, pp 517-520

Pierce F J; Warncke D D; Everett M W (1995). Yield and Nutrient variability in glacial soils of Michigan. Proceedings of the Second International Conference on Site-Specific Management for Agricultural Systems, Minneapolis, MN, USA, pp 133-149, ASA, CSSA, SSSA, Madison, WI, USA

Portiek J H (1977). Workable time and the weather. Research report 77-6. Institute of agricultural engineering, Wageningen, The Netherlands

Rawlins S L (1996). Moving from precision to prescription farming: the next plateau. Proceedings of the Third International Conference on Precision Agriculture, Minneapolis, MN, USA, pp 283-294, ASA, CSSA, SSSA, Madison, WI, USA

Searcy S W; Schueller J K; Bae Y H; Borgelt S C; Stout B A (1989). Mapping of spatially variable yield during grain combining. Transactions of the ASAE, 32(3), 826-829

Stafford J V; Ambler B (1994). In-field location using GPS for spatially variable field operations. Computers and Electronics in Agriculture, 11, 23-36

Stafford J V; Bolam H C (1996). Improving the reliability of position resolution using GPS for precision agriculture. AgEng96, Madrid

Stone M L; Solie J B; Raun W R; Whitney R W; Taylor S L; Ringer J D (1996). Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Transactions of the ASAE, 39(5), 1623-1631

van Aartsen J J (1995). Mest- en ammoniakbeleid [Manure and ammonia directives], Tweede Kamer, vergaderjaar 1995–1996, 24 445, nr. 1. Ministerie van Landbouw, Natuurbeheer en Visserij, Sdu Uitgeverij Plantijnstraat. 's-Gravenhage.

van Burg P F J; Holmes M R J; Dilz K (1984). Sugar beet, nitrogen supply from fertilizers and manures. Agricultural bureau of the Netherlands fertiliser industry, The Hague

van Es H M; Sogbedji J M; Cox W J; Klausner S D; Bouldin D R (2000). Spatial vs. temporal management of nitrogen in precision agriculture. Proceedings (CD) of the Fifth International Conference on Precision Agriculture, Minneapolis, MN, USA, ASA, CSSA, SSSA, Madison, WI, USA

Verhagen A (1997). Site specific fertilizer application for potato production and effects on N-leaching using dynamic simulation modelling. Agricultural Ecosystems & Environment, 66, 165-175

Verhagen A; Verburg P; Sybesma M; Bouma J (1995). Terrain modelling as a basis for optimal agroecological land management using dynamic simulation. Proceedings of the Second International Conference on Site-Specific Management for Agricultural Systems, Minneapolis, MN, USA, pp 229-250, ASA, CSSA, SSSA, Madison, WI, USA

Wösten J H M; Bannink M H; de Gruijter J J; Bouma J (1986). A procedure to identify different groups of hydraulic-conductivity and moisture-retention curves for soil horizons. Journal of Hydrology, 86, 133-145

Zachariasse L C (1974). Analyse van de verschillen in fysieke opbrengsten van enkele gewassen op overeenkomstige akkerbouwbedrijven in de noord-oost-polder. [analysis of the yield differences of several crops on alike farms in the 'noord-oost-polder']. Publikatie no. 7. Agrarische bedrijfseconomie, Landbouwhogeschool, Wageningen

Zangh M; Nyborg M; Solberg E D (1996). The factor time: a new consideration in precision farming. Proceedings of the Third International Conference on Precision Agriculture, Minneapolis, MN, USA, ASA, CSSA, SSSA, Madison, WI, USA

Chapter 2

Digital Filters to Integrate Global Positioning System and Dead Reckoning

Bergeijk J. van[1] , Goense D.[2], Keesman K. J.[1], L. Speelman

[1]Wageningen University, Department for Agricultural, Environmental and Systems Technology, Bomenweg 4, 6703 HD Wageningen, The Netherlands

[2]Institute for Agricultural and Environmental Engineering (IMAG), PO Box 43, 6700 AA Wageningen, The Netherlands

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Abstract

The design, test and results of a positioning system consisting of a differential global positioning system (DGPS) receiver, a radar velocity sensor, a wheel velocity sensor and an electronic compass are discussed. The characteristics of the individual sensors were investigated and with these results a Kalman filter was designed to integrate the different signals into a single estimate of position, velocity and heading. Field tests were conducted to investigate both the real time performance of the system and the robustness against distortions caused by malfunctioning of the sensors. An extended Kalman filter was found to improve accuracy of positioning and was able to bridge gaps in position information due to blockage of the DGPS receiver. The position measurements from the DGPS receiver had a standard deviation of 1.18 m. The use of a nine state filter reduced the standard deviation of positioning to 0.71 m. On a track which ran along a line of trees and between buildings, the filter was able to maintain position for 12 s, while the DGPS receiver lost satellite fix.

Keywords: Precision Agriculture, Global Positioning System, GPS, Dead Reckoning, Kalman filter.

Notation

A	acceleration, m/s^2
a	parameter first order autoregressive model
b,c,d,e	parameters compass correction model
E	expected value
F_{dose}	application dose, kg/ha
F_{rate}	application rate, kg/s
G	system noise matrix
H	observation matrix
h	input coupling matrix
I	identity matrix
K	Kalman gain matrix
P	covariance matrix of state estimate uncertainty
Q	covariance matrix of process noise
R	covariance matrix of measurement noise
S	position, m
T_s	sample interval, s
u	white noise term
V	velocity, m/s
v	measurement noise
W	applicator width, m
w	process noise
x	state vector
z	measurement vector
α	heading on xy plane, 0 rad = north, 0.5π rad = east
Φ	state transition matrix

Superscripts

T	transpose
^	estimate

Subscripts

a	autoregressive state
c	compass heading measurement
i	time index
gps	gps heading measurement
gx	gps x position measurement
gy	gps y position measurement
k	time index
r	radar velocity measurement
w	wheel velocity measurement
x	in x direction of 2 dimensional plane
y	in y direction of 2 dimensional plane

2.1. Introduction

Precision agriculture is one of the descriptions for a crop management method in which spatial and temporal variations within fields are identified and analysed in order to optimize the agricultural production process for both profitability and sustainability, (Robert *et al.*, 1994). An essential part of this site specific crop management is the use of positioning systems on agricultural machinery. Recent research has shown that positioning based on satellite signals offers good possibilities for machinery operating under field conditions (Stafford & Ambler, 1994). With sufficient satellites 'in view', such a system is able to determine its horizontal position with an accuracy from several meters down to one centimeter, depending on the signal processing mode (Larsen *et al.*, 1994). Despite these promising accuracies, the major drawback of a positioning system based on satellite signals is the reliability. When, for instance, obstacles such as trees and buildings block the satellite signals, positioning becomes difficult and can lead to erratic results. In a precision agriculture context, field operations such as fertilizer application or herbicide spraying relate the application rate to a specific site in a field. These 'variable rate technology' (VRT) based operations require a reliable continuous update of implement position.

Another type of navigation is to measure the dynamics of the vehicle to reconstruct the followed track. This positioning method, known as dead reckoning, works without the use of external beacons such as satellites. In aviation, several accelerometers, integrated into an inertial navigation system (INS), reconstruct a followed trajectory (Hofman *et al.*, 1992). For navigation on land and sea, the combination of travelled distance with the measured heading or steering angle is used to estimate position from a known starting point (Auernhammer & Muhr, 1991). The advantage of a dead reckoning method is that it is not dependent on the presence of external beacons. However, over a longer period of operation, degradation of accuracy is inevitable and this is the major drawback of dead reckoning. Another point of concern is that calibration of dead reckoning sensors is required. With the characteristics of the two positioning methods, i.e. with beacons or without beacons, combined, it is possible to construct an even more reliable positioning system with long term, stable accuracy.

The object of this study is to design a positioning system that is able to provide an accurate position, velocity and heading under field conditions. In order to avoid incorrect application rates, both accuracy and reliability of these quantities must be estimated in real time by the positioning system itself. Another function of the positioning system is the calibration of individual sensors, such as odometer, gyroscope and flux gate compass.

The positioning system is intended for agricultural applications which require different application rates of, for instance, fertilizers, at different locations in a field. Position errors might lead to the application of incorrect doses with respect to these locations. As the application rate is directly related to velocity according to Eqn (2.1), velocity errors must be minimized.

$$F_{rate} = \frac{F_{dose}}{10000} W V \tag{2.1}$$

where: F_{rate} is the application rate in kg/s; F_{dose} is the application dose in kg/ha; W is the applicator width in m; and V velocity in m/s.

A correct heading measurement is required to calculate the position of the applicator's sections relative to the position reference point. To ensure correct application rates, a fault detection method must detect when accuracy of one of the measurements drops below a specified limit for the particular field operation.

2.2. Kalman filtering

The term filtering generally refers to methods to remove unwanted components from a signal. Analog filters, limited by their actual implementation, were usually designed to just remove high frequency noise. Digital filters can handle more complex signal processing tasks. A digital filter contains an algorithm that acts on a sequence of input values producing another sequence of output values.

Navigation is one of the areas in which the Kalman filter procedure has proven its usefulness (Hofman *et al.*, 1992). Enhancements of the Wiener filter around 1960 by Kalman resulted in a filter which theoretically is the optimal estimator to linear-quadratic-Gaussian problems (Grewal & Andrews, 1993). While originally designed to be used on linear systems, an extension to the algorithm more widely known as the extended Kalman filter (EKF) was made (Schmidt, 1966).

The starting point of the Kalman filter is the state space model of the dynamical system. In the case of a positioning system, a discrete time state space model without control inputs is used:

$$x_{k+1} = \Phi\, x_k + G_k\, w_k$$
$$z_k = h(x_k) + v_k$$

where: $x_k = [\ S_x\ \ V_x\ \ A_x\ \ S_y\ \ V_y\ \ A_y\ ]^T$ is the state vector; $z_k = [\ S_{gx}\ \ S_{gy}\ \ V_w\ \ V_r\ \ \alpha_c\ ]^T$ is the measurement vector; w_k is the system noise and v_k is the measurement noise.

Other symbols are defined in the Notation. In addition, the system matrix Φ is given by:

$$\Phi = \begin{bmatrix} 1 & T_s & \frac{1}{2}T_s^2 & 0 & 0 & 0 \\ 0 & 1 & T_s & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & T_s & \frac{1}{2}T_s^2 \\ 0 & 0 & 0 & 0 & 1 & T_s \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where T_s is the sampling interval. The noise matrix G is specified as $G = [0\ 0\ 1\ 0\ 0\ 1]^T$.

Notice that the system noise is specified only for the unknown acceleration terms. A nonlinear vector $h(x_k)$ Relates the states to the measurements and is defined as:

$$h(x_k) = \begin{bmatrix} S_x \\ S_y \\ \sqrt{V_x^2 + V_y^2} \\ \sqrt{V_x^2 + V_y^2} \\ \arctan(\frac{V_x}{V_y}) \end{bmatrix}_k$$

However, for the implementation of the EKF this function has to be linearized with respect to the state variables. The linearization is performed around the previously estimated values, so that the observation matrix H_k takes the following form:

$$H_k = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & \frac{V_x}{\sqrt{V_x^2+V_y^2}} & 0 & 0 & \frac{V_y}{\sqrt{V_x^2+V_y^2}} & 0 \\ 0 & \frac{V_x}{\sqrt{V_x^2+V_y^2}} & 0 & 0 & \frac{V_y}{\sqrt{V_x^2+V_y^2}} & 0 \\ 0 & \frac{V_y}{V_x^2+V_y^2} & 0 & 0 & -\frac{V_x}{V_x^2+V_y^2} & 0 \end{bmatrix}_{k-1}$$

On the basis of the linearized state space model, the EKF prediction and correction steps for the specific problem can be implemented as follows.

Prediction step :

$$\hat{x}_{k/k-1} = \Phi\, x_{k-1}$$

$$P_{k/k-1} = \Phi\, P_{k-1}\, \Phi^T + G\, Q_k\, G^T$$

Correction step:

$$K_k = P_{k/k-1}\, H_k^T\, [H_k\, P_{k/k-1}\, H_k^T + R_k]^{-1}$$

$$\hat{x}_{k/k} = \hat{x}_{k/k-1} + K_k[z_k - h(\hat{x}_{k/k-1})]$$

$$P_{k/k} = [I - K_k\, H_k]P_{k/k-1}$$

In the first step $\hat{x}_{k/k-1}$ denotes the prediction of x_k given x_{k-1}. The 6 x 5 matrix K_k is called the Kalman gain matrix, which weights the effect of the prediction error $[z_k-h(\hat{x}_{k/k-1})]$ on the final estimate $\hat{x}_{k/k}$. The matrices Q_k and R_k are the covariance matrices of the system noise w_k and the measurement noise v_k, respectively. These covariance matrices are defined as:

$$E[w_k w_i^T] = \begin{cases} Q_k, i = k \\ 0, i \neq k \end{cases}$$

In this particular case Q_k is a 6 x 6 diagonal matrix and R_k is 5 x 5 diagonal matrix. For further interpretation of the filter and specific implementation aspects the reader is

$$E[v_k v_i^T] = \begin{cases} R_k, i=k \\ 0, i \neq k \end{cases}$$

$$E[w_k v_i^T] = 0 \qquad \forall\ i, k$$

referred to (Grewal & Andrews, 1993) and (Bierman, 1977).

2.3. Experiment architecture

Two different GPS receiver sets were used in the experiment. The first one, mounted on the tractor, is a coarse acquisition code receiver with an accuracy of 2-5 m r.m.s. in differential mode. The second GPS receiver set was used to digitize the validation track of the field trials. This receiver uses carrier phase information of the satellite signals to enhance accuracy to 1-2 cm in the horizontal plane in differential mode. A more comprehensive explanation of different GPS receivers and signal processing modes is given by (Krüger *et al.*, 1994) and (Hofman *et al.*, 1992).

The dead reckoning method was based on wheel velocity, radar velocity and compass heading. Wheel velocity was measured by an inductive sensor which counted rotations of the driving-axle. A second velocity measurement was acquired by a standard radar device. The compass heading was measured with an electronic flux gate compass mounted on an aluminium boom to minimize magnetic interferance. The characteristics of the individual sensors are discussed in Section 2.4.

Figure 2.1 shows schematically, the structure of the positioning system. The sensors for position, velocity and heading were connected to a personal computer based data acquisition system equipped with analogue to digital conversion, counter inputs and RS-232 port. The datalogging rate for the GPS receiver was restricted to the maximum update rate of 4 Hz. Velocity and heading measurements were acquired at 40 Hz sample frequency.

The individual sensors were analysed by examination of the logged data from several experiments. The experiments covered both different tractors and different road and field conditions. The in-field validation track, mapped in cartesian coordinates of the map projection for the Netherlands, is depicted in *Fig. 2.2*. Alongside this validation track, ten reference points were marked by a pole and digitized in the data files through the

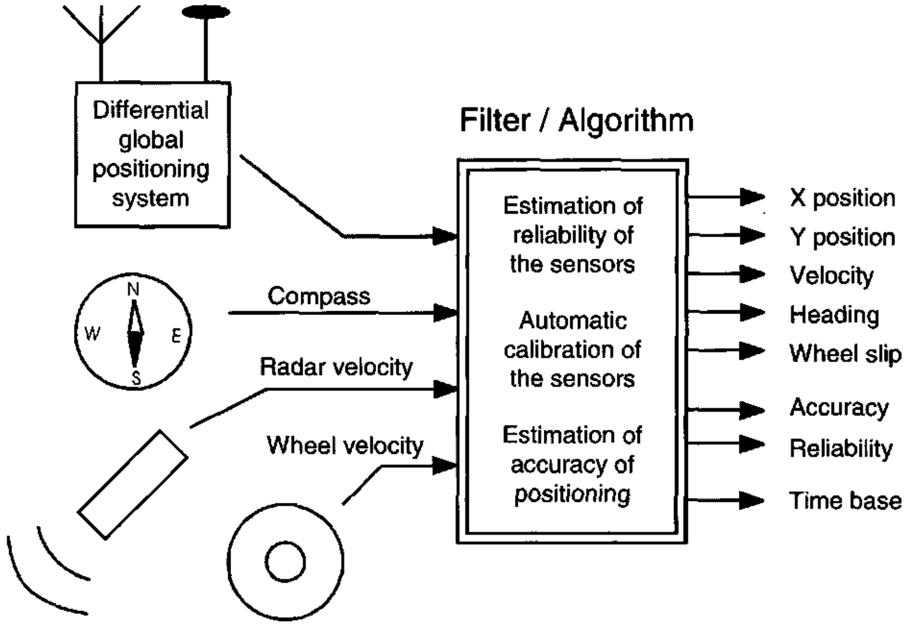

Fig. 2.1. Components of positioning system

interruption of a light bridge on the tractor. On each validation run, the tractor started at a reference point marked as the start point, travelled along the southermost path to the turning where it completed a turn of one and a half circles before returning along the northern path to stop at the start point again. Different runs at different velocities were conducted during which all data was stored on hard disk. Manual modifications to the data made it possible to simulate disturbances of sensor signals and to evaluate the filter response. Of the various Kalman filter designs, three different filters are discussed in Section 2.4. A real time version of each filter was implemented on the personal computer to operate on a tractor. However, the results, presented in Section 2.6, are based on postprocessing of the data stored during the validation runs.

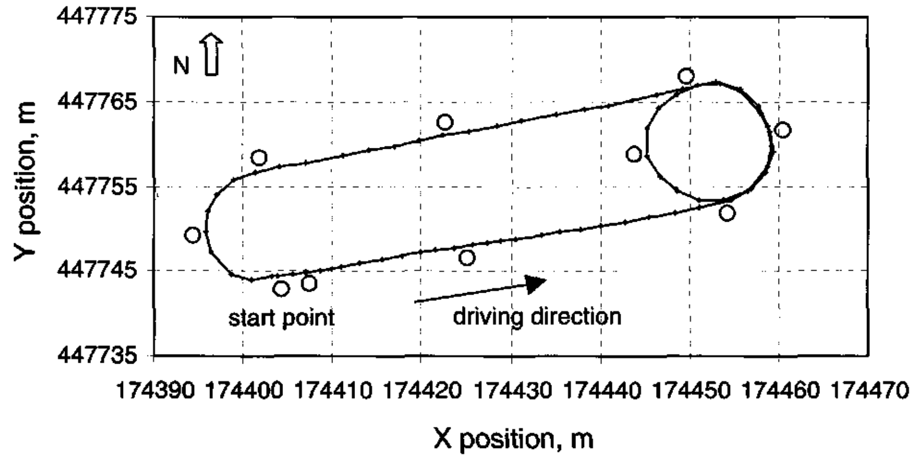

Fig. 2.2. Validation track with marked (o) reference points

2.4. Sensor analysis

2.4.1. *Global positioning system*

The C/A (coarse acquisition) code differential GPS system consisted of a Navstar XR5M-6 channel rover and a Navstar XR5M-12 channel base station connected by an UHF data link. The position information from the rover was updated at 4 Hz. The data string from the rover contained the following information:

(1) Position (WGS-84 latitude, longitude and altitude);
(2) GPS time and date;
(3) GPS velocity (km/h);
(4) GPS heading (degrees);
(5) Receiver operational mode;
(6) PDOP (positional dilution of precision); and
(7) Identifiers of the satellites used to calculate solution

Position data was converted from WGS-84 coordinates to a local cartesian system in meters. This datum transformation was required as the state variables of the filter were defined in a cartesian coordinate system. For Dutch geodetic coordinates, the conversion procedure and its parameters are described by (Strang van Hees, 1994) and implemented in the data acquisition software. The GPS velocity and heading were calculated in the receiver by comparing subsequent position measurements. At low velocities (<1 m/s), these data were rather inaccurate because of the small displacements between position measurements and the errors of the individual measurements. At velocities greater than 1 m/s, the heading was sufficiently accurate to calibrate the electronic compass. The receiver operational mode allows the user to check the status of the receiver. Operational modes varied between 'no fix' where positioning by GPS is impossible and 'differential three dimensional' for the most accurate (2-5 m r.m.s.) positioning in both horizontal plane and vertical height. The different operational modes required different error modelling of the GPS signals. The PDOP is the estimated accuracy of the position measurements, based on the geometry of the satellites in view. Low values of PDOP indicate that the satellites used to calculate the position are all in different directions across the sky. A high PDOP value indicates that all visible satellites are in the same area of the sky, either due to obscuration of satellite signals from other directions or due to malfunctioning of a satellite itself. Similar to the operational mode, the PDOP value was

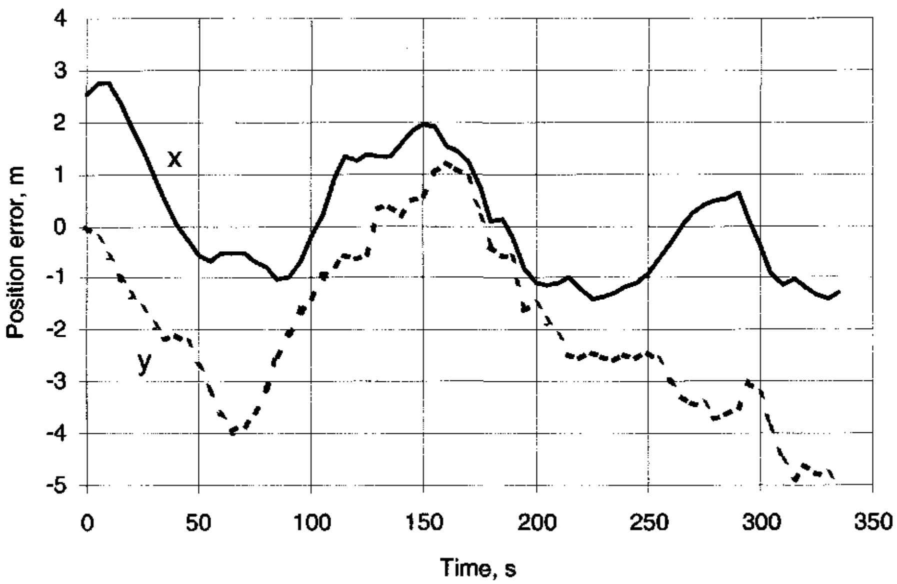

Fig. 2.3. GPS errors on the validation track; x position error (x) and y position error (y)

used to optimize positioning system performance.

Figure 2.3 shows the position performance of the GPS receiver while driving the validation track at a constant velocity of 0.6 m/s. Both x and y position errors show high autocorrelation. A first order autoregressive function describes a large part of the error. Eqn (2.2) gives this function in state transition form and expresses the relation between two values of output x from successive time steps.

$$x_{k+1} = a\, x_k + u_k \tag{2.2}$$

where: x_k is output at time k; a is the parameter of the first order autoregressive model; and u_k is the noise term.

Table 2.1 lists the characterizing parameters for these position errors.

Table 2.1
Coarse acquisition differential GPS position errors at validation track

	Variance, m^2	*Parameter (a) of the first order auto-regressive model*	*Variance of residuals of auto-regressive model*
X position error	3.25	0.9994	0.0028
Y position error	1.72	0.999	0.0059

2.4.2. *Wheel and radar velocity*

On current agricultural vehicles, various methods are used to determine wheel velocity. Often, a velocity measurement on a non driven wheel or obtained from a radar sensor is referred to as 'true ground velocity' (ISO, 1995). The output of a sensor mounted in the drive train or connected to the rear driven wheels is affected by slip. Special care must be taken when a velocity sensor is mounted on the drive axle of a tractor with an extra front wheel drive option. When the front wheel drive is switched on or off, the sensor measures two different parameters.

Two tractors were used to test the positioning system. During the experiments the same radar velocity sensor was used, but each tractor had its own wheel velocity measurement method. On the first tractor (MB-trac 65/70), an inductive switch was mounted near a ring of bolts on the rear drive axle. The output pulse rate of this sensor (wheel sensor 1) is 21 pulses/m which is rather low for good resolution at low velocities. The second tractor (Deutz 6.38SE) was equipped with a velocity sensor according to ISO standard 11786. This sensor (wheel sensor 2) was mounted on the front wheel drive axle and was calibrated with front wheel drive turned off. With the front wheel drive turned on the sensor output needed a gain correction for the velocity ratio between front and rear wheels. The calibrated output pulse rate of this sensor was 136 pulses/m which is close to the 130 pulses/m according to ISO standard 11786.

On the validation tracks, the MB-trac was used. The on-farm reliability tests were conducted with the Deutz tractor. The different error model parameters are listed in Table 2.2. Autocorrelation in the signal was low when the sensor calibration was optimized on a straight road surface. During field tests, autocorrelation was higher and had to be modelled by a first order autoregressive model. The explanation is that wheel slip during turnings on the validation track led to velocity sensor errors up to 5% with high autocorrelation. For the signal characterisation, data from field tests were used.

The radar velocity measurement device outputs a pulse train with a frequency dependent on both the angle between radar beam and soil surface and the velocity. In the experiment, a Dickey John RADAR II was used. Typically, the radar device outputs pulses at 100 Hz at 1 m/s, but calibration for mounting angle is needed to obtain a more accurate velocity measurement. Specifications of this sensor, important for further processing, are: velocity range of 0.11 to 19.7 m/s; velocity error (calibrated) of ± 1 to 3%; and response time less than 200 ms to a velocity change of 1.78 ms^{-2}

The error of the radar signal had low autocorrelation on straight tracks driven at constant velocity. During turning and over the irregular ground surface on the validation track, autocorrelation increased. Table 2.2 lists the parameter values of the radar velocity error model. These values were obtained from a field validation track marked on a dry sandy loam soil without crop.

th radar and wheel velocity are measured in the positioning system by a frequency method. If the velocity range on agricultural equipment is in the range 0 to 20 m/s, the frequency method must be able to measure frequencies from 0 to 2.8 kHz (20 m/s x maximum of 140 pulses/m). In the datalogger, two AMD 9513 interated circuits are used to implement the frequency measurement algorithm for the radar and wheel velocity signals. Two important criteria for the design of a frequency measurement algorithm are a fast response to frequency changes and low noise in frequency reading. The algorithm has an update rate of 40 Hz and is basically a time period measurement combined with a smoothing filter. The lowest measurable frequency is set at 4 Hz, equivelent to 0.04 m/s for the radar sensor and 0.03 m/s for the ISO standard velocity sensor. The capability to measure lower frequencies would cause a too large time lag in the frequency measurement. The counter operates in 'hardware triggered sample and hold' mode. With a source clock of 2.5 MHz, the resolution at the upper limit of 2.8 kHz is 3.1 Hz which represents an accuracy of 0.1%. Measurement frequencies above 40 Hz have a fixed time lag of 0.1 s due to smoothing eight period times. From 40 Hz down to 4 Hz, the time lag increases to a maximum of 0.5 s.

Table 2.2
Velocity sensor error characteristics

Velocity sensor	*Variance, m^2/s^2*	*Parameter (a) of the first order autoregressive model*	*Variance of residuals of autoregressive model*
Wheel sensor 1	0.001	0.9904	$<10^{-4}$
Wheel sensor 2	0.002	0.8684	$3x10^{-4}$
Radar sensor	0.002	0.8381	$3x10^{-4}$

The standard Kalman filter assumes that the sensor signals are only disturbed by white noise. For velocity sensors, the signal is both affected by an offset due to miscalibration and a noise factor. To handle these signals, either the variance of the error must be increased to match the miscalibration or an extra state has to be added to the filter to model the calibration error. Both methods will be discussed in Section 2.5.

2.4.3. *Compass heading*

The electronic compass, VDO type Adis 360, outputs two analogue voltages with an amplitude corresponding to the heading relative to the earth's magnetic field. The positioning system acquires both analogue voltages at 40 Hz sample rate and smooths the signals. From these signals, the heading is calculated and updated at 4 Hz rate. The dynamic behaviour of the compass was not specified by the manufacturer. A manual calibration procedure to correct compass output for local magnetic disturbances was part of the compass electronics.

The compass had to be at least 1.5 m clear of any iron or steel parts on the tractor to avoid magnetic disturbances. A mounting place conforming to these requirements was

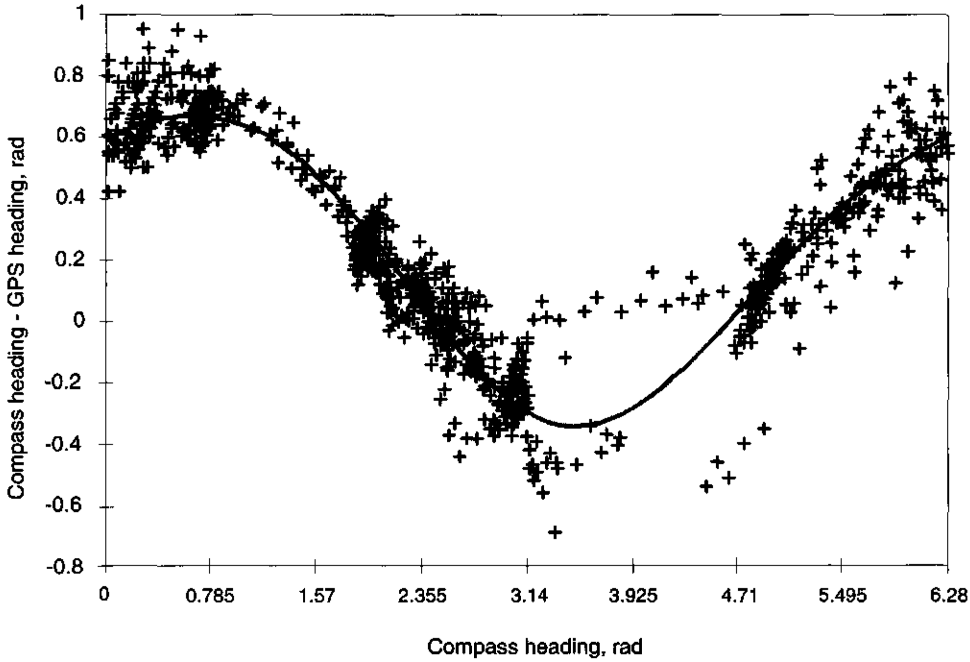

Fig. 2.4. Measured (+) and modelled (solid line) compass and GPS heading differences against compass heading

difficult to find on a standard tractor. As a result, it was not possible to manually calibrate the compass correctly on the Deutz tractor. However, comparison of the compass heading measurements with the GPS heading measurements showed a consistent pattern of compass deviation over the full measurement range. This deviation could be modelled by a function according to Eqn (2.3).

$$\alpha_c - \alpha_{gps} \approx b \sin(c + \alpha_c) + d \sin(e + 2\alpha_c) \tag{2.3}$$

Where: α_c is compass heading [rad], 0 rad = north, 0.5π rad = east; α_{gps} is GPS heading [rad], 0 rad = north, 0.5π rad = east; b,c,d,e are parameters of the correction model.

Figure 2.4 shows both the compass deviation as a function of compass heading and the modelled correction. Data in this figure was obtained from six hours of data logged during field work (ploughing), where periods with low GPS accuracy were filtered out before comparison with compass heading measurements was made. For a different tractor or for a different mounting position of the flux gate compass, the parameters b, c, d and e in Eqn (2.3) had to be adapted. This adjustment can be done off-line on the basis of an experiment in which a circle is driven at constant speed with accurate GPS measurements acquired. An on-line procedure might do this calibration automatically by comparing compass heading measurements with reliable periods of GPS heading measurements.

The compass error characteristics after the correction for local deviations are listed in Table 2.3. Due to autocorrelation in the signal, an extra state for the compass error has to be added to the state model of the Kalman filter.

Table 2.3
Flux gate compass error characteristics

	Variance, rad^2	*Parameter (a) of the first order autoregressive model*	*Variance of residuals of autoregressive model*
Flux gate compass	0.0128	0.8434	$2x10^{-4}$

2.5. Filter design

The first filter design (filter A) was an extended Kalman filter with six states (x and y positions S_x and S_y, x and y velocities V_x and V_y, and x and y accelerations A_x and A_y) and five sensor inputs (S_{gx} and S_{gy} from the GPS, wheel velocity V_w, radar velocity V_r and compass heading α_c). The general structure for a GPS-INS navigation system, described in (Grewal & Andrews, 1993), was followed. Precautions had to be taken at the coupling between the dead reckoning sensor signals and the state estimate update. For instance, the compass sensor signal range is defined between 0 and 2π radians. Part of the liniarizations was to correct the compass measurement estimator to be continuous over the 0 and 2π boundaries. The velocity measurements were decomposed into the corresponding V_x and V_y in the same cartesian coordinate system as the position measurements. In this filter A, the system model noise was coupled to the acceleration states only.

While on our platform no acceleration sensors were used, another option was to omit the acceleration states and have the system model noise acting directly on the velocity states. This resulted in Filter B which had the advantage of a reduced of computation time when compared to filter A.

Filter C was based on filter B but had five states added to model the individual sensor errors ($x_{a,gx}\ x_{a,gy}\ x_{a,w}\ x_{a,r}\ x_{a,c}$). The first order autoregressive model parameters, determined for each sensor, were used to correctly model autocorrelation present in the sensor signals. The additional error states were estimated parallel to the position velocity part of the model. Whether it pays off to process this more complicated filter depends on the accuracy requirements.

The state and measurement vectors for these three filter configurations are summarized below. The applied linearization method is the evaluation of partial derivatives in the measurement equations at every time step.

Filter A

State vector:	$x_1 = [\ S_x\ \ V_x\ \ A_x\ \ S_y\ \ V_y\ \ A_y\ ]^T$
Measurement vector:	$z = [\ S_{gx}\ \ S_{gy}\ \ V_w\ \ V_r\ \ \alpha_c\ ]^T$
System dynamic model:	$x_{1,k} = \Phi_{k-1}\, x_{1,k-1} + w_{k-1}$
	$w_k \sim N(0,Q_k)$
Measurement model:	$z_k = H_k\, x_{1,k} + v_k$
	$v_k \sim N(0,R_k)$

Filter B

State vector:	$x_2 = [\ S_x\ \ V_x\ \ S_y\ \ V_y\ ]^T$
Measurement vector:	$z = [\ S_{gx}\ \ S_{gy}\ \ V_w\ \ V_r\ \ \alpha_c\ ]^T$
System dynamic model:	$x_{2,k} = \Phi_{k-1}\, x_{2,k-1} + w_{k-1}$
	$w_k \sim N(0,Q_k)$
Measurement model:	$z_k = H_k\, x_{2,k} + v_k$
	$v_k \sim N(0,R_k)$

Filter C

Autoregressive states: $x_3 = [\ x_{a,gx}\ x_{a,gy}\ x_{a,w}\ x_{a,r}\ x_{a,c}\ ]^T$

State vector: $x_4 = [\ x_2\ \ x_3\ ]^T$

Measurement vector: $z = [\ S_{gx}\ \ S_{gy}\ \ V_w\ \ V_r\ \ \alpha_c\ ]^T$

System dynamic model: $x_{2,k} = \Phi_{k\text{-}1}\, x_{2,k\text{-}1} + w_{k\text{-}1}$

$x_{3,k} = x_{3,k\text{-}1} + w_{k\text{-}1}$

$w_k \sim N(0,Q_k)$

Measurement model:

$$z_k = \begin{bmatrix} H_k & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} x_2 \\ x_3 \end{bmatrix}_k + v_k$$

$v_k \sim N(0,R_k)$

Table 2.4

Filter performance compared with sensor performance

	Position error, m		*Velocity error, m/s*		*Heading error, rad*	
	Mean	*St.dev.*	*Mean*	*St.dev.*	*Mean*	*St.dev.*
GPS	2.21	1.18	-	-	0.088	0.44
Wheel	-	-	0.014	0.034	-	-
Radar	-	-	-0.012	0.049	-	-
Compass	-	-	-	-	0.068	0.38
Filter A	1.86	0.99	0.008	0.037	0.063	0.40
Filter B	1.89	0.97	0.006	0.035	0.062	0.43
Filter C	1.54	0.71	-0.009	0.041	0.072	0.41

2.6. Results

The filter and sensor performance on several validation runs, totalling 3600 observations, is listed in Table 2.4. The position error was defined as the distance between filter position output and actual position on the x,y-plane. The velocity error is the difference between filter velocity output and actual velocity. A positive mean velocity error indicates that the filter velocity output is on average larger than the actual velocity while a

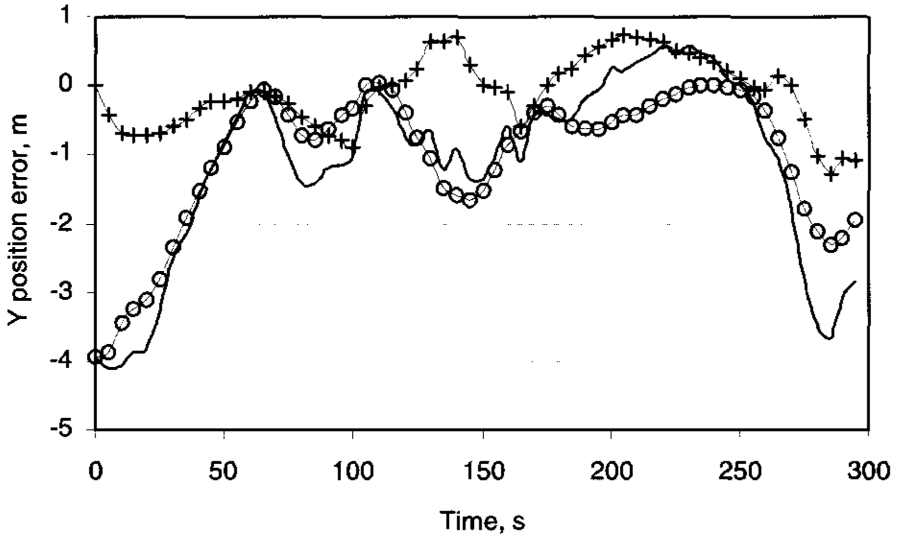

Fig. 2.5. Filter C y position error (+) compared with GPS error (solid line) and GPS error estimate (o)

negative mean velocity error quantified the bias between filter velocity output and actual velocity as negative. The heading error was defined as the difference between filter heading output and actual heading. The mean heading error is, similar to mean velocity error, the bias of the filter heading output. The high standard deviation of the GPS heading error was due to the low velocity, 0.6 m/s, on this evaluation track. The standard deviation of the compass heading error was only slightly smaller when compared to GPS heading error.

The errors of the individual sensors were in general larger than the filter output. Only the heading output error of filter C was slightly worse than the original compass error. The difference between filter A and filter B was small. Filter C reduced the position error, though the velocity and heading errors slightly increased. The improvement of position accuracy is illustrated in *Fig. 2.5*. The effect of estimating the position error by an autoregressive model error state was especially important for this y position improvement. As shown in *Fig. 2.5*, the estimate of the GPS y position error followed the actual GPS y position error quite closely.

To test the behaviour of the filter under poor satellite 'visibility' conditions, a track on a farm yard, between several buildings and parallel to a line of trees, was chosen. In *Fig. 2.6*, the driving direction was from southeast at the start to northwest at the finish. At the northeast corner when the tractor crossed the tree line, the GPS lost satellite fix and jumped to positions 20-30 m from the real position. The positioning system then relied on dead reckoning and the reconstructed path of the tractor shows the turn from the yard onto the road parallel to the tree line. The GPS receiver needed about 80 m, during 12 s, to recover from the satellite loss. For this track, no accurate reference position data existed, so a numerical value for the filter performance cannot be given.

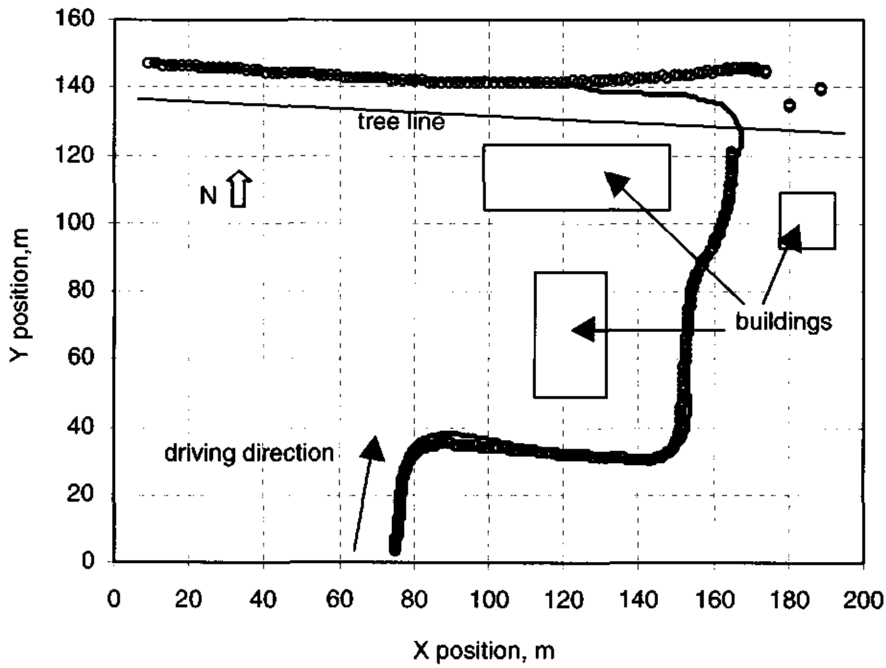

Fig. 2.6. Filter A position output (solid line) compared with GPS measurements (o) during a satellite no fix period in the north east corner

2.7. Discussion

The extra states in filter C allowed a more accurate description of errors in the different signals. Table 2.4 shows that this approach works since the accuracy of the filter output improved. Two arguments against these extra states must be mentioned. First, real time performance of filter C will cost more processing power compared with filter A to maintain the same update rate. Secondly, filter C is less stable due to interference between estimating both GPS error states and dead reckoning error states. While the effect of the autoregressive model is strongest on the GPS position, the optimal filter might be filter A with two states added to handle x and y autocorrelations.

The effect of omitting the accelerations in the state model was low on the validation track (Table 2.4). In practice, the difference between filter A and filter B output on the track through the farm yard was larger. If one of the sensors degrades, it seems to be more important to have an accurate system model. Therefore even when no acceleration sensor is used and accelerations are not needed outside the filter, the acceleration states proved to be useful for maintaining the accuracy of the positioning system.

The flux gate compass sensor is the weakest point in the positioning system. Both for accuracy and mounting possibility, an alternative is needed. For short periods of dead reckoning, a gyroscope might give better results. GPS heading, measured during a correct satellite fix when driving at a velocity above 1 m/s, was more accurate than compass heading. GPS heading might therefore be used as an extra sensor to calibrate an independent heading device in the dead reckoning part of the positioning system.

2.8. Conclusions

The standard deviation of positioning decreased from 1.18 m to 0.71 m for a nine state Kalman filter integrating dead reckoning with GPS. The reliability of a dead reckoning - GPS integrating positioning system improved too. Under practical circumstances, dead reckoning was able to bridge up to 12 s of GPS no-fix status without a dramatic decrease in accuracy.

The system model for a position filter was most accurate with a position-velocity-acceleration state model. Extra states to model autocorrelation in the sensor signals are needed for both GPS and dead reckoning sensors. If improvement of positional accuracy is the main object of the positioning system, then two extra error states for the autocorrelation factors of the GPS must be added to the system model. Calibration errors of the velocity sensors were not incorporated in the filter. However temporary velocity sensor degradations were filtered out through the implementation of extra error states, similar to the mechanism for handling autocorrelation in the sensor signals.

References

Auernhammer H; Muhr T (1991). GPS in a basic rule for environment protection in agriculture. In: Automated agriculture for the 21st century, publication 11-91 (pp 394-402, ASAE, Chicago

Bierman G J (1977). Factorization methods for discrete sequential estimation. Academic Press. New York.

Grewal M S; Andrews A P (1993). Kalman filtering : theory and practice. Prentice Hall. New Jersey.

Hofman B; Lichtenegger H; Collins J (1992). GPS, Theory and Practice. Springer-Verlag. New York.

ISO (1995). Standard 11786, Agricultural tractors and machinery - Tractor mounted sensor interface - Specifications (06/95).

Krüger G; Springer R; Lechner W (1994). Global navigation satellite systems (GNSS). Computer and Electronics in Agriculture, (11), 3-21

Larsen W E; Nielsen G A; Tyler D A (1994). Precision navigation with GPS. Computers and Electronics in Agriculture, (11), 85-95

Robert P C; Rust R H; Larson W E (1994). Proceedings of site specific management for agricultural systems,. Second international conference on precision agriculture, Minneapolis, American Society of Agronomy

Schmidt S F (1966). Applications of State-Space Methods to Navigation Problems, Advances in Control Systems. Academic Press. San Diego. Vol. 3.

Stafford J V; Ambler B (1994). In-field location using GPS for spatially variable field operations. Computers and Electronics in Agriculture, 11, 23-36

Strang van Hees G L (1994). Globale en lokale geodetische systemen [Global and local geodetic systems]. Nederlandse commissie voor geodesie. Delft

Chapter 3

Soil Tillage Resistance as a Tool to map Soil Type Differences

J. van Bergeijk[1]; D. Goense[2]; L. Speelman

[1] Wageningen University, Department for Agricultural, Environmental and Systems Technology, Bomenweg 4, 6703 HD Wageningen, The Netherlands.

[2] Institute for Agricultural and Environmental Engineering (IMAG), PO Box 43, 6700 AA Wageningen, The Netherlands,

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Abstract

Precision agriculture is based on spatial knowledge of soil and crop conditions in the management decisions. In this paper, a method to improve determination of soil physical properties is proposed. Current practice is to analyse soil samples, taken at several locations in a field, for physical properties. To obtain a sound coverage, many soil samples have to be analysed. When soil properties are correlated, it is possible to reduce the number of soil samples of one property and enhance its spatial resolution with the information of a more dense sampled other property. In this study, information gathered automatically during the major soil tillage operation, ploughing, is used to improve the spatial resolution of sampled top soil clay contents.

Plough draught was measured during two seasons on a six ha. field. The specific plough draught varied between 30 and 50 kN/m^2. Clay contents varied between 6 to 22 % and top soil moisture content range was 120 to 240 g kg^{-1} during the first year and 180 to 300 g kg^{-1} in the second year. The specific plough draught maps of both years showed a similar spatial pattern with a cross correlation coefficient at zero distance of 0.6.

The use of specific plough draught as co-variable in the co-kriging technique made it possible to decrease the number of top soil clay contents samples from 60 per ha to 18 per ha with only 20% increase in prediction error. On this field, the spatial variation in top soil clay contents was correlated with the spatial variation of the crop yield.

Keywords: Plough draught, soil mapping, kriging, co-kriging, precision agriculture

3.1. Introduction

The results of yield mapping on a highly variable fine-loamy, calcareous soil, show that grain yield and soil types are correlated (Finke & Goense, 1993). While yield mapping, at least in cereals, can be done automatically by harvesting equipment, determination of soil physical properties is more time and resource consuming. In precision agriculture, every cause of crop variability can be useful for management. Differences in water and nutrient availability are functions of soil type and have to be known in order to optimise field management.

Monitoring of soil tillage operations might recognise different soil types within a field. Mouldboard ploughing in the autumn at approximately 30 cm depth covers an entire field in a very comprehensive way and is general practice in Dutch agriculture. The electronic hitch control on modern tractors offers the opportunity to log the signals on working depth and draught force in order to create a soil tillage resistance map.

The main objective of the specific plough draught measurement is to support field management with information on the top soil condition. A detailed map of plough draught might help to subdivide a field into units that should be treated individually in precision agriculture field management. In addition, the recording of plough draught might reveal causes of local yield decreases due to, for example, soil compaction.

At an experimental level, the implementation of a plough draught recording system itself is a derived objective. The data acquisition system architecture and data recording requirements are more or less similar to yield mapping systems in the sense that various sensor signals, inclusive position, are measured and logged. Differences appear in the data processing algorithms regarding the depth correction and other plough operation specific issues.

The field experiments are designed to investigate the additional value of plough draught maps for site specific management. The experiments are part of a monitoring scheme established to quantify soil and crop characteristics, such as moisture dynamics, crop growth and crop yield. Related precision agriculture research in the same project focuses on the use of crop growth simulation models to support farm management activities. These models require many samples in space and time to properly determine soil properties such as bulk density, pore volume, hydraulic properties and moisture status. Utilisation of the spatially dense information provided by the measurement of specific plough draught might reduce the number of samples necessary to support site specific farm management.

In this study, a plough draught measurement system will be discussed. Furthermore, relations between soil and crop properties and plough draught are investigated and an effort is made to assess the contribution of plough draught measurements for the determination of a soil property map.

3.2. Literature review

Previous work shows the technical feasibility of the plough draught force measuring method (Wolfgang, 1992). Boundaries between adjacent soil types were detected, although soil physical characteristics were not quantified. The resolution of the measurement method was high enough to show local distortions, such as tramlines in a field.

Literature in which plough draught is mentioned focuses mainly on determination of factors influencing soil tillage draught. Research objectives were for instance to find the optimal mouldboard design for a certain soil type, to estimate the necessary tractor power for a given plough and soil condition and to optimise timing of tillage operations. Influences of velocity and depth on specific draught for four soil series have been measured to compare different plough bottom designs (Reaves & Schafer, 1975). Cone penetration resistance, specific weight, moisture content, mouldboard tail angle and plough speed are reported as major factors influencing specific draught. The cone index, closely related to soil moisture content, contributes most to a specific draught estimate (Oskoui & Witney, 1982; Oskoui *et al.*, 1982). In a study to investigate tillage draught and fuel consumption for different tillage implements for twelve soil series the specific draught force varied from 20 to 76 kN/m^2 (Bowers, 1989). The soil series ranged from loamy sands to clay loams with different soil moisture contents and tillage history. The influence of velocity and depth on tillage draught for four primary tillage tools on four Oklahoma soils have been investigated by Summers *et al.* (1986). Their interpretation of the experiments led to regression type formulaes that could only be compared with other regions if other factors, such as soil moisture content, are in the same range. More generic relations between tillage operations and draught may be useful for machine management but show large ranges in estimated draught (Harrigan & Rotz, 1995). Recent investigations to predict tillage implement draught force defined the draught of a standard tine as the product of a soil strength factor and a tool geometry factor

(Desbiolles *et al.*, 1997). In this model, the soil strength factor is a function of soil properties and depth and is correlated to the cone penetration energy (Desbiolles *et al.*, 1999). The tool geometrical factors of different tillage tools were reported and predicted draughts were on average within 18% of the measured draughts, acquired at low speeds (1.6 km/h).

Literature on the influence of individual soil physical properties on plough resistance shows that soil moisture content, soil texture and bulk density are the most important factors (Canarache, 1993; Kuczewski, 1982). The soil structure, roughness of the soil surface (Klenin *et al.*, 1985) and previous crop in the crop rotation (Perfect, 1997) also have influence on plough draught but these factors are less important. However, these influences might complicate comparison of plough draught maps of a single field acquired over several years.

3.3. Materials and methods

Two plough draught measurement systems, both based on conventional farm equipment, have been built. The first system (sensor evaluation system) was designed to allow a comparison of different sensors for measurement of draught, working width and working depth. This system operated on a research farm. The objective of the second system (prototype system) was to implement a plough draught measurement system that could be operated by a farmer. This system is equipped with a minimal set of sensors added to the plough and functions as a plough draught recording system in an on-farm precision agriculture research programme.

3.3.1. *Data Acquisition System*

The tractor-plough combination is equipped with a data logging system, consisting of an industrial personal computer chassis fitted with analogue and digital data acquisition cards. A number of sensors is mounted on the tractor-plough combination and connected to the data logger by a signal conditioning unit. The signal conditioning unit amplifies and low pass filters the analogue signals and optically separates the digital signals. The specifications of both plough draught recording systems are listed in Table 3.1.

Table 3.1
Plough draught recording systems specifications

	Draught sensor evaluation system (A)	*Draught measurement prototype system (B)*
Implements	Deutz 6.31 tractor with Rumptstad 3 furrow mouldboard plough, high speed, wide furrow bodies (RS 480)	Massey Ferguson 3125 tractor with Rumptstad/Kverneland 3 furrow mouldboard plough, high speed, wide furrow bodies (RS480)
Position	C/A DGPS[1], local base station	C/A DGPS, DCI-RDS[2] corrections
Velocity	Radar speed sensor, Driven wheel speed	Radar speed sensor, Driven wheel speed
Heading	Flux gate compass	
Draught	Lower link draught sensors, Draught measurement frame	Lower link draught sensors
Plough depth	Slider on plough, Hitch position	Slider on plough
Plough width	Plough adjustment, First share plough width	Plough adjustment

[1]C/A DGPS, coarse acquisition code differential global positioning system
[2]DCI-RDS, differential corrections incorporated, shortwave side band data link

Both tractors are equipped with a Bosch Hitchtronic® system. Both mouldboard ploughs are fitted with Rumptstadt RS480 mouldboard bodies. Additional sensors on the plough record plough width adjustment, effective width of the first mouldboard and plough depth. The effective width of the first mouldboard of the plough from the sensor evaluation system can be adjusted by rotation of the plough frame. A sensor alongside the hydraulic cylinder records rotation angle of this width adjustment. Between the rear tractor wheel and the first mouldboard, an ultrasonic sensor measures effective width of this mouldboard by measuring the distance to the furrow wall. Ploughing depth is measured by an angle encoder on a sliding plate on the landside of the plough. The depth measurement accuracy of the sliding plate might decrease due to attached soil when ploughing on bare soil but on the winter wheat stubble the plate remained clean. A complication of mounting sensors on a reversible plough is that either a double set of sensors is needed or the sensors have to be displaced to the working side. The sliding plate of the plough depth sensor rotated on an axis through the centre of the plough frame and was in this way able to measure plough depth on both sides of the plough. The ultrasonic sensor was mounted on a boom that displaced the ultrasonic sensor when reversing the plough. *Figure 3.1* shows the locations of the sensors used in the sensor evaluation system on the plough and on the tractor.

Between the tractor and the plough, a measurement frame for draught force was mounted. This calibrated measurement frame provided the sensor evaluation system with a hitch independent draught force measurement.

Velocity measurements were obtained from the driven wheel and the radar. A coarse acquisition differential global positioning system (C/A code DGPS) receiver updated position information at a rate of 4 Hz. On the sensor evaluation system, an electronic compass was added to augment GPS data. All analogue signals were sampled at a rate of 40 Hz and stored on the hard disc of the data logger.

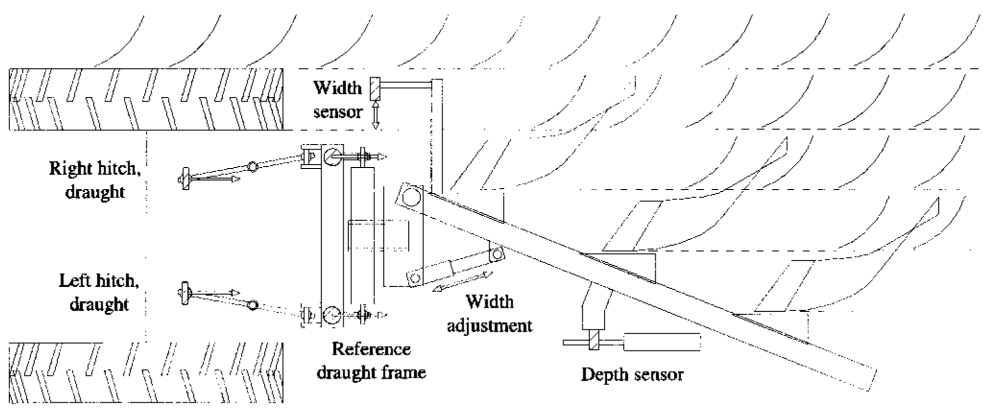


Fig. 3.1. Sensor configuration for specific plough draught measurements for the sensor evaluation system (A)

3.3.2. *Data Processing*

A first step in data processing is enhancement of the positioning data. Position, velocity, heading and wheelslip were reconstructed from the GPS, wheel and radar velocities and set from the experimental fields varied between 1.4 and 1.7 m/s. To be able to compare specific draught within one field, a correction to a standardised velocity of 1.6 m/s was made. According to the ASAE, draught is quadratic related to velocity (Harrigan & Rotz, 1995). For velocities in the range 1.25 - 2.35 m/s, the quadratic relation fitted data best (Summers *et al.*, 1986). For different soil types, both articles mention different parameters to relate specific draught to velocity. Due to the small velocity range present in the experimental data, a linear relation was used. The estimated correction factor is 5 kN/m^2 specific draught increase at 1 m/s velocity increase based on figures from Reaves and Schafer (1975) and Summers *et al.* (1986). Eqn (3.2) displays the form of this velocity correction.

$$F_{s,v_0} = F_{s,v} + 5.0 * (1.6 - v) \qquad (3.2)$$

where: $F_{s,v0}$ is the specific plough draught in kN/m^2 at a velocity v_0 of 1.6 m/s; $F_{s,v}$ is the specific plough draught in kN/m^2 at velocity v; and v is actual velocity in m/s.

Prior to the ploughing of the experimental field in 1996, six test runs with three different velocities (1.3, 1.7 & 2.3 m/s) were conducted on an adjacent field. Based on the assumption that adjacent plough lanes without disturbances like tramlines should have a similar specific plough draught, the influence of the velocity on specific plough draught was tested. For these test runs a correction factor of 4.6 kN/m^2 specific draught increase at 1 m/s velocity increase over 1.3 - 1.7 m/s minimised the specific draught differences between the adjacent lanes. This correction factor is close to the 5.0 kN/m^2 obtained from literature and this experiment did not cover enough repetitions to justify modification of the correction factor in Eqn (3.2) to 4.6 kN/m^2.

3.3.4. *Spatial interpolation*

The plough draught measurement system records approximately 20,000 samples per hectare. For comparison with other, less dense sampled, spatial data sets, a spatial interpolation operation is necessary.

The first method to analyse the data is to plot a colour indexed dot, representing specific plough draught, for every location in the data set. This method shows the smallest details measured with the system.

A distinction can be made between small scale and large scale variation. An example of a small scale variation is the effect of tramlines. Large scale variations are for example the different soil types. Dependent on the spatial characteristics of a factor that influences

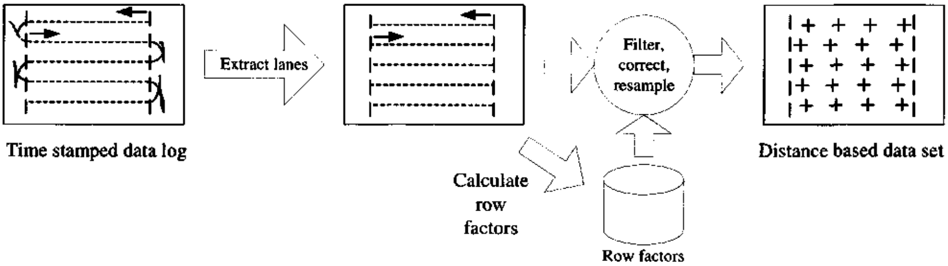


Fig. 3.2. Plough data filter procedure

plough draught, a spatial interpolation has to be applied to the data set to differentiate between noise and information. In the case of analysis of specific plough draught as indicator for different soil types, the assumption regarding spatial variability of soil types might be that soil types do not vary within, for instance, 10 m. Based on this assumption, a filter operation is implemented to reduce small scale variation and to differentiate between soil types.

Next to the spatial characteristics of the factor to be analysed, the implementation of the spatial filter depends on characteristics of the plough draught measurement system and its operation. Two characteristics are hysteresis in the draught sensors of the three point linkage and a plough direction that is parallel to the tramlines in the field. As a result, small scale variation is mostly present across the driving direction and the variations along the driving direction have to be preserved. The filter to meet these requirements operates in three steps. The first step is to determine the average specific plough draught for each ploughed lane. After this step, a correction factor is calculated for each lane to minimise the variation of the specific plough draught of adjacent lanes. The second step is to apply this lane specific correction factor. This step effectively implements a low pass filter that operates perpendicular to the driving direction. The third step is to apply a low pass filter along the driving direction. This is done by a filter and resample operation that results in a distance based set of specific plough draught samples. This procedure is shown in *Fig. 3.2.*

The distance based data set consists of approximately 1000 data records per ha. For presentation purposes, conversion to a grid is done by an ordinary kriging method based on a local semi-variogram (range < 50 m) (Minasny *et al.*, 1999). A grid size of 5 m is, given the working width of 1.2 m, a reasonable choice for the plough data set.

3.3.5. *Map comparison*

In order to determine the spatial relation between two characteristics a comparison between their spatial patterns has to be made. Several methods are available to compute whether two characteristics have matching low and high values in the same area, have no spatial correlation at all or have an inverse pattern (Stein *et al.*, 1997). One of these methods, the cross-correllogram, is used to calculate the correlation between two variables as a function of the distance between observation points. A cross-correllogram $\rho_{AB}(h)$ measures the correlation between two variables $z_{xy,A}$ and $z_{x'y',B}$ as a function of the distance h between observations of these variables. The distance h is calculated as a vector between a pair of observations $z_{xy,A}$ and $z_{x'y',B}$ according to Eqn (3.3):

$$h = \sqrt{(x-x')^2 + (y-y')^2} \tag{3.3}$$

where x and x' are the coordinates on the x-axis of a cartesian coordinate system and y and y' are the coordinates on the y-axis of a cartesian coordinate system.

The cross-correllogram $\rho_{AB}(h)$ as a function of the distance h is given by Eqn (3.4):

$$\rho_{AB}(h) = \frac{E[z_{xy,A}\ z_{x'y',B}] - m_A m_B}{S_A S_B} \tag{3.4}$$

where E is the mathematical expectation with population means m_A and m_B and standard deviations S_A and S_B. A value of 1 for $\rho_{AB}(0)$ indicates that the patterns are completely similar. For inverse patterns, $\rho_{AB}(0)$ is -1.

3.3.6. *Kriging and Cokriging*

An important objective of a plough draught measurement system is the reduction of the number of soil samples to characterise a field. In this experiment, plough draught measurements are used as covariable to predict the value of other soil characteristics. The prediction techniques kriging and co-kriging (Goovaerts, 1997) are used for this purpose. *Kriging uses just the values of a variable to predict its value in non-sampled locations*, while co-kriging allows the use of a co-variable to improve the prediction in non-sampled locations. When the variable to be predicted is sampled in a sufficiently dense way, several test and validation sets can be made with different sample densities. The cross validation consists of application of both kriging and co-kriging based on the test set to predict the values at the locations from the validation set. The performance of the kriging and co-kriging predictors can be evaluated by the mean squared error of the predicted values denoted by E_{mp} in Eqn (3.5) and by the mean variances of the individually predicted values V_{mp} according to Eqn (3.6).

$$E_{mp} = (1/n) \sum_{i=1}^{n} (p_i - z_i)^2 \qquad (3.5)$$

$$V_{mp} = (1/n) \sum_{i=1}^{n} var(p_i) \qquad (3.6)$$

where n is the number of samples in the validation set; p_i is the predicted value at location i; and z_i is the measured value at location i.

3.4. Experimental arrangement

3.4.1. *Field experiments*

The sensor evaluation system (A) was operated for two seasons (1995 and 1996) on an experimental field (referred to as site 1) in the north west part of The Netherlands; the Wieringermeer polder. The total examined area of the nearly square field was six ha (240 m by 250 m).The field belongs to a regional research station where a soil survey was carried out about twenty years ago (*Fig. 3.3*). The soil type varies between sandy loam and clay loam with relatively large small scale variations due to former sand banks and currents. During plough draught measurements, samples of the top soil layer of the field were taken to determine soil moisture content and bulk density. Table 3.3 lists weather and cropping conditions for this field.

Table 3.3
Experimental field properties

System	*Season*	*Property*	*Value*
Sensor evaluation system (A) on site 1	1995	Annual precipitation	718 mm
		Precipitation in week before ploughing	10 mm
		Previous crop	Potatoes
		Crop	Winter wheat
		Catch crop	Ryegrass
		Surface condition	Stubble with catch crop
	1996	Annual precipitation	589 mm
		Precipitation in week before ploughing	40 mm
		Crop	Summer barley
		Catch crop	None
		Surface condition	Stubble
Prototype system (B)	1996	Crop in field (2)	Winter wheat + set-aside
		Crop in field (5)	Winter wheat

The prototype system (B) was operated during the autumn of 1996 on a farm in the south west part of the Netherlands (site 2). The plough draught data acquisition was part of an on-farm precision agriculture study, so additional measurements on soil moisture status and a detailed soil survey were conducted parallel to these experiments. The soil types on this farm are marine sediments with large variation in both clay and calcium contents. The individual fields were often build up from smaller fields due to a recent land reorganisation and these historical differences in land use are important for site specific field management.

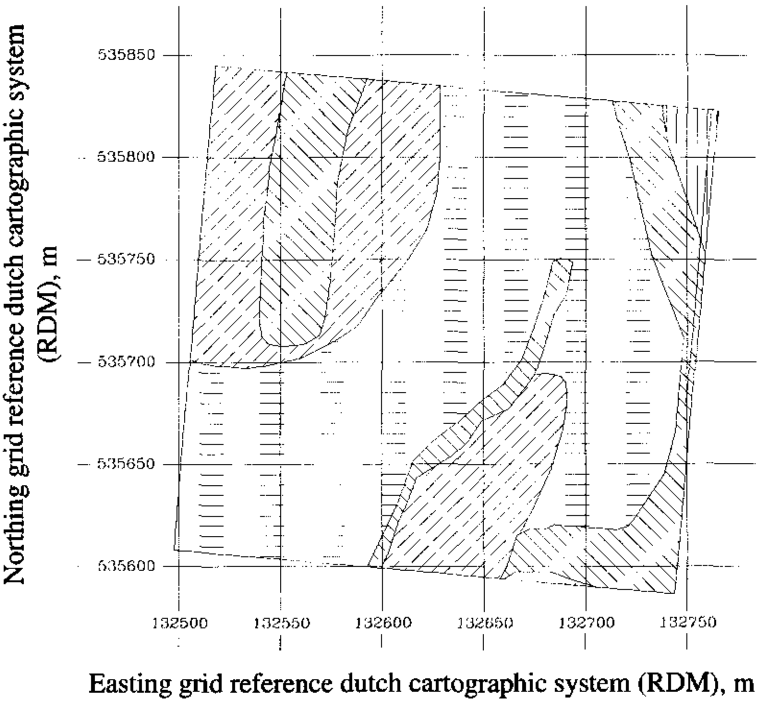


Fig. 3. Soil survay of site 1 for clay content: , *25-35 %;* , *14-25%;* , *8-14%;* , *< 8%*

3.5. Results

3.5.1. *Spatial variation of crop and soil characteristics*

Several soil physical and chemical properties were sampled in site 1 before and after the cropping seasons (Table 3.4). When more than 50 spatially distributed samples were made, semivariogram parameters are added in Table 3.5.

Table 3.4
Statistical characteristics of properties on site 1

Property	*Sample depth, m*	*Sample date, yyyy/mm/dd*	*Number of samples*	*Mean*	*Min*	*Max*	*Standard deviation*
Clay contents, %	0-0.3	1996/11/28	628	14.1	6.87	22.1	3.15
Moisture field cond., %	0-0.3	1995/11/06	71	19	12.6	24.2	2.73
Moisture at PF2[1], %	0-0.3	1995/11/06	71	17.6	10.9	23.4	2.83
Moisture field cond, %	0-0.3	1996/11/28	17	24.1	17.8	30.2	4.02
$CaCO^3$, %	0-0.3	1996/11/28	17	8.9	6.9	10.6	1.18
Organic matter, %	0-0.6	1996/02/27	14	1.52	1.1	2.3	0.35
pH-KCl	0-0.6	1996/02/27	14	7.7	7.6	7.8	0.07
Phosphate index (Pw)[2]	0-0.6	1996/02/27	14	31.9	19	47	8.86
K-HCl	0-0.6	1996/02/27	14	13.1	9	22	4.04
Nitrate, kg/ha	0-0.9	1995/02/20	60	33.8	7.5	113	24.8
Nitrate, kg/ha	0-0.9	1995/11/23	60	21.6	6.2	72.9	12.7
Nitrate, kg/ha	0-0.6	1996/02/27	57	26.5	12	48	8.43
Nitrate, kg/ha	0-1.0	1996/09/05	63	89	31.3	168	30.5
Grain yield, t/ha		1995/08/10	12825	9.66	2.17	14.9	1.11
Straw yield, t/ha		1995/08/10	12734	12.5	2.83	20	2.58
Grain yield, t/ha		1996/08/20	9482	7.01	3.08	9.79	1.01
Straw yield, t/ha		1996/08/20	9482	2.59	0.25	6.77	0.72

[1] moisture retention at field capacity

[2] calculation of this index (van der Paauw *et al.*, 1971)

Table 3.5
Spatial characteristics of properties on site 1

Property	*Sample depth, m*	*Sample date yyyy/mm/dd*	*S.V. model*[1]	*Nugget*	*Range, m*	*Sill*	*AIC*[2]
Clay contents, %	0-0.3	1996/11/28	Spherical	0.91	124	7.18	263
Moisture field cond., %	0-0.3	1995/11/06	Spherical	0.65	123	6	37
Moisture at PF2, %	0-0.3	1995/11/06	Spherical	0.63	115	7.4	35
Nitrate, kg/ha	0-0.9	1995/02/20	Linear+sill	323	114	370	428
Nitrate, kg/ha	0-0.9	1995/11/23	Linear+sill	20.9	54.4	123	372
Nitrate, kg/ha	0-0.6	1996/02/27	Spherical	20.8	40.8	34.8	76
Nitrate, kg/ha	0-1.0	1996/09/05	Spherical	210	46.2	447	210
Grain yield, t/ha		1995/08/10	Spherical	0.45	65	0.37	-50
Straw yield, t/ha		1995/08/10	Spherical	1.34	32.8	3.98	27
Grain yield, t/ha		1996/08/20	Spherical	0.41	82.4	0.44	-52
Straw yield, t/ha		1996/08/20	Spherical	0.34	43.5	0.57	-63

[1]S.V. model: Semivariogram model
[2]AIC: Akaike Information Criterion

The semivariogram parameters are calculated by use of the Vesper software (Minasny *et al.*, 1999). A best model is chosen based on the Akaike Information Criterion (AIC). The semivariogram models of clay contents and of field moisture contents have the largest ranges (> 120 m). Soil nitrate contents, measured to provide initial and final conditions for crop growth simulation studies for both seasons, have a shorter range (40-114 m) and a high variation at short distances. The nugget/sill ratio varies between 0.17 and 0.6. The crop yields show slightly shorter ranges for the semivariogram models compared to clay contents and field moisture contents. The crop yields for both years have a clear spatial pattern which is also indicated by the low nugget values.

3.5.2. *Plough draught recording system*

The random noise of the plough depth sensor remained within a range of two centimetres. The estimated accuracy after low-pass filtering is about one centimetre. The influence of the draught control of the hitch on the ploughing depth is a point of concern. The plough depth varied four centimetres at the same hitch control settings in different areas of the field. As will be discussed later the hitch should maintain ploughing depth constant but is affected by soil type. Exact determination of ploughing depth is important regarding to Eqn (3.1). Small variations in depth have a large impact on specific draught.

Measurements of the ploughing width of the first mouldboard body with the ultrasonic distance sensor required severe filtering. Due to irregularities, such as clods, in the plough furrow many ultrasonic echos were lost. The filter algorithm first skipped all measurements which were logically out of range. The next step was to fit a smooth line through the measurements that remained. However, the influence of errors in the plough width determination have low impact on specific draught. Visualisation of the data under assumption of an equal ploughing width of 1.2 m over the entire field resulted in the same pattern. The width of the first furrow varied between 35 and 47 cm.

Analysis of the plough draught measurements after correction for depth, width and speed, and before spatial interpolation, revealed that the draught force of adjacent lanes differed more than expected. This might be due to unmodelled errors in plough draught Eqns (3.1) and (3.2), and other not measured factors that influence plough draught, such as tramlines. After application of the spatial filter procedure, *figure 3.4* shows specific plough draught for the 1995 season. The pattern is consistent with the conventional soil

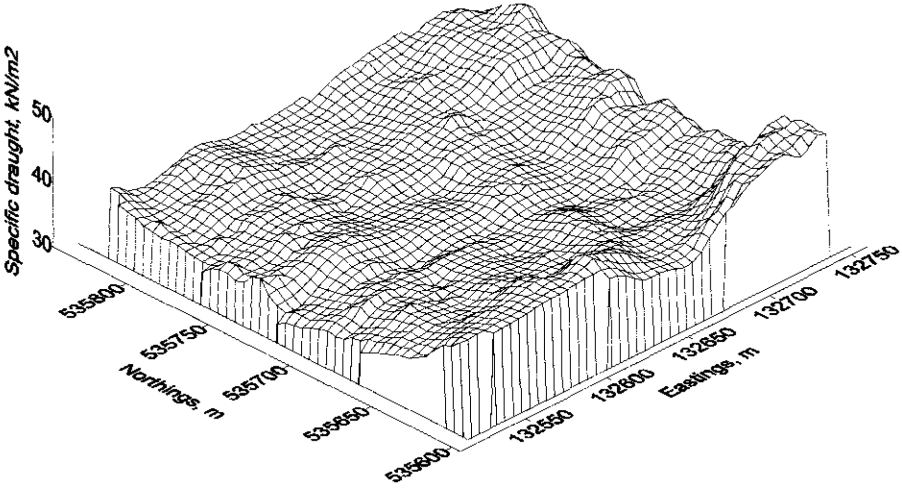


Fig. 3.4. Specific plough draught based on hitch sensor signals, 1995

survey as depicted in *Fig. 3.3*. The sandy areas in the north-west part can be recognised as well as the more draught requiring clay part along the east border. The initial furrows down the south side are less easily explained; the large specific draught peak at the south-east corner might be due to soil compaction while this was the entrance of the field used most often by equipment during this season.

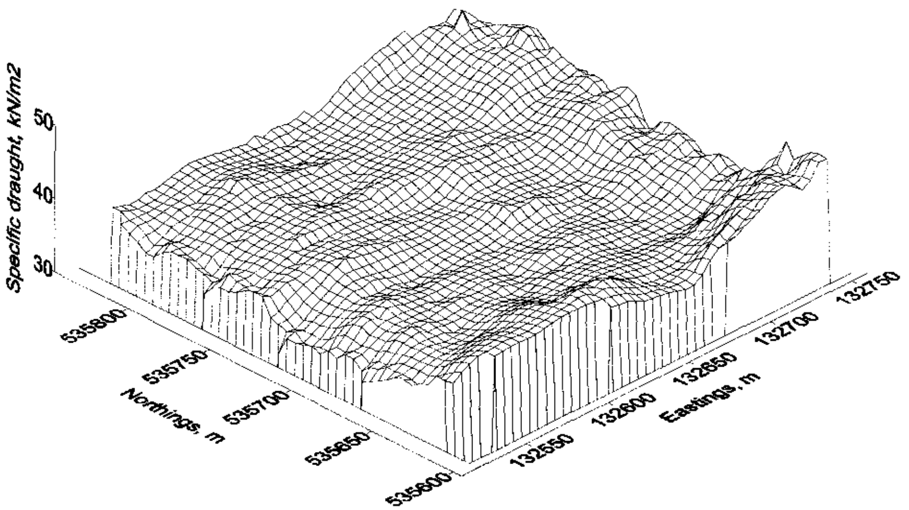


Fig. 3.5. Specific plough draught based on measurement frame signals, 1995

The relation between measured draught by the reference frame and the sensor output of the hitch draught sensors showed large disturbances. A linear regression between reference frame draught and hitch draught has a value for the coefficient of determination R^2 of 0.75 for the 1995 season and 0.79 in 1996. These disturbances might be caused by hitch geometry affecting the hitch draught sensor output, by hysteresis in these sensors and by the relatively low measurement range. After application of the filter and grid methods on the data, the plough draught patterns of both measurement systems are similar. *Figure 3.5* shows the specific plough draught measured by the reference frame, the pattern is similar to *Fig. 3.4* but the variations are smaller.

The specific draught differences in 1996 (*Fig. 3.6*) were smaller when compared to the map of 1995 (*Fig. 3.4*) but the pattern is consistent. The main differences from 1995 to 1996 are that the ridge on the south part of the field has disappeared and that the main entrance to the field was moved to the north-east part of the field. A cross-correllogram

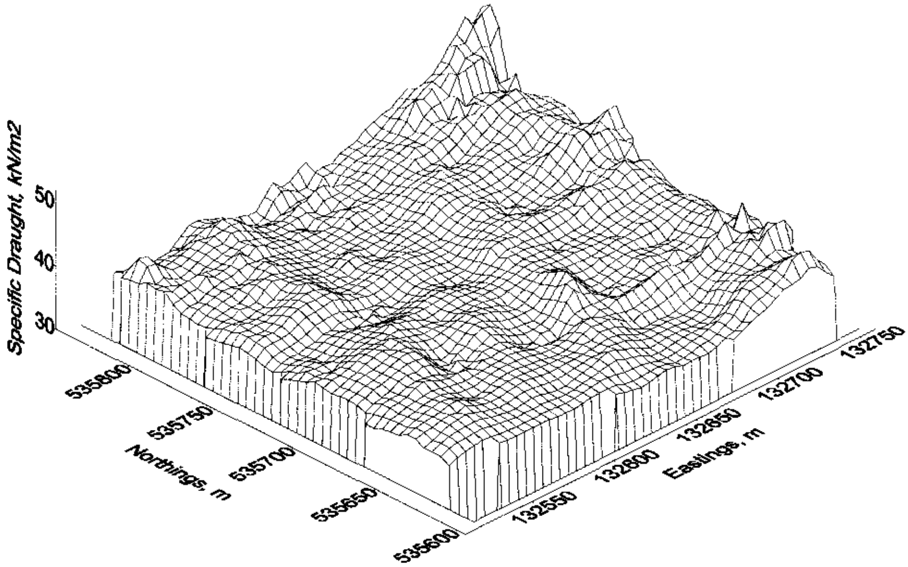


Fig. 3.6. Specific plough draught based on hitch signals, 1996

between the two data sets (*Fig. 3.7*) shows a high correlation at short distances which steadily decreases at increasing distance.

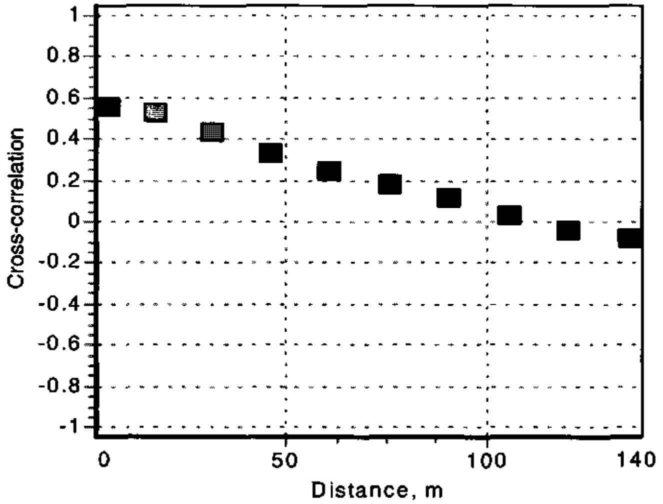
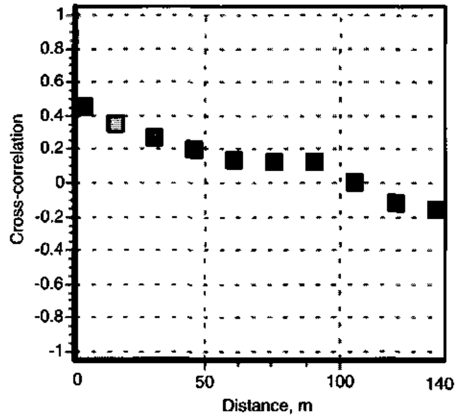


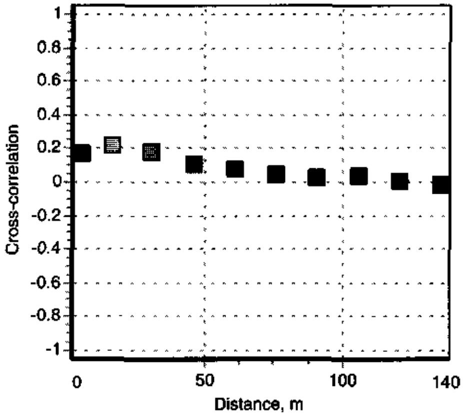
Fig. 3.7. Correlation between specific plough draught 1995 and specific plough draught 1996 on site 1

3.5.3. *Map comparison*

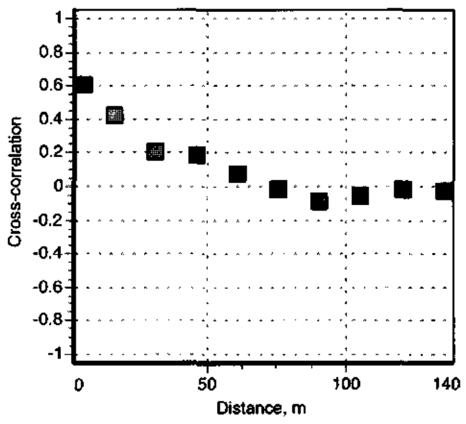
The cross-correllograms of nitrate contents at different sample dates with top soil clay contents (*Fig. 3.8*) show that the patterns of the pre-growing season samples have a higher correlation at short distances than the samples at the end of the growing season.



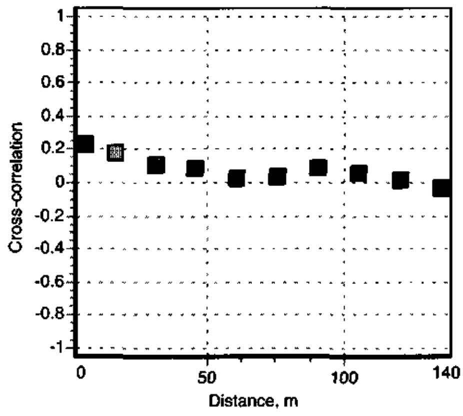
Correlation of NO³ (1995/02) with clay contents



Correlation of NO³ (1995/11) with clay contents



Correlation of NO³ (1996/02) with clay contents

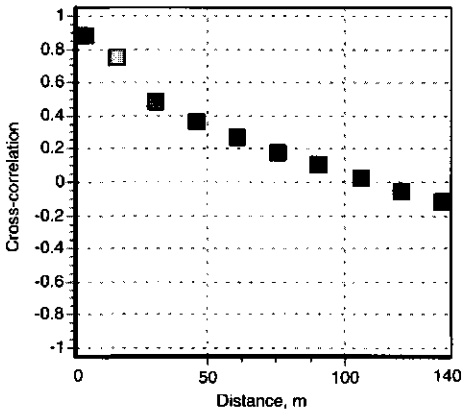


Correlation of NO³ (1996/09) with clay contents

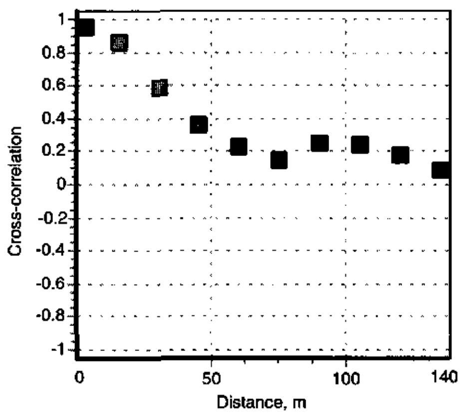
Fig. 3.8. Cross correlation variograms of NO^3 at four different sample dates with clay contents for site 1

According to the cross-correllograms of top soil moisture contents during plowing with top soil clay contents (*Figs 3.9a & 3.9b*), the spatial patterns of these characteristics are almost identical.

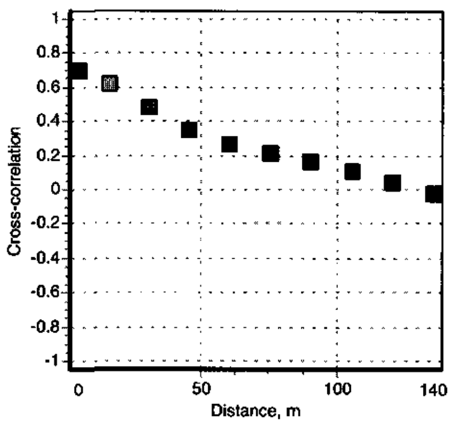
The cross-correllograms between top soil clay contents and both specific plow draught maps are depicted in *figure 3.9c* and *figure 3.9d*. Both correlations are high at short distances. The correlation of clay contents with specific plough draught recorded in 1996 shows a slightly sharper decrease with lag distance increase compared to the correlation between clay contents and specific plough draught from the 1995 season.



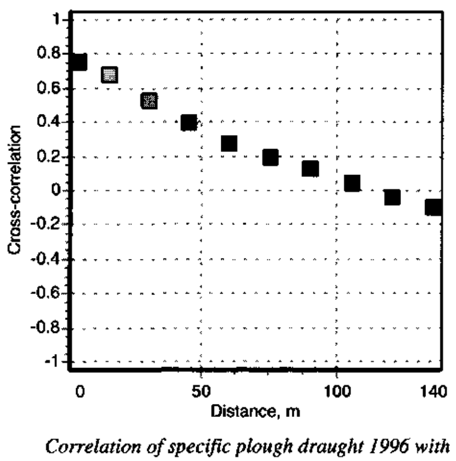
Correlation of top soil moisture contents during ploughing 1995 with clay contents



Correlation of top soil moisture contents during ploughing 1996 with clay contents



Correlation of specific plough draught 1995 with clay contents



Correlation of specific plough draught 1996 with clay contents

Fig. 3.9. Cross correlation variograms of soil moisture contents 1995 & 1996 and specific plough draught 1995 & 1996 with clay contents for site 1

3.5.4. *Kriging and co-kriging*

Of the different variables, top soil clay contents seems to be the most promising variable to predict with plough draught measurements. The original 628 clay contents samples were reduced to 503 samples valid for the same area as the plough draught measurements. These 503 samples where divided into a test and a validation set by random selection. The validation set consisted of 200 locations. From the test set, seven different sample densities where simulated by random extraction of a number of samples (Table 3.6). For each sample set, semivariograms were constructed. A combination of a nugget model with a linear model was able to satisfy the constraints for the co-kriging linear model of co-regionalisation (Goovaerts, 1997). Note that for the lowest clay contents sample densities the number of observation pairs in each distance class is too low to reliably fit a semivariogram model. However, these low sample densities are useful to test the performance of co-kriging with the spatially far more dense measured plough draught.

Table 3.6
Kriging and co-kriging performance on prediction of clay contents

	Ordinary kriging		*Co-kriging, plough draught 1995*		*Co-kriging, plough draught 1996*	
Samples, ha^{-1}	E_{mp}[1]	V_{mp}[2]	E_{mp}[1]	V_{mp}[2]	E_{mp}[1]	V_{mp}[2]
6	5.1	3.65	3.99	3.09	3.8	3.19
12	3.95	3.78	2.66	3.22	2.74	3.32
18	3.02	2.53	2.21	1.85	2.34	1.99
24	2.71	3.36	2.16	2.77	2.34	2.89
30	2.61	2.46	2.19	1.86	2.16	1.99
40	2.03	2.98	1.94	2.5	1.91	2.61
60	1.72	2.7	1.83	2.26	1.72	2.36

[1]E_{mp}: Mean squared errors of prediction

[2]V_{mp}: Mean variance of prediction

Figure 3.10 depicts the relation between the E_{mp} and the number of clay contents samples in each sample set. From 40 samples/ha upwards the prediction error is fairly constant. Reduction of the number of samples shows an increase in prediction error for both kriging and co-kriging. Of these methods, co-kriging with plough draught as co-variable performs better in terms of maintaining a lower prediction error at low clay contents sample densities. Of both years data sets, the plough draught measurements of 1995 yield slightly lower prediction errors. Co-kriging reduces the variances of the predicted clay contents (V_{mp}) when compared to ordinary kriging (Table 3.6).

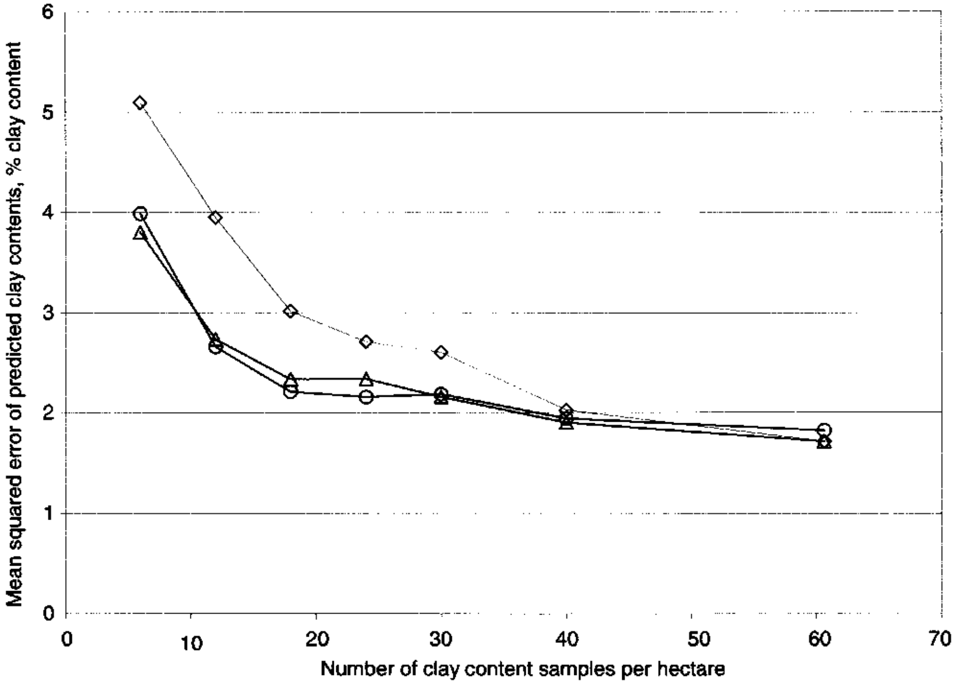


Fig. 10. Mean squared errors of predicted clay contents in clay content % from ordinary kriging, (-◇-); co-kriging with plough draught 1995, (-○-); and plough draught 1996, (-△-) at different sample densities

Visual comparison of the original clay contents map (*Fig. 3.11*) with the predicted clay contents based on 40 samples per hectare (*Figs 3.12 & 3.13*) show that although the E_{mp} values of the different kriging methods are almost identical, the pattern is better predicted using co-kriging. The E_{mp} measure hardly detects this: a further investigation on the spatial distribution showed that the prediction errors are not evenly distributed but increase at the field boundaries. Next to the logical reason that at the map borders less observations are available for the kriging interpolator there are two more reasons why inaccuracy at the field boundaries increases. At the field boundaries plough draught might be affected by other factors like headland compaction and the plough needs a certain working distance to reach the normal conditions for depth and speed.

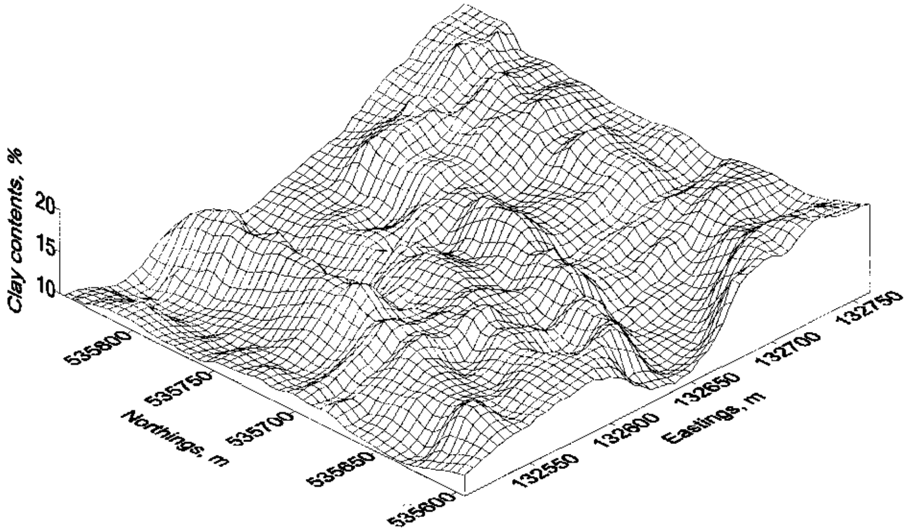


Fig. 3.11. Top soil clay contents in %, ordinary kriging based on all 628 samples (± 100 samples/ha)

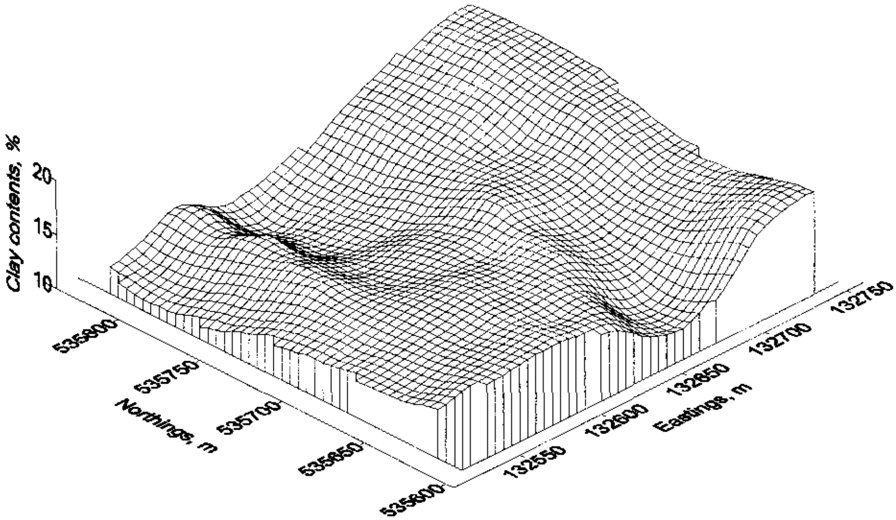


Fig. 3.12. Top soil clay contents in %, ordinary kriging based on 40 samples/ha

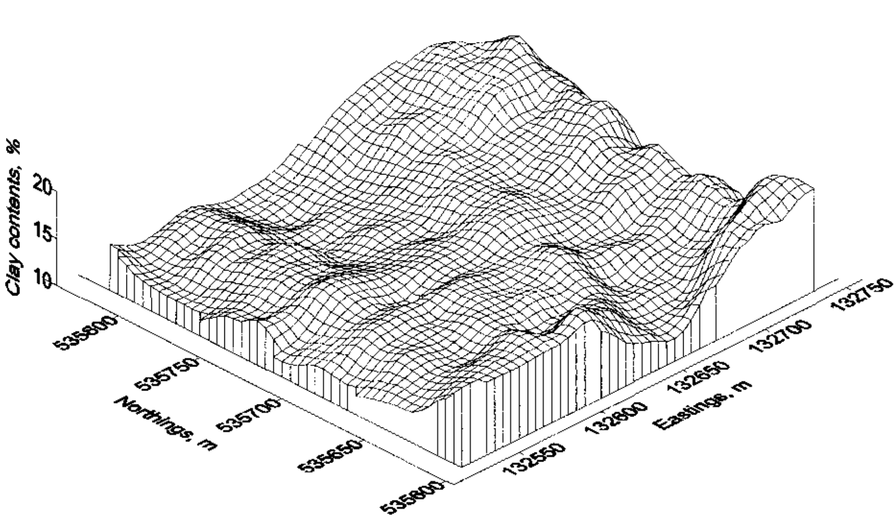


Fig. 3.13. Top soil clay contents in %, co-kriged with plough draught 1995 and based on 40 samples/ha

Yield maps for grain and straw were collected by a combine harvester in 1995 and 1996. To illustrate the influence of soil type on crop yield, *figure 3.14* depicts the summer barley grain and straw yield maps from 1996. The pattern is similar to the top soil clay contents (*Fig. 3.11*). In this season, the crop growth was mainly limited by the availability of water. The resolution of the straw yield map was higher than the resolution of the grain yield map for the same harvest due to the different measurement methods and crop characteristics. The spatial correlations between straw yield and specific plough draught and straw yield and top soil clay contents are depicted in *figure 3.15*.

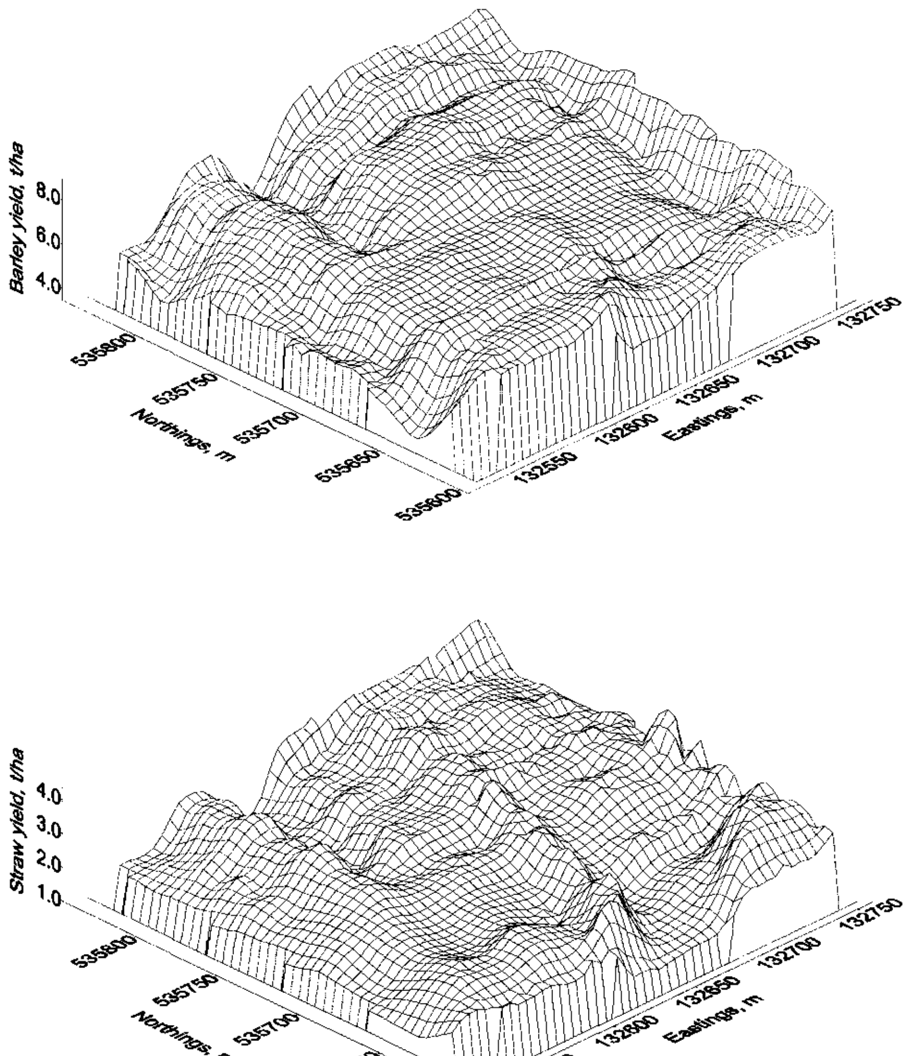
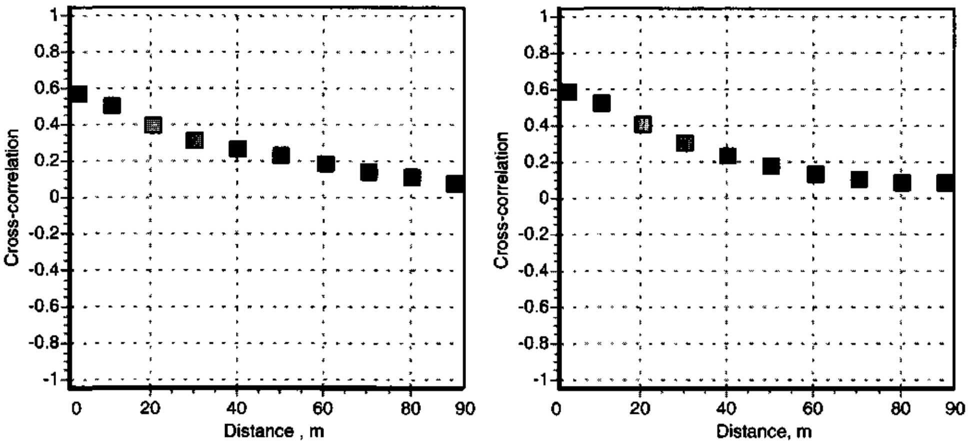


Fig. 3.14. Summer barley grain and straw yield in t/ha on site 1, 1996



Correlation of straw yield 1996 with specific plough draught 1996

Correlation of straw yield 1996 with top soil clay contents

Fig. 3.15. Cross correlation variograms of straw yield 1996 with specific plough draught 1996 and top soil clay contents

3.6. Discussion

The availability of an electronic hitch control on a tractor makes it relatively easy to locate different soil types in a field. For determination of specific draught however, several complications were encountered. Firstly there is a problem of interference between the draught and position control options of the hitch controller. A compromise between position control mode and draught control mode exists: for good quality plough work, position control is not sufficient while the other extreme, draught control, tries to minimize draught differences in a field by adjustment of plough depth. In the experiments, the hitch control was set at a mix between position and draught control but still depth varied significantly at different locations in the field. This leads to a second point: plough depth determination. An additional plough depth measurement has to be installed on the plough to calculate specific draught. Third point is the calibration and signal quality of the hitch sensors. The calibration depends upon the geometry of the three point hitch linked to a specific implement and is therefore difficult to maintain in farm practice. Especially when comparisons have to be made between specific draught data from different fields or from different years, measurements need a common quantitative basis. The signal quality of the hitch sensors was lowest at low draught forces. The specifications of the draught sensors mounted in both tractors showed that hysteresis was largest at low draught forces. Combined with the low draught range in the experiments, approximately 20% of the draught sensors' maximum measurable draught, this resulted in a low measurement accuracy for individual draught samples. For a more detailed specific plough draught map another type of draught sensor might provide better results.

The obtained specific plough draught figures were equal to or lower than the specific draught figures from literature. When compared to studies where draught was measured at a low speed (0.5 m/s) (Kirisci, 1994; Desbiolles *et al.*, 1997), application of a correction for depth and speed of this study resulted in 20-30% over estimation of specific plough draught. Of the studies with measurements at the same speed as in this study (1.6 m/s) Reaves & Schafer (1975) and Bowers (1989) report specific plough draught values that are in the same range as in this study (30-50 kN/m^2), while Summers *et al.* (1986) reports higher specific draught values (60-75 kN/m^2). One of the reasons for the low specific plough draught values in this study might be the structure of the top soil. In both 1995 and 1996, grain crops were cultivated and while these are harvested under dry summer conditions, hardly no soil compaction was present at the time of ploughing.

The top soil spatial variability and crop growth spatial variability as presented in this study are positively correlated. However, it is debatable whether the influence of deeper soil layers on crop growth is larger and subsequently, whether it makes sense to map only top soil layer spatial variability. The soil on site 1 was examined up to 2.0 m depth by 65 augerings (Verhagen, 1997; Booltink & Verhagen, 1997). Analysis of soil hydrological parameters led to distinction of 4, so called, functional layers. Each augering was then described as a series of soil layers where each soil layer represents 1 of the 4 functional layers. The top soil (0-0.3 m) on site 1 was classified as either functional layer 1 or functional layer 4. It is remarkable that when the top soil layer is an instance of functional layer 1 (17% of the augerings), the deeper layers are also dominated by functional layer 1. When the top soil layer is classified as functional layer 4, the functional layers 1, 2 and 3 are all present in the 0.3-1.0 m layers, equally divided over the number of augerings. For this site therefore, measurement of the spatial variation of the top soil layer texture also covers approximately 70% of the spatial variation of the 0.3-1.0 m soil layer.

On-farm or farm-scale research is an important information source for precision agriculture. The advantage is the close cooperation between practise and theory. A disadvantage is the difficulty to determine relations between different variables, for instance in this paper the influence of velocity and depth on specific plough draught. Test plots with these variables individually varied over a wide range would give a more accurate correction model but have the disadvantage that the model parameters might not be portable to another field or another season. Another approach is to find algorithms that separate influences of single factors from the field scale experiment itself. For instance, from a comparison of adjacent ploughed passes that differ only in velocity, a correction figure for velocity might be distilled. The resultant correction model, valid primarily for one particular data set, might even perform better compared to general figures made over larger factor ranges. The remaining question is whether enough different measurements are available in a data set to carry out this exercise. In addition to this, it is not a farmers' practice to vary working conditions for experimental purposes. In practice, when velocity drops during ploughing, it is likely to be correlated with a heavier soil structure where the tractor-plough combination has difficulty in maintaining velocity. Thus, the usual objective of the farmer to minimise fuel use and maximise work capacity conflicts with the experimental objective to detect and model the factors that influence plough draught correctly.

3.7. Conclusions

A normal tractor-plough combination is suitable for plough draught measurement by farmer operation. Next to the electronic hitch control additional sensors for position information, such as a global positioning system (GPS), for speed, for plough depth, for working width and for plough geometry had to be mounted. Plough working width measurement had low impact on the specific draught and might be replaced by only the plough geometry measurement combined with a calibration model on future implementations. Accurate plough depth measurement is essential for specific draught calculations. Velocity measurements were important to convert the specific draught data to a standard velocity in order to compare data sets from different years or from different fields.

Within a six ha. field, specific plough draught varied between 30 and 50 kN/m^2 in the experiments carried out during two growing seasons. Clay contents varied between 6 to

22 %. The soil moisture content range in the top soil during the first year was 120 to 240 g kg^{-1} and in the second year 180 to 300 g kg^{-1}. The specific plough draught figures corresponded well with the classical soil survey on clay contents but had a higher spatial resolution. The specific plough draught maps of both years showed a similar pattern with a cross correlation coefficient at zero distance of 0.6.

The specific plough draught map enabled reduction of the number of soil samples required to make a sound coverage for a top soil clay contents map. Application of the co-kriging technique to estimate top soil clay contents showed that the use of specific plough draught information made it possible to decrease the number of top soil clay contents samples from 60 per ha to 18 per ha with only 20% increase in prediction error. The variation patterns in top soil clay contents within this field were also visible in the crop yields for both years. Water storage capacity of the different soil types was an important factor for the observed yield differences.

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References

Al-Janobi A A; Al-Suhaibani S A (1998). Draft of primary tillage implements in sandy loam soil. Applied engineering in agriculture, 14(4), 343-348

Bernacki H; Haman J (1972). Grundlagen der Bodenbearbeitung und Pflugbau, [Principles of soil tillage and plough design]. Veb Verlag Technik. Berlin.

Booltink H W G; Verhagen A (1997). Using decision support systems to optimise barley management on spatial variable soil. In: Applications of systems approaches at the field level (Kropff M J; Teng P S; Aggarwal P K; Bouma J; Bouman B A M; Jones J W; van Laar H H eds), pp 219-233, Kluwer, Dordrecht, The Netherlands

Bowers J C G (1989). Tillage draft and energy requirements for twelve southeastern soil series. Transactions of the ASAE, 32(5), 1492-1502

Canarache A (1993). A preliminary model estimating soil specific resistance to ploughing. Soil & Tillage Research, 27, 355-363

Desbiolles J M A; Godwin R J; Kilgour J; Blackmore S A (1997). A Novel Approach to the Prediction of Tillage Tool Draught using a Standard Tine. Journal of Agricultural Engineering Research, 66, 295-309

Desbiolles J M A; Godwin R J; Kilgour J; Blackmore S A (1999). Prediction of Tillage Implement Draught using Cone Penetrometer Data. Journal of Agricultural Engineering Research, 73, 65-76

Finke P A; Goense D (1993). Differences in barley grain yields as a result of soil variability. Journal of Agricultural Science, 120, 171-180

Gebresenbet G (1991).Analysis of forces acting on mouldboard ploughs and seed drill coulters in relation to speed, depth and soil conditions: static and dynamic studies. PhD Thesis, Swedish university for agricultural sciences, Uppsala, Sweden

Goovaerts P (1997). Geostatistics for natural resources evaluation. Oxford University Press. New York.

Harrigan T M; Rotz C A (1995). Draft relationships for tillage and seeding equipment. Applied Engineering in Agriculture, 11(6), 773-783

Kirisci V A (1994).A field method for predicting the draught forces of tillage implements. PhD thesis, Cranfield University, Silsoe, Bedford

Klenin N L; Popov I F; Sakun V A (1985). Agricultural machines; theory of operation computations of controlling parameters and the conditions of operations, Published for the United States Department of Agriculture, and the National Science Foundation, (original: Kolos Publishers, Moscow, 1970). Amerind Publishing Co.

New Delhi.

Kuczewski J (1982). A multi parametric model for predicting the draught of two model plough bodies in four different soils. Soil & Tillage Research, 2, 213-223

Minasny B; McBratney A B; Whelan B M (1999). VESPER version 1.0.; Australian Centre for Precision Agriculture: McMillan Building A05, The University of Sydney, NSW 2006.

Oskoui K E; Rackham D H; Witney B D (1982). The determination of plough draught - part II. the measurement and prediction of plough draught for two mouldboard shapes in three soil series. Journal of Terramechanics, 19(3), 153-164

Oskoui K E; Witney B D (1982). The determination of plough draught - part I. prediction from soil and meteorological data with cone index as the soil strength parameter. Journal of Terramechanics, 19(2), 97-106

Reaves C A; Schafer R L (1975). Force versus width of cut for moldboard bottoms. Transactions of the ASAE,, 852-859

Stein A; Brouwer J; Bouma J (1997). Methods for comparing spatial variability patterns of millet yield and soil data. Soil Science Society of America Journal, 61, 861-870

Strang van Hees G L (1994). Globale en lokale geodetische systemen [Global and local geodetic systems]. Publikatie 30. Nederlandse commissie voor geodesie, Delft

Summers J D; Khalilian A; Batchelder D G (1986). Draft relationships for primary tillage in oklahoma soils. Transactions of the ASAE, 29(1), 37-39

van der Paauw F; Sissingh H A; Ris J (1971). Een verbeterde methode van fosfaatextractie van grond met water: het Pw-getal [an improved method of phosphate extraction of soil with water]. reports of agricultural research, 749. Pudoc, Wageningen

Verhagen A (1997). Site specific fertilizer application for potato production and effects on N-leaching using dynamic simulation modelling. Agricultural Ecosystems & Environment, 66, 165-175

Wolfgang P (1992). Zugkraftmessungen zur Teilschlagkartierung [Draught measurements for site specific mapping]. Landtechnik, 47(10), 490-491

Chapter 4

Dynamic Weighing for Accurate Fertilizer Application and Monitoring

J. van Bergeijk[1], D. Goense[2], L.G. van Willigenburg[1], L. Speelman

[1]Wageningen University, Department for Agricultural, Environmental and Systems Technology, Bomenweg 4, 6703 HD Wageningen, The Netherlands

[2]Institute for Agricultural and Environmental Engineering (IMAG), PO Box 43, 6700 AA Wageningen, The Netherlands

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Abstract

The mass flow of fertilizer spreaders must be calibrated for the different types of fertilizer used. To obtain accurate fertilizer application manual calibration of actual mass flow must be repeated frequently. Automatic calibration is possible by measurement of the actual mass flow, based on dynamic weighing of the spreader. This paper describes the design and test of a dynamic weighing system. Under field condition, this system was able to provide spreader weight force readings that have a standard deviation of 20 N, over a measurement range of 6 kN to 20 kN, at a maximum time delay of 1 second.

Time stamped data logging of the spreader weight and the theoretical application rate combined with position information allows determination of the realized spatial application of fertilizer. A comparison can be made between realized and prescribed application rates. This information is necessary for evaluation of fertilizer management in a precision agriculture farming system and to accurately target fertilizer application to crop and soil status.

Keywords: Fertilizer application, Granular, Weighing, Variable rate technology, Precision agriculture

4.1. Introduction

Application of mineral fertilizer in a precision agriculture system is focussed on site specific crop requirements and is based on the estimated crop-soil-weather interactions. To address spatial variability of available nutrients in the soil, three functional requirements for site specific fertilizer spreading can be formulated.

(1) The prescribed application rate must be varied for different locations in a field;
(2) The prescribed application rate must be realised through a correct setpoint mass flow; and
(3) The obtained mass flow has to be precisely distributed.

For granular fertilizers, this means that the spreading technique must be able to vary the application rate at a scale corresponding to the variations in crop and soil. Application rate errors due to mass flow deviations in the spreader have to be minimised and the realised spatial application rate must be reported to the management system to analyse site specific crop response and to adjust future applications within a growing season.

Mass flow determination of fertilizer spreaders is needed to calibrate the flow control device for different types of fertilizer with different physical properties (Hofstee & Huisman, 1990). Due to hygroscopic properties of fertilizer even the calibration for a single type of fertilizer might differ during spreading. The flow control device on a spreader is equipped with a sensor measuring either the aperture of a valve or the rotational speed of studded roller feeders, depending on the type of device used. The information based on this sensor is called theoretical mass flow and is determined by the calibration currently used for the flow control device. Conventional calibration is carried out by collection of a small sample of about 25 kg out of the fertilizer spreader during a test run. This sample is weighed and compared with the theoretically applied amount and yields a new calibration valid for the current fertilizer conditions. To reduce application rate errors, several manufacturers mount load cells in the spreaders to monitor the applied amount of fertilizer. The semi-automatic way to calibrate these type of spreaders is to weigh the loaded and unloaded spreader when stationary on a level surface. The measured load difference must be equal to the theoretically spread amount of fertilizer during the period between two weighing operations. If a difference occurs, the calibration is adjusted. This calibration method is an improvement over the manual method because of the larger measurement range on the actual flow characteristics and because it is less labour and time consuming.

A next step is continuous measurement of the spreader weight. Contrary to conventional weight measurement, where the load has to remain static during the measurement, this method is called dynamic weighing. Dynamic weighing of the fertilizer spreader enables automatic calibration of the flow control device during fertilizer application. In this paper, the design and results of a dynamic weighing system are discussed in the context of automated calibration of the flow control device. Furthermore, the addition of a positioning device and a datalogger to create a report of the applied amount of fertilizer is discussed.

4.2. Objectives

The implementation of an automatic calibration algorithm for a flow control device requires an accurate and reliable weight measurement system. Disturbances due to uneven terrain, mechanical vibrations of tractor and spreader, and the operation of the spreader on slopes must be compensated or suppressed. The first objective therefore is to design a dynamic weighing system suitable for operation under field conditions in agriculture.

The second objective is the automatic calibration of the mass flow control mechanism of a granular fertilizer spreader. In order to do this, the driving speed and effective working width also must be known with sufficient accuracy. In this research, the working width is specified by the type of spreader used and driving speed is supplied by an integrated 'position-speed-heading' system on the tractor (van Bergeijk *et al.*, 1998).

Third and last objective is to store both theoretical application rate and weight measurements during spreading to be able to reconstruct the actual applied amount of fertilizer.

4.3. Literature review

Several methods for weight measurement of implements in the three point hitch already exist. Separate derricks or weighing frames used to weigh silage handling implements or livestock carriers are available for static weighing (Knechtges, 1988). These frames are mounted between the tractor three point hitch and the standard implement. Though the design is a versatile solution, the major drawbacks regarding dynamic weighing are the displacement of the implement away from the tractor and the static weight reading restriction. More rigid design resulted in a derrick suitable for dynamic use which has been released on the market (Lely, 1993).

Integration of dynamic weighing in the tractor, or implement itself, offers a more compact solution. On the tractor, it is possible to measure forces at different positions in the three point hitch system (Auernhammer *et al.*, 1988; Auernhammer *et al.*, 1990; van den Heuvel & van Meeteren, 1991). They conclude that implement weighing by measurement of forces in the three point hitch is technically feasible but, in practice, disturbed by different hitch geometries. At the implement attachment point side, experiments with three extended octagonal sensors at the individual three points of the hitch resulted into measurement errors of 2% on a force range of 6 kN to 20 kN (van Noort, 1995).

Under field condition, in addition to deviations due to vertical accelerations, also vibrations due to engine, power take-off and implement shaft rotations, and deviations due to operation on slope have to be compensated for. Inclination sensors can be used to determine slope angle and are used, for instance, on combine harvesters to level the sieves. Vertical accelerations can be measured by an acceleration sensor. When no separate information on inclination or vertical acceleration is needed, both sensors can be replaced by a single sensor which measures a reference weight mounted parallel to the unknown weight (Böttinger, 1989). Both disturbances due to accelerations and due to slopes can be compensated for, based on the information provided by the reference weight sensor.

4.4. Materials and methods

4.4.1. *Spreader*

A standard pneumatic spreader (Amazone Jet 1504) with a working width of twelve metres is used in the experiments. Three characteristics which make a pneumatic spreader suitable for precise application of fertilizer are the relatively small effective working width, the rapidly adjustable rate and the small application pattern size in the driving direction. The application rate of the spreader is steered by adjustment of the oil flow through a hydraulic motor. The hydraulic motor drives two separate studded roller feeders for the left and right side of the spreader. The rotational speed of the roller feeders is measured by an inductive switch near one of the axles and enters the data acquisition system as a pulse frequency. This pulse frequency has a linear relation to theoretical mass flow, *i.e.* the calibration for this type of flow control device is a single gain factor. The spreader is divided into four sections of three metre width each. These sections can be opened or closed individually by an electrically operated coupling mechanism between the studded roller feeders and the hydraulic motor. The force due to the weight of the spreader itself is approximately 6 kN and that due to the maximum additional fertilizer load is 12 kN.

4.4.2. *Sensor mounting*

The original hitch studs of the spreader were replaced by three spring blades on a triangular subframe. *Figures 4.1* and *4.2* illustrate the use of three spring blades, one at the top middle position of the subframe and two at the lower sides, to construct a reversed parallellogram. The subframe has mounting positions for two strain gauge force sensors. The vertical forces of the entire spreader act on the main sensor while the horizontal forces run parallel through the spring blades. The reference sensor measures a known weight. The mounting orientation of the reference sensor is similar to the main sensor to ensure that both sensors are affected by the same disturbances. Two strain gauge sensors, each with different dynamic behaviour, were tested as reference sensor. On the first reference sensor (referred to as 'reference sensor I'), a static force of 1.776

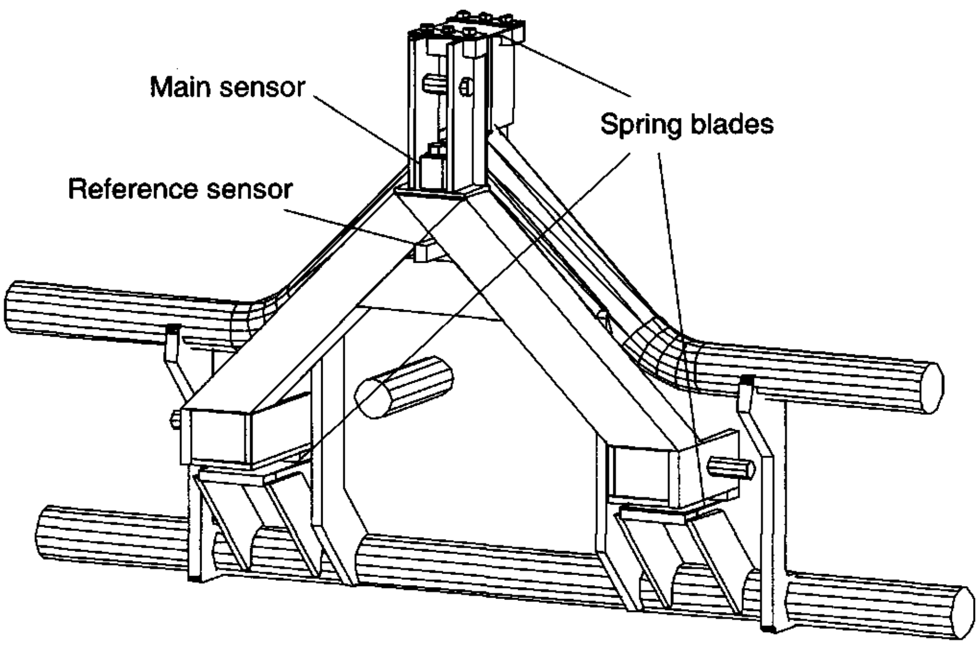

Fig. 4.1. Construction view of weighing subframe in front of spreader assembly

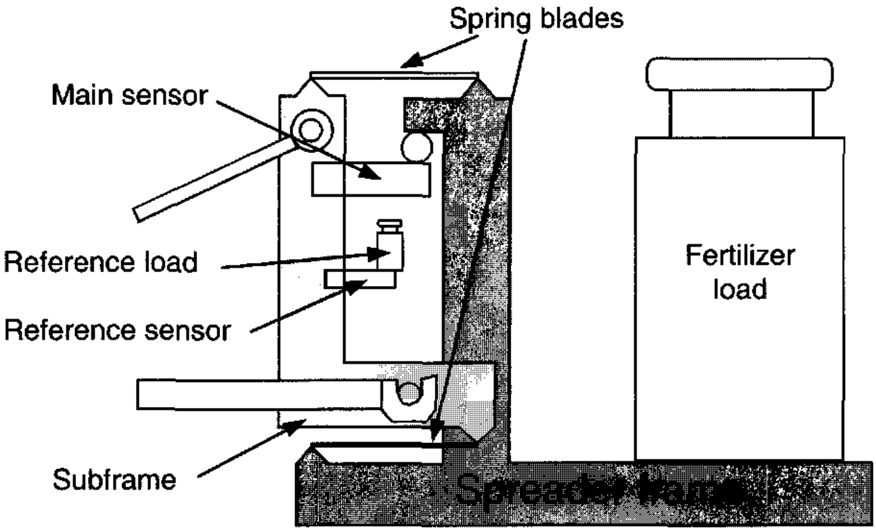

Fig. 4.2. Schematic view of the load sensor mounting positions

N was applied. On the second reference sensor (referred to as 'reference sensor II'), a static force of 38.40 N was applied. Table 4.1 lists the specifications of the sensors used in the experiments.

Table 4.1
Strain gauge sensor specifications

Sensor	*Type*	*Maximum force, N*	*Total error*, % of applied load*
Reference sensor I	Celtron LPS2, single point load cell	20	0.025
Reference sensor II	Celtron LOC50, single point load cell	500	0.02
Main sensor	Tedea huntleigh 3510, shear beam load cell	50000	0.02

*according to manufacturer

4.4.3. *Data acquisition*

Two different data acquisition systems for the strain gauge sensors were examined. The first method consisted of a strain gauge amplifier connected through a low pass filter to an analog to digital conversion card in a personal computer system. Though the quality of the individual data acquisition components was high an alternative was needed to minimise the number of noise sources in the weighing system. The second data acquisition method therefore uses a single integrated circuit directly connected to the strain gauge sensor. This AD7715 integrated circuit combines an amplifier, a low pass filter and a sigma delta analog to digital conversion in a single package. To connect the spreader weight sensor and the reference sensor to the data acquisition system, two AD7715 integrated circuits were used. The digitised sensor readings were time stamped and stored on hard disk together with the studded roller speed sensor readings.

4.4.4. *Experimental setup*

Several characteristics of the strain gauge sensors were investigated. Before mounting the reference sensor on the spreader, resonance frequency, temperature influence, linearity and hysteresis were determined. Of the main force sensor only the temperature influence was measured before mounting. Linearity and hysteresis were tested by applying calibrated loads on the pneumatic spreader while it was fixed in the three point hitch of a tractor. Deviations due to spreader operation in hilly terrain, were simulated by adjustment of the top link of the three point hitch.

Next to these static calibration series dynamic measurements with various loads in the spreader were carried out. These experiments consisted of both measurements while driving with a known load on a road with traffic obstacles and of measurements acquired during fertilizer spreading on a six ha field. The results of the dynamic measurements were used to implement a filter algorithm which combines the data from both sensors and estimates the spreader weight. Data from two field trials, where the spreader was used to spatially vary the fertilizer application rate, was available to check the conventional calibration of the studded roller feeder and to design an automatic calibration routine. In the field trials, a calcium ammonium nitrate 27% fertilizer was applied.

4.5. Results

4.5.1. *Sensor analysis*

The static weight sensor response is determined by applying calibrated loads on the sensor over a range similar to the maximum fertilizer load of the spreader. Table 4.2 lists the ranges and characteristics of the acquired responses of the different sensors and data acquisition methods. The response from both reference sensors is linear over the specified range; the value for the coefficient of determination (r^2) for a linear regression fit is close to 1.0. The main force sensor, mounted in the spreader, is slightly nonlinear. The standard deviation of the residues of this sensor decreases significantly with a second order polynomial fit. Static weighing accuracy also improves slightly with the replacement of the strain gauge amplifier with separate analog to digital conversion by an integrated circuit data acquisition method.

Table 4.2
Residue characteristics of sensor responses from static load/unload experiments

	Reference sensor I	*Reference sensor II*	*Main sensor*	*Main sensor*	*Main sensor*
Data acquisition	strain gauge amplifier, low pass filter and A/D card				AD7715 i.c.
Regression method	linear	linear	linear	2nd order polynomial	2nd order polynomial
r^2	0.9999983	0.99999993	0.9999773	0.9999955	0.9999978
Load range	0..5 N	0..100 N	6..16.50 kN	6..16.50 kN	6..16.50 kN
Standard deviation	2.45 mN	7.95 mN	11.7 N	5.69 N	4.42 N
Minimum	-4.12 mN	-13.7 mN	-30.3 N	-17.7 N	-10.9 N
Maximum	3.92 mN	11.8 mN	26.1 N	22.0 N	9.32 N

r^2, coefficient of determination
A/D, analog to digital conversion
i.c., integrated circuit

Hysteresis in all sensor responses was not detected by the data acquisition equipment. The influence of a slope on the reference force sensor output is depicted in *Fig. 4.3*. Comparison of the response of the main force sensor and of the reference force sensor on different slopes showed small errors in mounting position of the sensors. The main force sensor was mounted -0.29° non parallel to the horizontal plane. Results from a similar cosine fit through the signal of the reference force sensor resulted in -0.75° offset from the horizontal plane, *i.e.* the maximum of the cosine in *Fig. 4.3* is located at -0.75°.

The temperature influence on the main force sensor over a range 5°C to 25°C was negligible. In accordance with the manufacturer specifications for this sensor, a

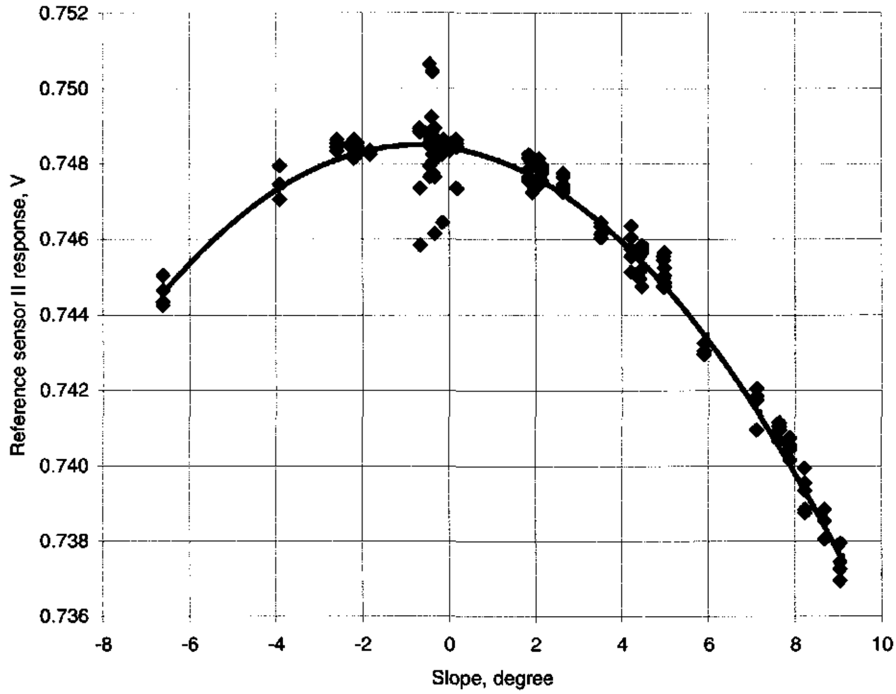

Fig. 4.3. Reference sensor II response to different slopes (◆) compared with the theoretical cosine shaped response to different slopes (continuous line)

temperature range of -10°C to 45 °C was correctly compensated for. Reference sensor I was slightly influenced by temperature fluctuations but the deviations remained within the 0.06% over 20°C, as specified by the manufacturer.

An important aspect of the reference sensors are the resonance characteristics. According to previous research (van den Heuvel & van Meeteren, 1991), especially low frequent (< 2 Hz) distortions during driving affect the weight readings. Higher frequency distortions have less energy and are more easily eliminated by a low pass filter. The typical resonance frequency for the chosen combination of sensor material and reference load must therefore be at least a decade above these low frequencies. Not only the resonance frequency but also the energy required for a sensor to get into resonance is an important criterium when using a reference sensor. Although the resonance frequency of reference sensor II with 38.40 N load is lower than the resonance frequency of sensor I loaded with 1.776 N (*Fig. 4.4*), the latter was much more affected by vibrations on the spreader and

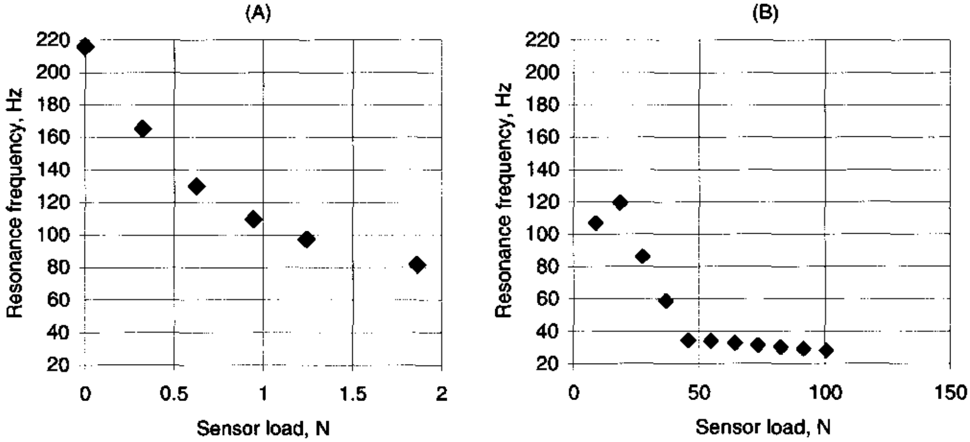

Fig. 4.4. Resonance frequencies of reference sensor I (A) and of reference sensor II (B) versus reference sensor load

performed worse than reference sensor II. This effect is visible in *Figure 4.5* where the resonance peak of reference sensor I under dynamic circumstances contains more energy than the resonance peak of reference sensor II.

4.5.2. *Dynamic weighing*

Three different combinations of sensors and data acquisition systems, series A to C, were investigated on their dynamic weighing performance. Data was acquired on road tracks with traffic obstacles at 3 m/s driving velocity. For series A, reference sensor I is used. Data was acquired with the strain gauge amplifier and the A/D extension card. Series B

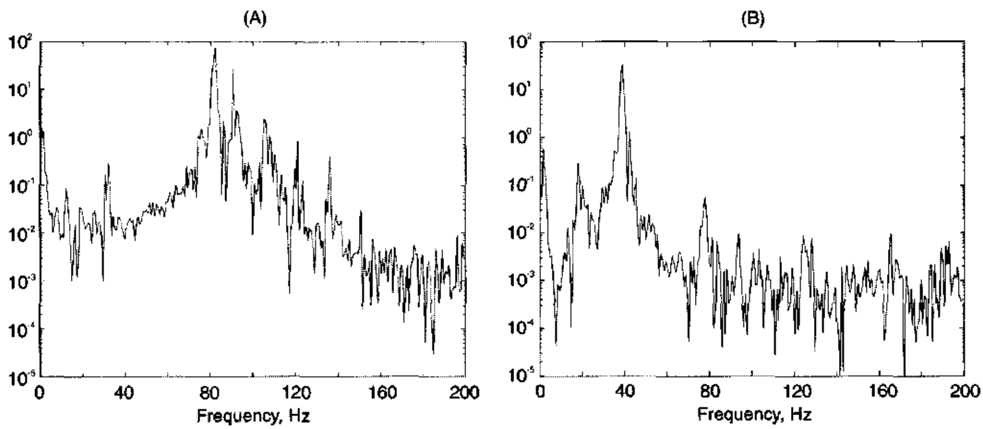

Fig. 4.5. Power spectral densities of reference sensor I (A) and reference sensor II (B)

uses the same data acquisition method but reference sensor II is used to compensate dynamic disturbances. In series C, the data acquisition method is replaced by the AD7715 integrated circuits while the sensors are identical to the procedure in series B. Table 4.3 summarises the experiment procedure and lists the measured force characteristics of the three series. To evaluate the filter and compensation algorithms, data series with comparable spreader load and disturbance magnitude were analysed. The main force sensor signal row lists the characteristics of the dynamic disturbances measured by the main force sensor. The last row of Table 4.3 lists the force characteristics after compensation and filtering the sampled data. Values on this row are obtained with a 0.5 Hz cutoff frequency of the second order Butterworth low pass filter in the compensation algorithm.

Table 4.3

Dynamic weighing system performance (N) of three experiments

		Series A	*Series B*	*Series C*
Data acquisition method		separate strain gauge amplifier, low pass filters and A/D card		AD7715 sigma delta A/D converters
Reference sensor (load)		I (1.776 N)	II (38.40 N)	II (38.40 N)
Total load on main sensor		9823.7	11312.9	9827.7
Main sensor signal	Standard deviation	948.6	1090.9	1063.4
	Minimum	5971.4	6826.8	6593.3
	Maximum	12545.0	15378.2	12921.7
Compensated and filtered signals	Standard deviation	168.7	18.6	19.6
	Minimum	9314.6	11241.3	9811.0
	Maximum	10063.1	11396.3	9903.2

A/D, analog to digital conversion

The power spectral density graph of reference sensor I shows a large resonance peak near 80 Hz (*Fig. 4.5*). Because compensation of the force signal is only needed for lower frequencies, the reference sensor signal is low pass filtered with a -3 dB point at 0.5 Hz. However, even after this low pass filter, the excitations due to resonance of reference sensor I limit compensation capability. The power spectral density graph of reference sensor II (*Fig. 4.5*) shows a similar peak near 40 Hz but required more energy to reach resonance. As a result, the compensation based on reference sensor II in series B and C reduces standard deviation of the force readings to 19.6 N (Table 4.3).

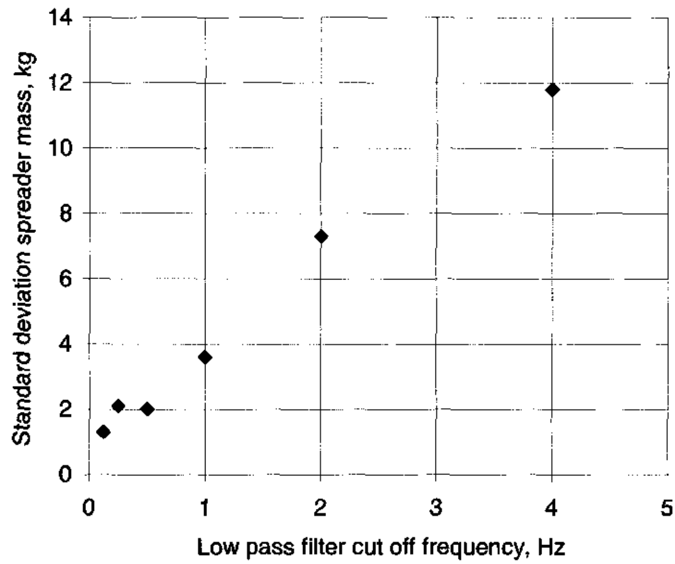

Fig. 4.6. Standard deviation of the filtered spreader mass versus the low pass filter cut off frequency

The specifications of the low pass filter in the compensation algorithm have to match a required update rate of force readings and maximum allowed standard deviation.*Figure 4.6* shows the influence of the filter cut off frequency on the standard deviation of dynamically acquired force. Increasing the force measurement accuracy will decrease the response time of the force measurement.

A two seconds wide window of samples from series C illustrates the effect of compensation and filtering (*Fig. 4.7*). The dynamic force fluctuates between 8.4 and 12.3 kN. After compensation with the reference sensor II signal, the magnitude of the distortions is reduced and noise with higher frequency remains. The second order low pass filter removes this noise and yields a reconstruction of the force due to the spreader weight with 19.6 N standard deviation.

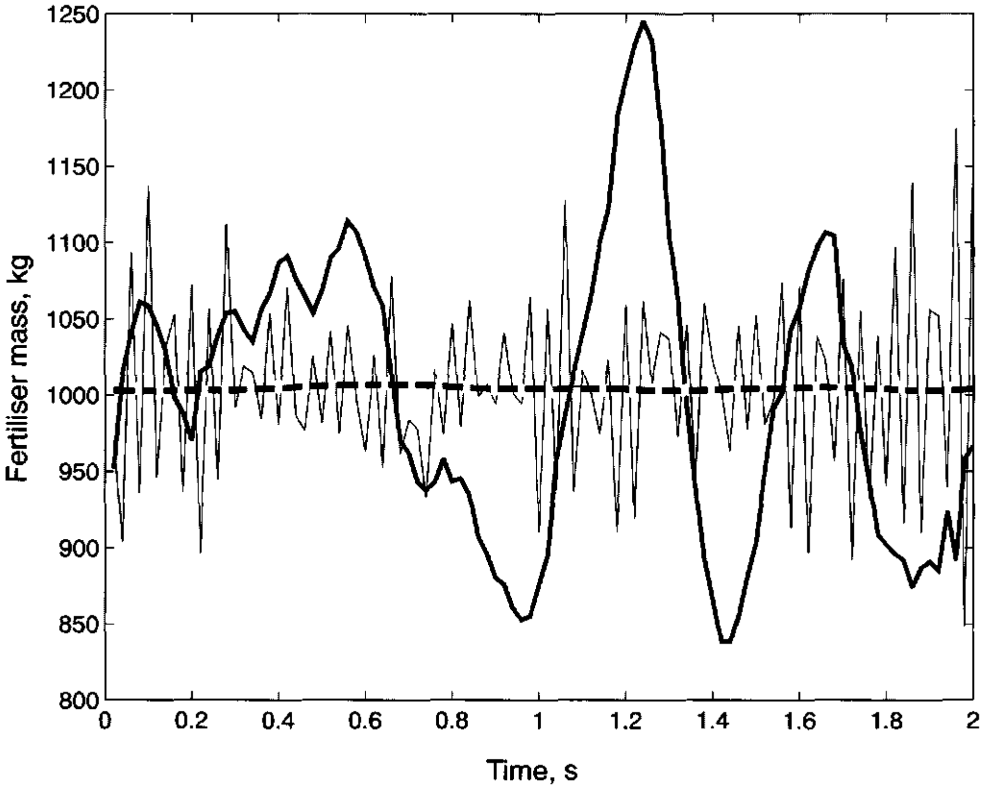

Fig. 4.7. Corrected and filtered fertilizer mass over 2 seconds of dynamic measurements; ▬, *dynamic mass;* ——, *corrected mass;* ▬ ▬, *corrected and filtered mass*

4.5.3. *Automatic calibration*

The fertilizer flow control algorithm of a single section fertilizer spreader is graphically represented by a data flow diagram (*Fig. 4.8*). A conventional fertilizer spreader with a velocity dependent fertilizer flow encorporates the processes 'Flow Control Device Setpoint Calculation' and 'Closed Loop Flow Control Device Controller'. To enable automatic update of the flow control device calibration the processes 'Dynamic Weighing' and 'Automatic Calibration' are added. The process 'Dynamic Weighing' produces a weight figure with accuracy according to the results of previous section. A method to implement the process 'Automatic Calibration' is discussed in this section.

The theoretical mass flow is calculated from the data flow 'flow control device actual

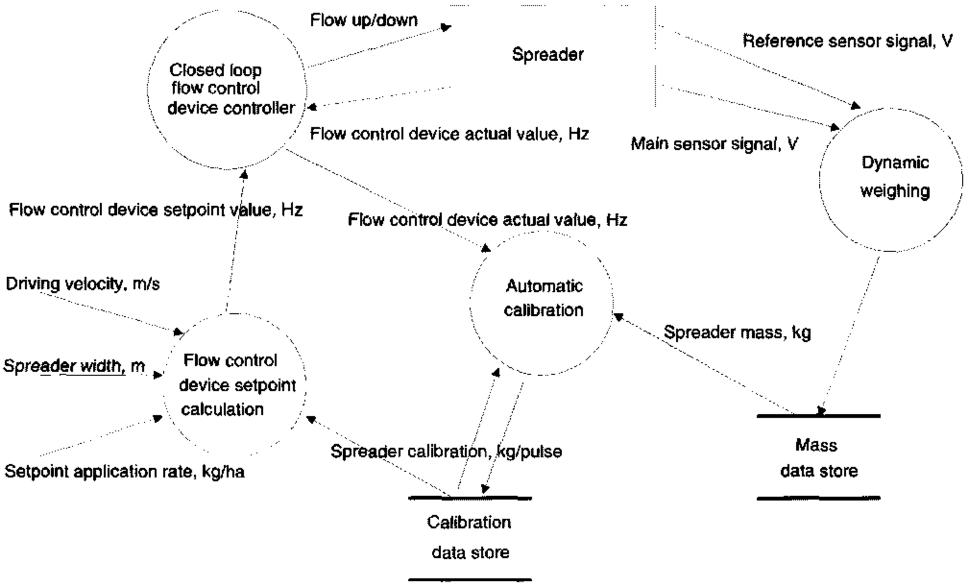

Fig. 4.8. Data flow diagram for automatic calibration of the flow control device

value' and 'spreader calibration'. Integration of theoretical mass flow over time yields theoretical applied amount of fertilizer which can be compared with the measured force, due to spreader weight, decrease over the same time period. Although this procedure is rather straightforward, any modification of the current calibration has to be justified by certain criteria. A correct initial calibration should not be altered due to less accurate force measurement results while on the other hand an incorrect calibration should be detected and modified in an early stage.

Based on a data set obtained in section 4.2 a linear regression model between theoretical weight decrease and measured weight decrease was analysed. The assumptions were: the use of a 12 m wide spreader, a velocity of approximately 2.8 m/s and an application rate of 300 kg/ha which results in a mass flow of 1 kg/s. The spreader weight from the dynamic weighing process enters the automatic calibration at 1 Hz update rate. A faster update rate is not necessary while the dynamic weighing process applies a low pass filter with 0.5 cut off frequency on the output signal. The time window for linear regression varied between 20 and 120 seconds. A correct calibration should produce a regression line according to Eqn (4.1) with values for coefficient *A* of 0 and for coefficient *B* of 1. Calibration deviations are recognised when theoretical force differs significantly from measured force and/or when coefficient *B* is significantly different from the value of 1:

$$W_{m,i} = A_i + B_i\, W_{t,i} \tag{4.1}$$

Where, $W_{m,i}$ it the measured force due to spreader weight at time i in N, $W_{t,i}$ is the theoretical force due to spreader weight at time i in N, A_i is the linear regression offset at time i in N, and B_i is the linear regression gain at time i.

Confidence intervals for coefficient B and for predicted force at each time step are possible criteria to justify calibration adjustment. *Figure 4.9a* depicts the confidence interval of coefficient B over linear regression windows ranging from 20 to 120 seconds length at a mass flow of 1 kg/s. A calibration accuracy of 4.3% can be obtained at 99% reliability within 60 seconds or after application of 60 kg of fertilizer. *Figure 4.9b* depicts the confidence interval of the predicted force $W_{m,i}$. Given a certain initial calibration accuracy at the start of a fertilizer application, correction of the calibration starts when the force measurements reach a better accuracy than initial calibration and continues to maintain a preset level of desired calibration accuracy.

Evaluation of the spreader calibration algorithm is done by a simulation study. Based on under dynamic circumstances obtained force recordings, the reaction of different calibration update criteria on simulated calibration errors was investigated. *Figure 4.10* shows the results of calibration updates from an algorithm which modifies the calibration based on the confidence interval of coefficient B. Initial calibration accuracy was set to 10% and the calibration accuracy goal is 1%. The data set covers a fertilizer application

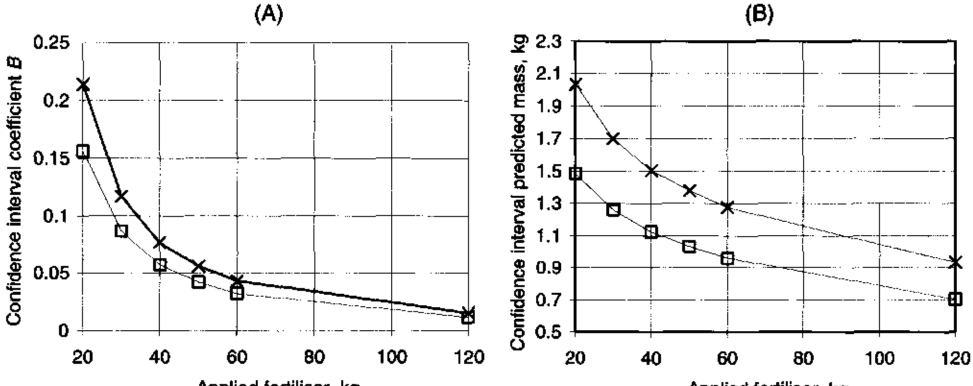

Fig. 4.9. Confidence intervals of the calibration regression coefficient B (A) and of the predicted mass (B) versus the applied amount of fertilizer at two reliability levels: x, *99%;* □, *95%*

range from 1000 kg down to 0 kg at a constant mass flow of 1 kg/s.

The confidence interval for the linear regression coefficient *B* at 99% reliability reaches an accuracy of 10% after application of 30 kg of fertilizer. The calibration, initially set at a 10% error value, is then modified. At increased applied fertilizer mass, the calibration accuracy increases until a 1% accuracy at 99% reliability for coefficient *B* is reached. The calibration error is already close to 0% after application of 60 kg fertilizer but only after application of approximately 160 kg of fertilizer 1% accuracy at 99% reliability is obtained.

During the application of the first 160 kg of fertilizer the linear regression window enlarges and comprises all weight samples available. The regression window is kept at a size needed to maintain the same accuracy after the accuracy goal is reached. Although accuracy might improve by further enlargement of the regression window, a quick response to calibration changes is also needed. This implies a regression window which is as small as allowed by the accuracy criterium and which depends on the actual dynamic weighing accuracy.

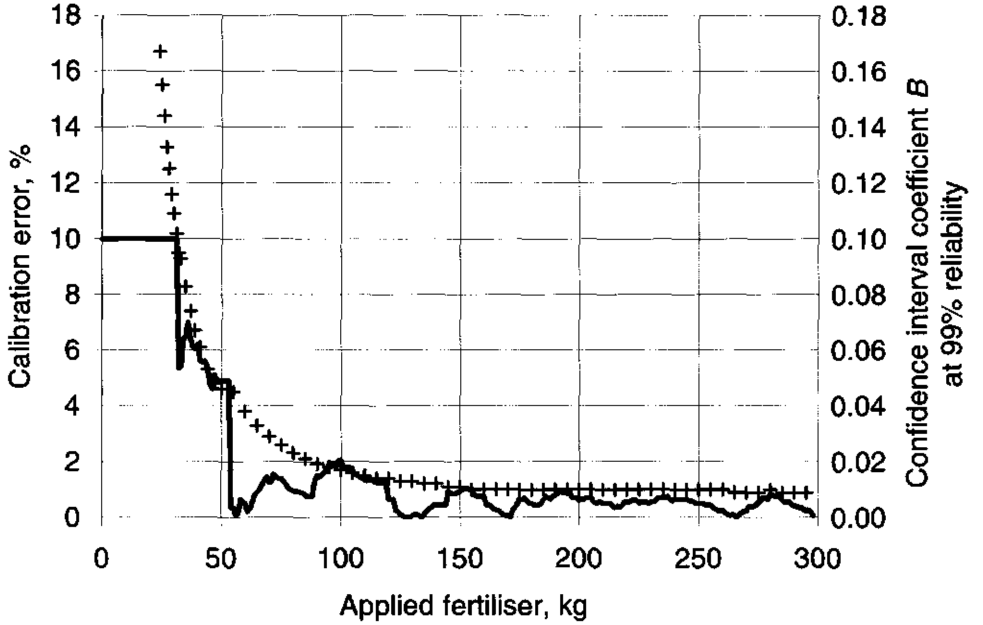

Fig. 4.10. Simulated calibration updates based on the confidence interval of the value for the calibration regression coefficient B: +, confidence interval of coefficient B at 99% reliability; --, calibration error, initially set at 10%

4.5.4. *Time stamped data logging*

To record the applied amount of fertilizer the following system components were added to the tractor-spreader combination:

(1) positional information system;
(2) map based information on prescribed fertilizer application rates;
(3) dynamic weighing of the fertilizer amount in the spreader bin; and
(4) a communication bus between tractor and implement.

Figure 4.11 shows the hardware architecture used in this experiment. Both 80486 personal computers were fitted with analog and digital acquisition cards and stored their acquired signals and operation characteristics on local hard disks.

The positional information system is a combination of a Global Positioning System (GPS) receiver with on-vehicle speed and heading measurements (van Bergeijk *et al.*, 1998). The prescribed application rates are stored in an object oriented geographical information system. Areas in a field with different prescribed application rates are stored as geographical regions bounded by a number of straight lines (Goense *et al.*, 1996). The prescribed application rate changes when the effective working area of the spreader enters an area with a different prescribed application rate.

The dynamic weighing implementation is according to the experimental procedure

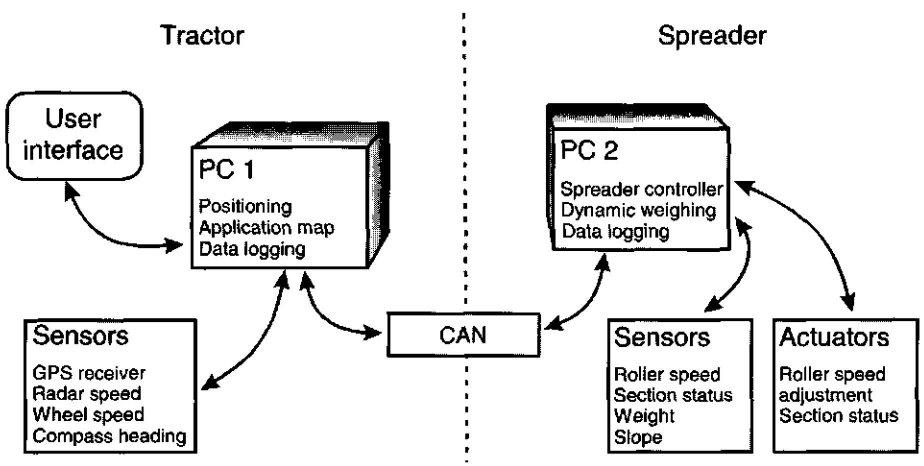

Fig. 4.11. Hardware architecture for control and logging of fertilizer application; PC, Personal Computer; CAN, Controller Area Network; GPS, Global Positioning System

in the previous sections. Automatic calibration of the studded roller feeders was not implemented but both studded roller feeder speed and spreader weight force are recorded to reconstruct spreader performance. The communication bus used in the system is the Controller Area Network (CAN) operating at 250 kBaud with 29-bit identifier (CAN2.0B) and a physical layer similar to the proposed ISO standard 11783.

Time stamped data logging at 4 Hz update rate of the following data items was conducted:

(1) position coordinates x and y in m;
(2) driving speed in m/s;
(3) heading in rad;
(4) setpoint application rate in kg/s;
(5) theoretical application rate in kg/s;
(6) section status; and
(7) spreader mass in kg.

With this information, reconstruction of the applied amount of fertilizer at a scale equal to the effective working width of the implement was carried out.

4.6. Discussion

The slightly non linear response of the main force sensor might be caused by bending of the weighing derrick or by non-parallel mounted spring plates. In both situations, a small portion of the vertical forces is not measured by the force sensor. At increased load, a linear model for the main force sensor signal shows an increased error and a reduced sensor response.

A previous version of spreader weight force determination used three extended octagonal ring transducers at the three hitch joints of the spreader. Advantages of this approach were mounting simplicity, the sensors basically just replaced the hitch studs, and the opportunity to measure vertical and horizontal forces separately. Processing of these signals made it possible to reconstruct gravity point of the spreader, slope and true vertical force due to spreader weight. However, individual errors on the sensors propagated through the required signal processing and affected overall accuracy negative. Therefore a design based on a single force sensor, combined with a construction that eliminates the effect of gravity point changes, was tested and proved to weigh more accurately.

Integration of required data acquisition and signal processing into a single integrated circuit and digital signal processor is especially in the direction of practical implementation of the dynamic weighing system an advantage. Next to a more compact implementation, accuracy slightly improved. One drawback of the use of an integrated data acquisition method is the required hardware and software for the interface, which had to be designed specific for our experiment setup. Another drawback of the use of an AD7715 integrated circuit is less flexibility in sample rate settings and low pass filter methods compared to the capabilities of an analogue data acquisition card mounted in a personal computer.

Based on dynamic weighing, several flow control device calibration correction methods can be defined. The fertilizer mass flow is, in practice, not constant in time due to changing application rates and fluctuations in driving speed. Both measured force and theoretical force should therefore not be compared as time series but related directly towards each other. Even with fluctuations in mass flow a linear regression between measured force and theoretical force can be made.

Next to the confidence interval for the values of coefficient B, other criteria for calibration have to be checked. For predicted force $W_{m,i}$ (Eqn 4.1), a confidence interval might indicate significant deviations between measured force and theoretical force. A reason for not using this criterion is that correction of the calibration entirely relies on the value for coefficient B. Even when the predicted force differs significantly from theoretical force, an inaccurate or less reliable value for coefficient B may not be used to alter the calibration. Although the confidence intervals for both the coefficient B and the predicted force are closely related, a criterion based on the coefficient B confidence interval could be used directly to modify the calibration.

It is not desirable to compensate calibration errors from areas already spread, with spreading more or less on areas that still have to be spread. Therefore, the value of the regression coefficient A (Eqn 4.1) can not be used as a criterion for calibration updates. For example, if due to a calibration error, the theoretical force becomes higher than the measured force, an update of the calibration will result in a negative value for coefficient A which reveals that too few fertilizer was spread. When the goal of the calibration update algorithm would be to minimise the value for coefficient A, consequently too much fertilizer would be spread in the time period that follows.

In a distributed data acquisition system used for time stamped data logging, synchronisation of the data must be taken care off. While logging of most data is defined at the relatively slow storage rate of 4 Hz the personal computer system timer (18.2 Hz) functions as time base. However, clock errors between both computers might lead to timeshifts between logfiles from different computers. In order to avoid these errors, a high priority CAN-message, repeated at 1 Hz, is used to distribute the timer status of one computer to other data logging devices on the network. In the experiment, the network load was low and excessive delays of the timer message during transmission on the network were not detected. A post processing algorithm calculates the time shift between the two data acquisition platforms. Within a five hour fertilizer application task the timeshift remained less than the measurable 1/18.2 s.

4.7. Conclusions

Fertilizer application errors due to mass flow calibration deviations can be reduced by spreader weight measurement during fertilizer application. The standard deviation of static weight force measurement with a conventional pneumatic fertilizer spreader, equipped with a reversed parallel weighing derrick, was approximately 8 N over 10 kN load range. An integrated data acquisition method, specifically designed for load cell measurements, performed slightly better than the use of a separate strain gauge amplifier and data acquisition card.

A second, reference, load cell with fixed mass was added to the weighing derrick to compensate for the operation on slopes and for the dynamic weight force fluctuations under field conditions. Compensation of spreader weight by the reference sensor response deviations due to vertical accelerations worked especially well for deviations with a frequency in the range from ±0.1 to 20 Hz. The combination of the reference load cell with the fixed mass had to be chosen such that the resonance frequency is above the deviation frequencies to compensate for. The use of a reference load cell reduced standard deviation of dynamic weighing from 1063 N to 19.6 N.

The flow control device calibration can be monitored and eventually modified when accurate spreader weight measurements are available. Based on the dynamic weighing results, a calibration accuracy goal of 1% can be maintained under field conditions. In a simulation study 1% calibration accuracy with 99% reliability was obtained after application of 160 kg of fertilizer. An initial calibration error of 5% was corrected after application of 60 kg fertilizer, thus minimizing the application error to approximately 3 kg.

For the reconstruction of actual applied amount of fertilizer both spreader weight, flow control device status and positional information must be logged against a certain time base. When a separate system for position information is equipped with own data logging facilities, synchronisation over an ISO compatible Controller Area Network is sufficiently accurate for a data logging rate of 4 Hz.

References

Auernhammer H; Demmel M; Stanzel H (1988). Wiegemöglichkeiten in dem Schlepperdreipunkthydraulik, [Weighing opportunities in tractor hitch hydraulics]. Landtechnik, 43(10), 414-419

Auernhammer H; Stanzel H; Demmel M (1990). Wiegemöglichkeiten im Schlepperheckkraftheber und in Transportfahrzeugen, [Weighing opportunities in rear tractor hitch and in transport vehicles]. Landtechnik Weihenstephan, Freising, Germany

Böttinger S (1989). Durchsatzbestimmung für eine Regelung der Mähdresser-reinigungsanlage, [Flow measurement for control of the combine harvester sieves]. Proceedings of the 11th International Congress on Agricultural Engineering, Dublin. In: Land and Water Use (Dodd V A; Grace P M eds), Vol. 3 (Agricultural Mechanisation), pp 1857-1862, Balkema, Rotterdam

Goense D; Hofstee J W; van Bergeijk J (1996). An information model to describe systems for spatially variable field operations. Computers and Electronics in Agriculture, 14, 197-214

Hofstee J W; Huisman W (1990). Handling and spreading of fertilizers, Part 1: Physical properties of fertilizer in relation to particle motion. Journal of Agricultural Engineering Research, 47, 213-234

Knechtges H (1988). Behälterwägung im Dreipunktanbau, [Implement weighing on three point hitch mounting]. Landtechnik, 44(5), 218-219

Lely (1993). An implement for spreading material. European Patent Application 0537857A2. Netherlands

van Bergeijk J; Goense D; Keesman K J; Speelman L (1998). Digital filters to integrate global positioning system and dead reckoning. Journal of Agricultural Engineering Research, 70, 135-143

van den Heuvel C L H; van Meeteren C M A (1991).Dynamische gewichtsmeting voor de bewerking kunstmeststrooien, [Dynamic weighing for fertilizer application]. Msc Thesis, Agricultural University, Wageningen

van Noort J (1995).On the improvement of actual applied rates of fertilizer spreaders. Msc Thesis, Agricultural University, Wageningen

Chapter 5

An Information System for Spatially Variable Field Management

J. van Bergeijk[1], D. Goense[2]

[1]Wageningen University, Department for Agricultural, Environmental and Systems Technology, Bomenweg 4, 6703 HD Wageningen, The Netherlands

[2]Institute for Agricultural and Environmental Engineering (IMAG), PO Box 43, 6700 AA Wageningen, The Netherlands

Abstract

A characteristic of precision agriculture research is that different disciplines are involved and that much information is exchanged. Especially when research is conducted at farm scale level, the data, collected by various measurement methods and often by different researchers, has to be available in a well described format. This prevents misinterpretation of the data and, more positively, encourages a multidisciplinary research approach. Based on an information model, an information system was implemented to support 'on farm' research. The system is split up in several components. One component, data storage, handles persistent storage of farm management activities with their spatial and temporal dimensions. At the application level, two components are discussed; one for the use of a crop growth simulation model to optimise field management prescription rates and another for the processing of yield measurements from farm implements.

The software engineering approach followed is an integration of the structured analysis and object oriented methods. For the different components of the information system different methods were applicable. A common factor for both methods is the use of the Unified Modelling Language (UML). It was possible to use the UML notation and a computer aided software engineering (CASE) tool for both the design and implementation of the data persistency component in a relational database as for the design of the application components according to an object oriented approach.

Keywords: Information Model, Relational Database, Object Oriented, Precision Agriculture

5.1. Introduction

The basis for site specific field management is the notice that crop and soil characteristics vary at a scale, smaller than the field size. To optimise crop production, field operations no longer act uniform at field scale but working conditions are adapted to the in-field variations. An example is the nitrate fertilizer application where the application rate depends on the local crop demand, the local nitrate availability in the soil and the local nitrate leaching risk of the soil.

A rational approach to obtain the set points for spatially variable field operations requires processing of data from various information sources. In the example of a nitrate fertilizer application, the following information sources are likely to be used: 1) Yield mapping activities during previous seasons provide an estimate of the target yield. 2) Remote sensing images indicate and possibly quantify certain crop characteristics. 3) Analysis of soil samples, taken at different locations provide a spatial measure of the soil characteristics. This information can be used as an input to crop growth simulation models that facilitate the search for an optimal application rate in both the spatial and the temporal dimension (Booltink & Verhagen, 1997). Finally, the actual nitrate application is realised and has to be monitored to ensure correct evaluation of nitrate efficiency of the crop at the end of the growing season.

In precision agriculture research, the data exchange between information sources introduces potential hazards. One of these hazards is an unknown or unspecified data source. For instance, when the use of data is limited due to the scale or the resolution at which data is collected, these limits should be part of the data. Likewise, the use of data collected by measurement equipment is subject to the calibration of sensors and to the configuration of a measurement system. To trace back possible error sources, access is required to calibration data and measurement system set up when these measurements are used. Another hazard lies in the use of calculation routines, embedded in post processing procedures for yield mapping, simulation models and decision support systems. When simulation models are used to support farm management decisions, care has to be taken to use a model only within its validated and calibrated ranges. Obviously, this can only be enforced when these ranges are specified and published or when the constraints are checked by the model itself.

In order to reduce these risks and to facilitate the exchange of data, an information model can be constructed. An information model describes real world objects and their interaction and gives definitions for all distinguishable data elements. An information model serves as a reference model for the implementation of applications that have to process information.

An information model for spatially variable field operations has previously been described (Goense *et al.*, 1996). A more generic information model for agricultural systems was build within the ESPRIT III project titled 'Computer Integrated Agriculture'. These models focused on the description of the farm structure and operations necessary to construct a farm management information system. The applicability of these models for precision farming had its origin in the specification of a link between geographic entities and field operation entities. The structure of the geographic entities was similar to the entities available in geographical information systems (GIS) (Burrough, 1986) and therefore this model could easily be supported by standard GIS applications. Although the analysis method used for these information models was most suitable for the design of a relational database as persistent storage in the information system other publications which use an object oriented analysis method are also available (Saraiva *et al.*, 1998; Gauthier & Guay, 1998). Gauthier and Guay (1998) motivate their focus on the use of an object oriented database management system with the observation that the complex nature of data in an agronomical information system cannot be modelled adequately by the entities and relations in a entity-relationship model. Especially the combined spatial, temporal and thematic aspects that occur also in a GIS would require an object oriented system design. However, the OpenGIS consortium does not endorse either an object-oriented or an entity-relational approach. They publish both object specifications and relational schemas which can be implemented as either an object oriented information system or as an extension to a relational database management system to support geometrical data types and queries (OpenGIS, 1998 and 1999).

Other examples of information systems used in agricultural research can be found in the area of integration of crop growth simulation models with GIS and decision support systems (DSS). DSSAT (Jones, 1993) originally recorded data from plot scale experiments to build and calibrate crop growth simulation models. Gradually it evolved into a model shell for simulation and evaluation of agricultural systems. APSIM (McCown *et al.*, 1994) has a similar approach although the core engine has additional provisions to check system integrity when different models, e.g. soil, crop and climate, are linked together. While their focus is the use of crop growth simulation models as a decision support system for farmers and extension services this is a vital part. The use of model shells has put some stress on the standardisation of data required by these models. For instance the definition of a general structure for soil data has been initiated by the

IBSNAT project (Uehara & Tsuji, 1993) while efforts on standardisation of crop data and crop model interfaces are continued within the ICASA program. Regarding the software techniques to use, several papers demonstrate prototypes ranging from relational databases to internet based, distributed systems (Caldeira & Pinto, 1998; Pan *et al.*, 1998).

This study will describe the process of the design and implementation of an information system for precision agriculture. The scope of the system is to store farm data necessary to carry out and evaluate site specific field operations. Both the structured analysis methodology and the object oriented approach will be used to meet the requirements of the different subsystems. In the discussion this combination of methodologies as well as the implementation aspects of the information system will be evaluated.

5.2. Information modelling

The purpose of information modelling is to define a structure for the data storage and data handling requirements of an organisation. Information modelling itself can be seen as a design process. For this process, several methods are available to analyse the requirements of an organisation and to translate these requirements into an information system. In this paper both a design process intended for implementation of a relational database (Structured Analysis) and the use of an object oriented approach for data handling will be discussed.

5.2.1. *Structured analysis, design and implementation*

The design process of a relational database using structured analysis and design is depicted in *Fig. 5.1*. A computer aided software engineering tool (CASE-tool) was used to maintain a consistent data dictionary (DD) of the information model. The model was graphically constructed by creation of entity relationship diagrams (ERD) and data flow (DFD) diagrams. The entities in the ERD were defined by adding the relevant properties together with their corresponding database variable types.

The ERD was translated into a relational database scheme by the generation of a structured query language (SQL) data definition query. The CASE tool is capable to generate and export these type of queries as an ASCII text file. The text file can be imported by a specific relational database management system (RDBMS) to generate the

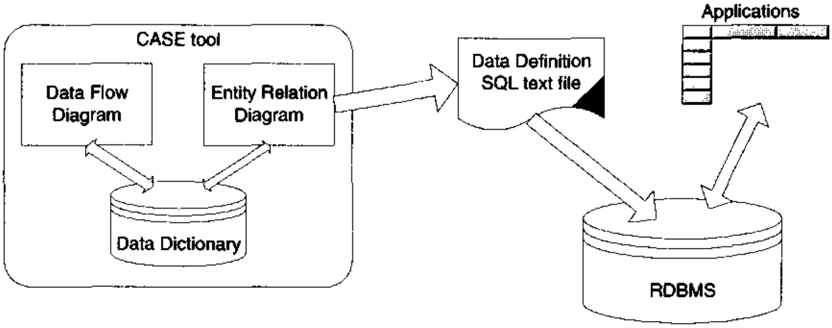

Fig. 5.1. Design process of a relational database

tables from the entities and to enforce consistency according to the specified constraints on the relations. The strict separation between the information analysis phase and the final implementation in a specific RDBMS, makes it easy to migrate from, for instance, a single user implementation on a personal computer, to a multi user database in a network environment.

After implementation in a RDBMS different users can write routine's to add data to, or retrieve data from the database. Rapid application development programs and form or query builders for the major programming languages are suitable tools to connect to relational databases and write custom analysis routines. For specific tasks like presentation of geographical data, the more specialised GIS packages offer capabilities to connect to remote databases through the use of a SQL interface.

5.2.2. *Object oriented analysis, design and implementation*

Where structured analysis and design focuses on the entities and the data flows, the object oriented approach distinguishes classes and formulates class relations. The most important difference between entities and classes is that the entities just contain data while the classes contain both data and algorithms. This gives the opportunity to model behaviour specific for a certain class together with the data of that class. In this way it is possible to simplify the external interface of a class and to create reusable software components.

The different CASE-tools for object oriented analysis and design offered a number of graphical notation methods for creation of class structure diagrams and class behaviour diagrams. After some years of coexistence of these methodologies, the unified modelling language (UML) became the common language for object oriented modelling.

The UML diagrams are a unification of previous object oriented analysis methodologies formulated by Booch, Rumbaugh and Jacobson (Fowler & Scott, 1997). It is important to notice that UML merely defines the modelling language, i.e. the graphical diagrams and their symbols. This language is one part of an object oriented analysis and design methodology. The other part, the *process* of analysis and design, has to be worked out separately and might differ from project to project. The iterative approach by (Shlaer & Mellor, 1991) and the focus on use cases to model system functionality (Jacobson*et al.*, 1992) provide more detail on the development process. Next to the use case diagram, the class diagram is regarded as the most essential part of the UML. The class diagram provides a description of the classes and of the static relations between classes. Interaction diagrams can be used to model the dynamic interaction between classes within a single use case. The two types of interaction diagrams defined in UML are the sequence and the collaboration diagram. In some CASE-tools these diagrams can be generated from each other and it depends on the preferences or focus of the modeller which diagram is used. When a model of the behaviour of a single class, for instance in more than one use case, is required, the state diagram is more applicable.

The challenge to break down a large complex system into smaller components in the most efficient way remains the same for both structured analysis and object oriented systems. One method used in UML is to define packages that consist of a number of classes with strong interrelationships. The subdivision aims for packages that have a clear internal domain and limited external dependencies. Examples of packages are the user interface of an application, the business logic of an application and the data persistency. The user interface of an application might in turn rely on another package, the graphical user interface as provided by for instance an operating system on a specific computer platform. Another method to hide complexity at a certain level of the system is to nest diagrams according to a system / subsystem classification. For instance, the state and activity diagrams can be nested to provide or hide details according to a chosen view on the system or on a subsystem.

Implementation of an object oriented system is done by coding the classes, using an object oriented programming language, and subsequently running the system in an object oriented environment. This environment might be part of the application itself, for instance when C++ code is compiled an executable is generated that contains mechanisms for class instantiation and class method calls, or the environment can be a separate system, for instance a Java interpreter or Smalltalk environment. Generation of the source code, based on the class structure, state and activity diagrams, is an option offered by several CASE tools. These diagrams are then used to generate source code or class templates for object oriented programming languages like C++ or Java.

5.2.3. *Structured analysis and design versus object oriented analysis and design*

The major difference between structured analysis and design and object oriented analysis and design is that the entities distinguished in the structured approach only contain data while the classes in an object oriented approach contain both data and algorithms. This gives the opportunity to store behaviour specific to a certain class together with the data of that class in order to simplify its external interface. Systems that benefit from an object oriented approach are those where many different entities with strong interrelations exist that can be replaced by a number of subsystems or classes that have a smaller interface and less interdependencies.

The object oriented approach is used extensively for programming graphical user interfaces, in application macro languages and for the creation of 'building blocks' or components in rapid application development programs. Code reuse and software maintenance benefit from this approach although relational databases will continue to play an important role as the data storage system.

A unified approach can lead to the use of a relational database technology within for instance a shell or encapsulation of interface objects as demonstrated in rapid application development packages and the Java 2 enterprise edition (anonymous, 2000). Another effort to combine the reliability and the efficiency of a relational database for persistency with the benefits from an object oriented approach is the object-relational database. An object-relational database allows the user to define new data types (classes) and to extend the database management system to store and query using methods of these classes (anonymous, 1999).

5.3. Materials and method

For both structured analysis and object oriented analysis a number of CASE-tools is available. One CASE-tool that provided an early implementation of the UML diagrams for object oriented analysis and had still a limited capability to support relational database design is Rational Rose (1998). In this study, therefore, Rational Rose was used. However, this choice had consequences for the relational model: the CASE-tool uses static class diagrams to model entities and their relations and although code generation for a relational database implementation (*Fig. 5.1*) is possible, the diagrams do not follow the conventional entity relationship diagram notation.

After specification of the entities, attributes and relations, a SQL data definition query was generated by the CASE tool. For the prototype applications, this data definition query was imported in a relational database management system (microsoft Access) and an object relational database management system (Cloudscape). The microsoft Access implementation provided data access through the open database connectivity (ODBC) protocol on microsoft windows platforms. The Cloudscape implementation is part of the Java 2 enterprise edition and runs on a java platform. Other java applications are able to connect to Cloudscape through the remote method invocation (RMI) interface.

The prototype applications were build using the object oriented languages C++ and Java. Code generation from the CASE-tool was investigated but the current implementation of the generator was restricted to create just the class templates and attribute definitions. Implementation of class behaviour and interaction with a graphical user interface required the use of developer environments. Both the C++Builder and the JBuilder environments were used for this purpose.

5.4. Functional requirements

5.4.1. *Applications*

The scope of the information system as described here is limited to precision agriculture research at the farm level. The, for this article relevant, applications within the information system are described by the following high level use cases that describe the functional requirements:

1. *Specify Farm Resources*. This use case covers creation and maintenance of the basic coding data. Basic coding data identifies the farm structure, i.e. fields, implements, workers and items, as well as providing a reference to standard codes for crop types, activity types, etc. In more detail, separate use cases might be 'to add an implement to the inventory' or 'to specify the boundary for a field'.

2. *Process Soil & Crop Samples*. Determine the locations for crop or soil samples, take the samples and store and process analysis results.

3. *Crop Plan Specification*. The allocation of fields to crop production units consists of specifying what type of crops will be cultivated on which fields. This use case relies on more detailed use cases that collect data on the performance of previous seasons cropping plans and that take into account legislation and farm economic constraints.

4. *Field Activity Management*. The specification of what to do, where to act, how to implement and when to carry out field activities belongs to this use case. Preparation of a field activity is a more detailed use case that in a precision agriculture system might even involve the set up, execution and evaluation of crop growth scenarios to determine activity properties. To report back actual activity properties and the processing of data from for instance yield measurement equipment are other examples of more detailed use cases.

5. *Plan on-farm experiment*. An experiment might consist of the application of different levels of fertilizer rates to evaluate crop responses or the use of a different working method. This use case has influence on the field operation management while it affects operation properties.

6. *Analyse on-farm experiment*. This covers the capability to retrieve, process and store data from on-farm experiments.

Several system requirements that are not directly associated to a single functional use case are listed below. They are classified under the themes 'External Systems Interface', 'User Interaction' and 'Data Persistency'.

5.4.2. *External systems interface*

The described high level use cases do not cover all functionality a farm management system could provide. Another requirement therefore is that the information system is able to interface to applications already available on a farm or to future applications. Examples of such applications are:

(1) models and algorithms for specific analysis or decision support tasks;
(2) external data sources, for example weather data and market information;
(3) on farm systems for process control and data collection; and

(4) existing databases on either the farm or at the research station.

5.4.3. *User Interaction*

The intended users of the information system are researchers, farm managers and students. Typical use by the researchers is to store crop and soil analysis data and to retrieve data for use in external models or procedures which are 'under development'. The farm manager is responsible for storage of farm operational data and farm resources. Preparation and execution of field tasks is also a typical farm management task, although interaction with research might be needed regarding the details of experiments on specific fields. The user interface on the farm can be restricted to a number of forms, including geographical presentations, for the farm management tasks. For research people, a user interface with only 'fixed' functionality is not sufficient, instead the system should provide an interface which is expandable to support various data analysis and data presentation methods.

5.4.4. *Data Persistency*

While most of the applications share similar data structures, it is useful to model and implement data storage and data access functionality independent of the applications. This leads to a multi-tier software architecture where the data persistency tier might be implemented as a relational database or object repository. Data structures that are likely to be stored in this component are:

(1) farm resource descriptions: fields, crop production units, equipment and personnel
(1) farm activities and related activity properties;
(2) soil properties;
(3) crop characteristics; and
(4) climate data.

5.5. Results

5.5.1. *Components*

The deployment diagram (*Fig. 5.2*) shows a subdivision of the information system into components. The components are used to build up devices. Devices are depicted as rectangular, shaded boxes and represent a distinguishable unit that can execute one or more component instances. In this diagram, the conventional three-tier distinction of a persistency, an application logic and a user interface tier is distributed over several devices. Four types of devices are distinguished:

1. *Data Persistency Server*, responsible for storage and retrieval of persistent data. Provides an interface to other devices that need access to persistent data.
2. *Farm Management PC*, responsible to provide a user interface for the farm manager. This device provides applications that implement the farm management use cases. It also provides an interface to mobile devices on a farm.
3. *Mobile Implement*, responsible for control of and data acquisition on mobile farm equipment. This device has a means of communication with the farm management PC through a distributed farm activity client component.
4. *Analysis Workstation*, provides an interface for research and analysis tools to use data collected in on farm research and prepare experimental farm activities. One of the

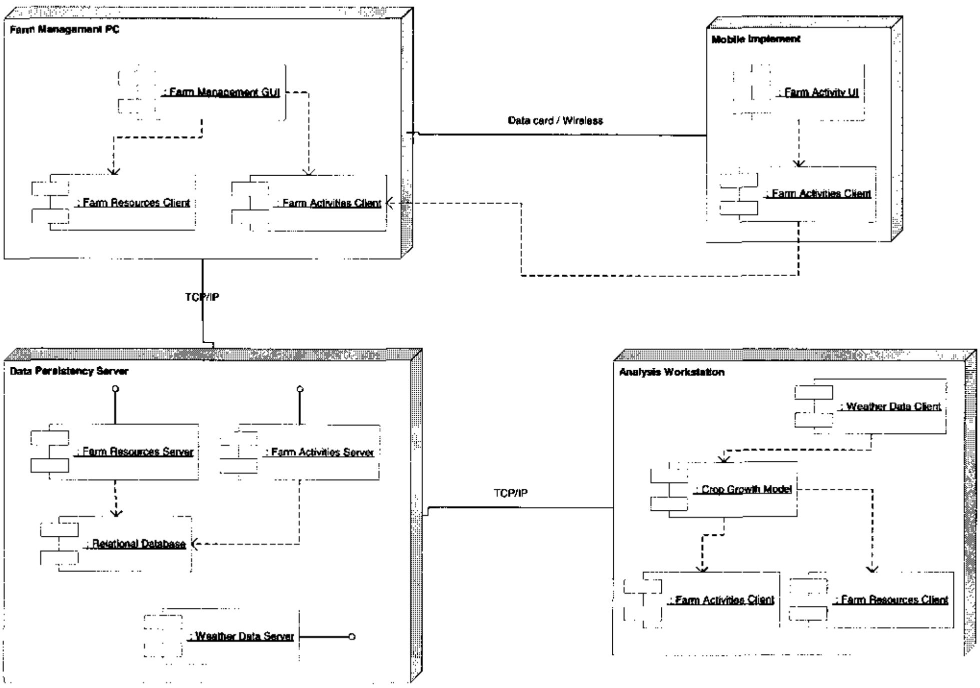

Fig. 5.2. Deployment diagram for a precision agriculture information system

components depicted might be a crop growth model to simulate crop cultivation options in order to minimise resource use and environmental impact.

In *Fig. 5.2*, the communication between devices uses TCP/IP connections. With a different component grouping or different interconnection implementations, other types of connections are possible. When modelled and implemented correctly, the components are not affected by the connection implementation but rely on interface components (not drawn in *Fig. 5.2*) that perform the conversion for specific platforms and connection management.

5.5.2. *Structured analysis*

The results of the structured analysis method to model the data storage component have been split up in six thematic diagrams; the farm resource entities (*Fig. 5.3*), the farm activity entities (*Fig. 5.4*), the specification pattern (*Fig. 5.5*), the soil properties (*Fig.*

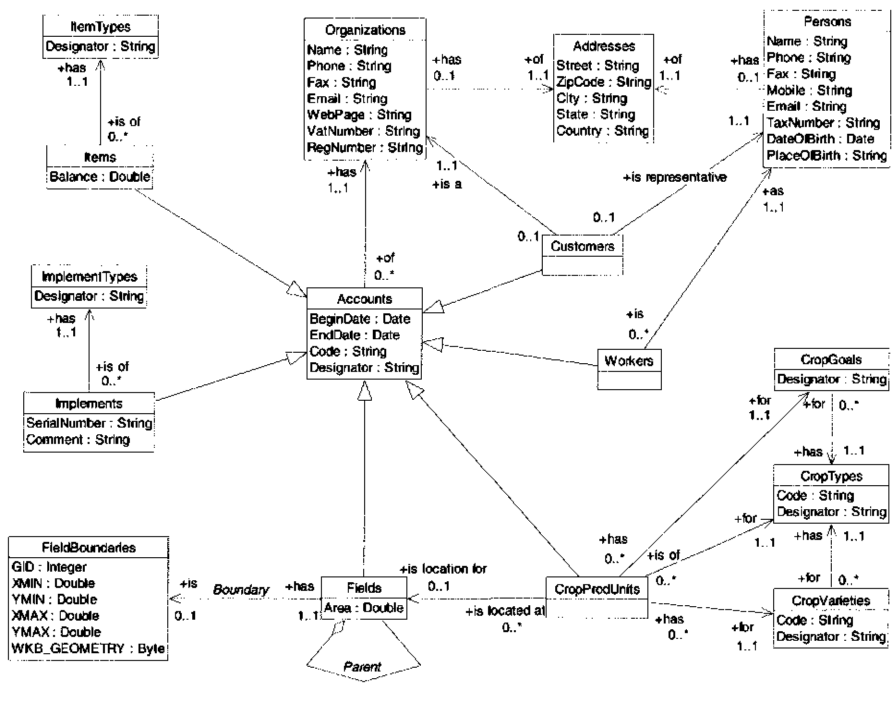

Fig. 5.3. Farm resources entity relationship diagram

5.6), the geometry pattern (*Fig. 5.7*) and the logfile entities (*Fig. 5.8*). In the discussion of these diagrams, entities will be printed in italic and named in singular form. The plural form as shown in the diagrams is used only to specify the table names for the generated SQL data definition query. The relations drawn in the diagrams are either identifying relations (lines with a closed arrow on one side) or associative relations (lines with an open arrow). The direction of the arrow is used to indicate navigability. When the SQL data definition query is generated, foreign keys are created that match the navigability rules in a diagram. The result is that a primary key of the entity pointed to by the arrow is referenced by a foreign key in the entity on the other side of the relation. The generated ANSI-SQL data definition query is listed in Appendix A.

5.5.2.1. Farm resources

In *Fig. 5.3*, the central entity *Account* has an identifying or super-type sub-type relation with the farm resource entities *Customer, Worker, CropProdUnit, Field, Implement* and *Item*. The purpose of the relations between the farm resources and an*Account* is to model identification and ownership of these entities in a generic way. An*Account* is owned by an *Organization* and represents an entity with an economic value and associated costs. *Customer* is a role of an *Organization* for another *Organization*, where *Customer* is an *Account*. A *Worker* is a role of a *Person* in an *Organization*.

The entity *CropProdUnit* stands for crop production unit and is defined as the production of a *CropType*. A *CropProdUnit* can be associated to a *Field* to express allocation of that *Field* for a *CropProdUnit*. In the temporal dimension, a *Field* can be associated with more than one *CropProdUnit*. In the spatial dimension a single *CropProdUnit* covers the entire *Field*. The entity *Field* has a recursive relation to model the possibility of subdivision of a *Field* into smaller *Fields*. Thus, when a several *CropTypes* are cultivated on one *Field*, that *Field* should be subdivided into smaller *Fields* that cover the areas for each *CropType*. Each *Field* can have a *FieldBoundary* to specify its geometry. The *FieldBoundary* is implemented conform the 'well known binary' (WKB) form of the OpenGIS (1999) specification. This approach will be discussed later. As for the *FieldBoundary*, this entity links an encoded polygon to a *Field*.

An *Implement* is a piece of equipment available for activities on a farm. The difference between *Implement* and *ImplementType* is that *ImplementType* describes a type of equipment, e.g. a '3-furrow plough of brand A', while *Implement* stands for the actual occurrence of that type of equipment on a farm. This distinction between type and instance is a method to administer more implements of the same type separately although they share a number of properties. The entities *Implement* and *ImplementType* can also describe instruments, measuring devices or other equipment available on a farm. A similar distinction to describe type and occurrence exists between *ItemType* and *Item*. The entity *ItemType* describes a product that can enter or leave a farm. *Item* stands for the stock or for an amount of a certain *ItemType* that is available on a farm.

5.5.2.2. Farm activities

The entities involved in the preparation and administration of farm activities are shown in *Fig. 5.4*. Compared to a previous model (Goense *et al.*, 1996), this is a simplified model valid for the data storage package. For instance for operational planning, several states and different aggregation levels for an activity might be necessary which have to be modelled by the respective applications. In this model, an *Activity* is defined as the allocation of farm resources to carry out an *ActivityType* on an *Account*. For field work, the *Account* is usually a *CropProdUnit* but this model allows administration of activities that have to be allocated to a *Field* (e.g. field leveling) or to an *Implement* (e.g. maintenance) as well.

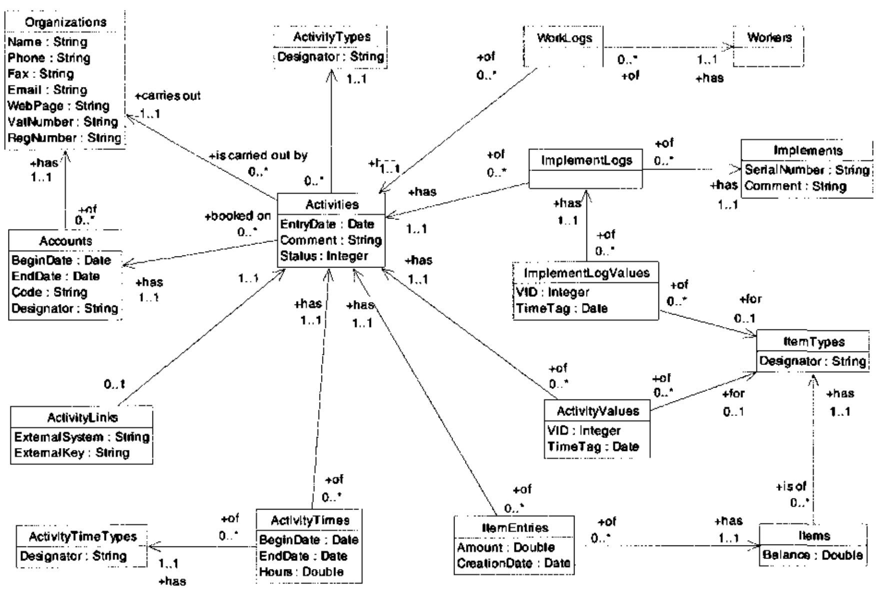

Fig. 5.4. Farm activities entity relationship diagram

A relation from *Activity* to *Organization* is used to specify the *Organization* that carries out the *Activity*. While this data storage package can store farm resources of several farms, contracting activities can be stored as well. The farm resources involved in an *Activity* are workers, implements and items, depicted on the right hand side of *Fig. 5.4*. For the specification of activity properties two levels of detail are possible. When a specification is directly associated to an *Activity*, the entity *ActivityValue* has to be used. For example, a fertilizer application map can be associated to an *Activity* as a series of *ActivityValues*. The second level of detail is properties associated to the use of implements for an activity. For instance, the actual applied fertilizer application rate is measured by an implement and stored as *ImplementLogValues*. Another example is the processing of yield data. When two combine harvesters operate on one *CropProdUnit*, each has a series of yield samples (*ImplementLogValues*) which can be processed in to a single yieldmap that can be stored as a *CropProdUnitValue*. The spatial link of these entities will be discussed in the specification and geometry sections.

5.5.2.3. Specifications

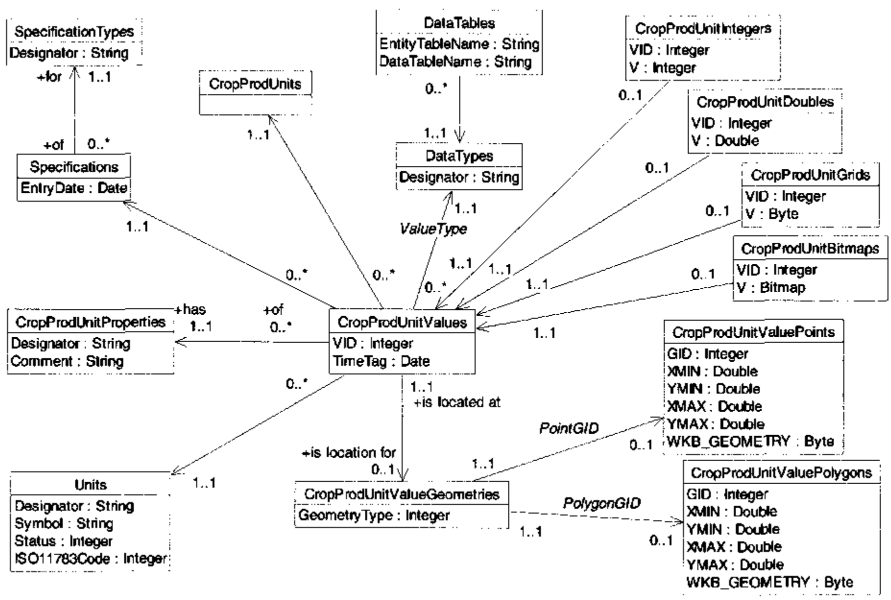

Fig. 5.5. Crop production unit specifications entity relationship diagram

The method of property specifications for farm resources and farm activities is adopted from the specification pattern (Fowler & Scott, 1997). In this model, the pattern is used to implement a flexible way to specify properties. As an example, the specification of properties for the farm resource *CropProdUnit* will be discussed (*Fig. 5.5*).

A *CropProdUnit* can have a number of *CropProdUnitValues*. These values are associated to a *CropProdUnitProperty* that describes a property that can be specified for a *CropProdUnit*. Example properties are an emergence date or a yieldmap. A *CropProdUnitValue* is part of a *Specification*. A *Specification* is used to group a number of values. In order to keep track of when and where values were generated an attribute 'EntryDate' is added to *Specification* and *Specification* itself is of a *SpecificationType*. The collection of specificationtypes describes the specification classification. Example specificationtypes are 'real world values' for measured properties and 'simulated values' for properties whose values are generated by model runs.

Each value is expressed in a *Unit* and is of a certain *DataType*. The entity *DataType* specifies the type of the data value and has a relation to *DataTable* where the table name to store the value is specified. Table 5.1 gives an example of tuples that describe specification of three properties. The first two tuples list the property 'Leaf Area Index' that is specified for two locations in a crop production unit. The datatype is 'Double', the tablename where the values are stored is 'CropProdUnitDoubles' and an associated geometry of type 'Point' is used to specify the locations. The third tuple is a specification of a 'Near Infra Red reflectance image' that can be stored as a bitmap value. In a similar way, the last tuple is a yield map that is stored as a grid in an associated 'CropProdUnitGrids' table.

Table 5.1

Examples of specifications for a crop production unit

Property	*Specification*	*TimeTag*	*Unit*	*DataType*	*DataTable*	*Value*	*Point*
Leaf Area Index	1	14-Jun-1999	Ratio	Double	CropProdUnitDoubles	1.5	X1,Y1
Leaf Area Index	1	14-Jun-1999	Ratio	Double	CropProdUnitDoubles	1.7	X2,Y2
NIR reflectance image	2	7-Jul-1999	%	Bitmap	CropProdUnitBitmaps	bitmap	-
Yield Map	3	16-Aug-1999	T/ha	Grid	CropProdUnitGrids	grid	-

The same specification pattern, implemented for soil properties is depicted in *Fig. 5.6*. The association between *SoilValue* and *Field* might be optional. When both the boundary of a *Field* and the location of a *SoilValue* are specified, this association is not necessary but to be able to store soil values without a specified location properly this association is implemented. Both the use of data types and of geometry is similar to the pattern for

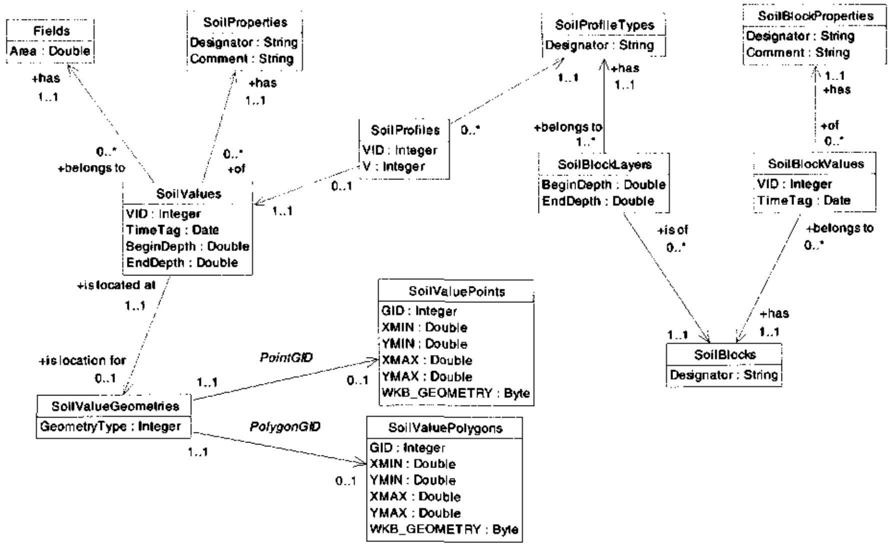

Fig. 5.6. Soil specifications entity relationship diagram

CropProdUnitValue in *Fig. 5.5*. A data type specific for *SoilValue* is the description of a *SoilProfile*. A *SoilProfileType* is described once and can be specified as a *SoilValue* when it is valid for a certain location. It consists of a number of soil layers where each layer is the occurrence of a *SoilBlock* with associated soil block properties and soil block values. These entities implement persistency for the functional layer approach in soil modelling (Verhagen *et al.*, 1995).

5.5.2.4. Geometry

The geometry entities present in *Figs 5.3, 5.5* and *5.6* are an implementation of the component 'SQL92 with geometry types implementation of feature tables' (OpenGIS, 1999). The objective of the OpenGIS consortium is to create common definitions for entities and classes used in geographic information systems. Although this is a difficult task it seems GIS manufacturers are adopting these definitions in order to facilitate geographical data exchange and access (Zeiler, 1999).

Figure 5.7 depicts some of the entities used to store geometries and link geometries to features. The entity *SPATIAL_REF_SYS* describes the spatial reference system in which the geometry for a feature is expressed. The table *GEOMETRY_COLUMNS* contains tuples that describe the association between features and geometries. For the example in *Fig. 5.7*, Table 5.2 lists the associations between *Well* and *GB_POINT* and between *District* and *GB_POLYGON*. For both associations the storage type binary is chosen. In the tables GB_POINTS and GB_POLYGONS this results in a binary attribute WKB_GEOMETRY that contains a serialised representation of the geometry. Another valid storage type is the normalised numerical representation. In this model, the binary representation is used. In an object-relational database the serialised form of an object matches the 'well known binary' (WKB) representation formulated by the OpenGIS consortium best. Appendix B lists the data definition and data insert script for this model.

Table 5.2
Tuples in GEOMETRY_COLUMNS for the sample entities in *Fig. 5.7*

F_TABLE_NAME	*F_GEOMETRY_COLUMN*	*G_TABLE_NAME*	*STORAGE_TYPE*	*GEOMETRY_TYPE*	*COORD_DIMENSION*	*SRID (foreign key)*
Wells	Location	GB_POINTS	1 (binary)	1 (Point)	2 (x,y)	1
Districts	Boundary	GB_POLYGONS	1 (binary)	5 (Polygon)	2 (x,y)	1

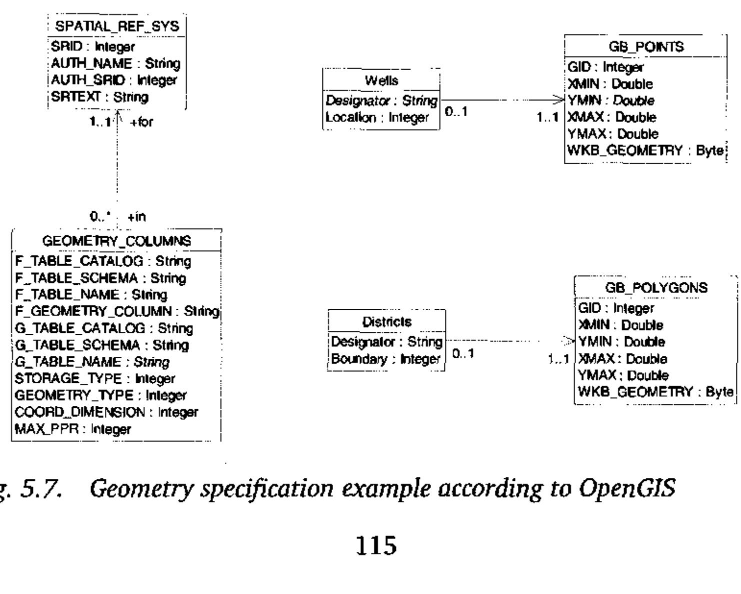

Fig. 5.7. Geometry specification example according to OpenGIS

5.5.2.5. Time stamped logfiles

The last part of the persistency package to discuss are the logfiles. Many instruments and implement controllers generate logfiles. Typically, a logfile is recorded at a fixed time or distance interval and post processed to generate specification values for the*CropProdUnit* and *Activity* entities discussed in previous paragraphs. After processing, a logfile might be discarded but especially in a research situation logfiles are archived to be able to test different post processing methods and to be able to trace back invalid data. Storage of these logfiles as large binary objects is one possibility but for infrequent used data an archive method seems more appropriate. *Figure 5.8* depicts the entities that describe textual, column formatted, log files. A *LogFile* is of a certain *LogFileType*. The *LogFileType* has a number of columns. The format of each column is defined by a *LogFileColumn* and refers to a *LogFileVariable*.

Next to a generic method for storage and access of log files themselves, the instrument configuration and sensor calibration data are essential for the post processing. This is covered by implementation of the specification template for the entity *Implement*. Configuration parameters and calibration options are defined as implement properties and the associated values are valid from the specified TimeTag attribute until a more recent specification is found. Notice the different levels of the association between *ImplementValue* and *Implement* and between *LogFile* and *ImplementLog* in *Fig. 5.8*. These differences imply that the configuration or calibration data belongs to an implement. Furthermore, a log file can only be generated when an implement is associated with an activity.

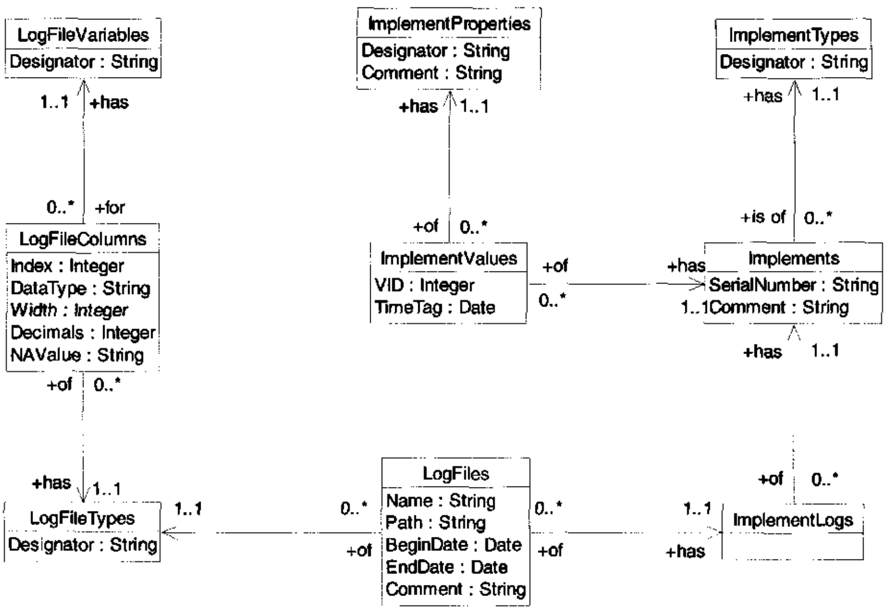

Fig. 5.8. Logfiles entity relationship diagram

5.5.3. *Object orientation*

In this section the application 'field activity management', as described in section 5.4.1, will be discussed in more detail. Several diagrams following the UML notation are used to describe the classes and their interactions.

5.5.3.1. Use case diagram

Figures 5.9 and *5.10* contain two use case diagrams, one for the use of a crop growth simulation model for the specification of activity properties (*Fig. 5.9*) and another for the execution and data handling for a harvest activity that includes yield measurements (*Fig. 5.10*). Within a use case diagram, each use case is depicted by an oval shape, and each actor by a stickman. An actor describes the role a user can play in the interaction with the information system. Although a user can play several roles the purpose of the definition of several actors is to clearly define distinguishable responsibilities. The actors depicted in *Fig. 5.9* and *Fig. 5.10* are:

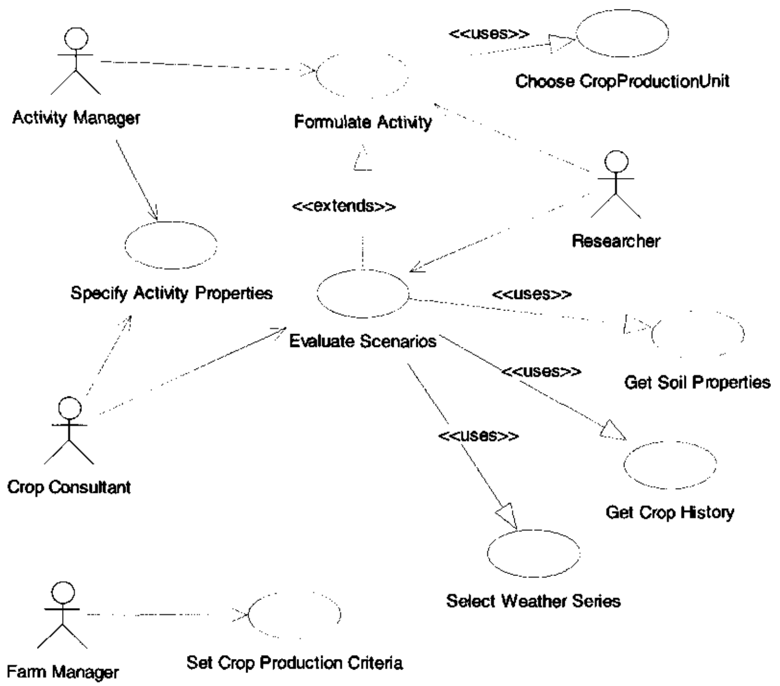

Fig. 5.9. Use case for the formulation of an activity that involves the use of crop growth simulations

1. *Farm Manager.* Takes decisions regarding financial matters, management objectives and operational criteria.
2. *Activity Manager.* The farm operational planner role. This role consists of activity planning, allocation of resources to activities, specification of activity properties and finalisation of activities.
3. *Implement Operator.* This role realises the activities on the farm where implements are involved.
4. *Crop Consultant.* Is a specialist to be consulted for decisions regarding crop planning, crop production activity specifications and crop plan evaluation.
5. *Researcher.* A role to carry out research on farm activities. Example tasks are the analyses of obtained data and a study on scenarios with optional decisions.

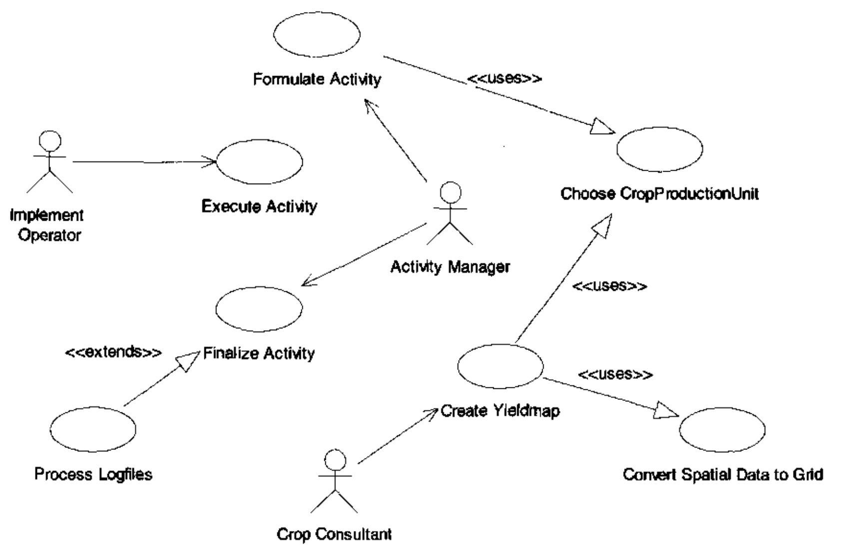

Fig. 5.10. Use case for the processing of yield data from a harvest activity

In *Fig. 5.9*, the use case 'Formulate Activity' is initiated by the 'Activity Manager'. The formulation of an activity consists of the specification which activity type has to be executed, what resources should be allocated, and when and where it should be carried out. The question where to carry out an activity is answered by a separate use case 'Choose CropProductionUnit'. The definition of a separate use case is a method to define model elements that can be reused in other use case diagrams. When a crop growth simulation model is used to specify activity properties, the use case 'Formulate Activity' is extended by the use case 'Evaluate Scenarios'. The UML use case diagram '<<extends>>' stereotype denotes a use case that is a special version of another use case. For example, a less complex activity can be entirely formulated and specified by the 'Activity Manager' while a more complex activity might require that some scenarios are evaluated by a 'Crop Consultant' in order to specify the activity properties. The 'Evaluate Scenarios' use case uses three smaller use cases. 1) 'Get Soil Properties' to retrieve the soil properties of the field where the crop production unit is cultivated. 2) 'Get Crop History' to retrieve properties of earlier activities and crop production unit properties like emergence date. 3) 'Select Weather Series' to specify the climatic data to be used for the scenarios. The use cases 'Formulate Activity' and 'Evaluate Scenarios' can also interact with the actor 'Researcher' for the purpose of scenario analysis. The actor 'Farm Manager' and the associated use case 'Set Crop Production Criteria' are added in *Fig. 5.9* to specify the production goals and environmental constraints that should be met by the activities.

A use case diagram for the data processing to obtain a yield map from a harvest activity is shown in *Fig. 5.10*. The actor 'Implement Operator' executes an activity of the type 'harvest'. When the activity is finished, the 'Activity Manager' actor finalises the activity. While this harvest activity generates logfiles, the extended use case 'Process Logfiles' is used. When the harvest activity for a crop production unit is finished, a yield map can be created. This is the responsibility of the 'Crop Consultant' actor. Note the reuse of the use case 'Choose CropProductionUnit' when the 'Crop Consultant' creates a yieldmap. Spatial interpolation of yield data points into a grid is depicted as a separate use case because this use case can be reused for spatial properties of other objects.

5.5.3.2. Static class diagram

A static class diagram with classes that participate in the use case 'Formulate Activity' is depicted in *Fig. 5.11*. When compared to the entity relationship diagram of *Fig. 5.3* and *Fig. 5.4* the definitions for the entities and classes are similar. One of the differences is that in the class diagram the classes have methods to express behaviour and responsibilities that are typical for a class. Furthermore, the object oriented techniques 'inheritance' and 'multiple inheritance' (interfaces) are used and many-to-many relations are not normalized to one-to-many relations. An example of the use of multiple inheritance is illustrated by the classes 'Worker', 'Implement' and 'Item'. Each of these classes inherits the protected and public members of 'Account' (solid line with closed arrow) and implements the methods of the interface 'Allocatable' (dashed line with closed arrow). The purpose of the methods that were added to the classes 'Activity' and 'Account' will be discussed using a sequence diagram.

5.5.3.3. Sequence diagram

A Sequence diagram is one of the UML diagrams to visualise the interaction between classes. It is a suitable technique to describe the classes involved in a use case and to

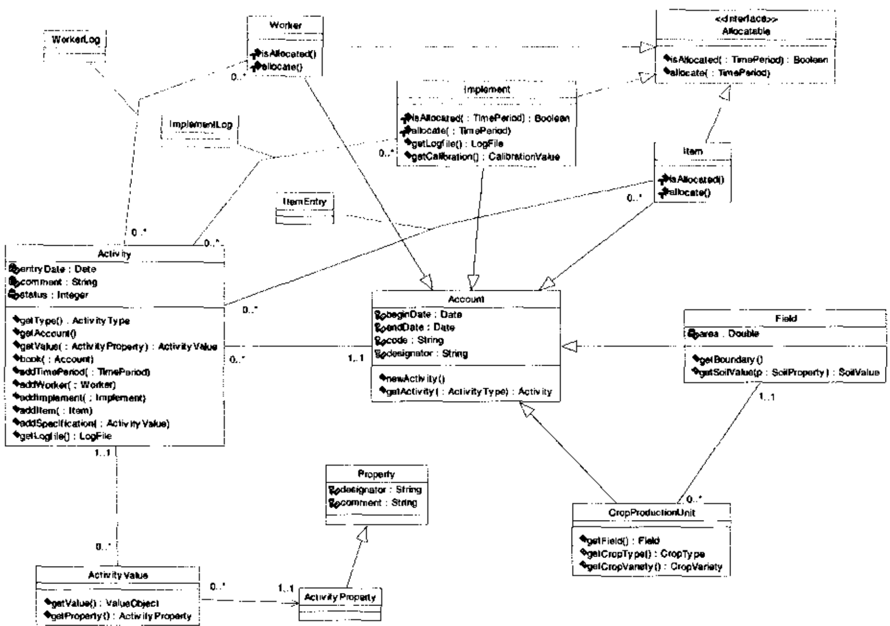

Fig. 5.11. Class diagram for the use case 'Formulate activity'

specify the control flow to meet the requirements of the use case. *Figure 5.12* depicts a sequence diagram for the use case 'Formulate Activity' (*Fig. 5.10*). The actor involved is the 'Activity Manager' who wants to add a new activity to a crop production unit. After creation of the activity, a dialog is started between the 'Activity' and the 'Activity Manager' to allocate sufficient resources. Note that the responsibility to adequately specify an activity belongs primarily to the class 'Activity' and not to the 'Activity Manager'. This is illustrated by the allocation of implements and items. When an implement is allocated that cannot handle any items, the 'Activity' can get this information from the allocated implement and can successively skip the allocation of items. In this way, the interaction with the 'Activity Manager' is limited to the relevant questions based on previous specifications. Of course, the sketched resource allocation order is not mandatory. Another approach might be to allocate an 'Item' first and to allocate a suitable implement secondly. This would result in another sequence diagram for the same use case that emphasises other class responsibilities.

For the 'Create Yieldmap' use case (*Fig. 5.10*), a sequence diagram is depicted in *Fig. 5.13*. The actor is the 'Crop Consultant' whose intention is to create a yieldmap for a crop

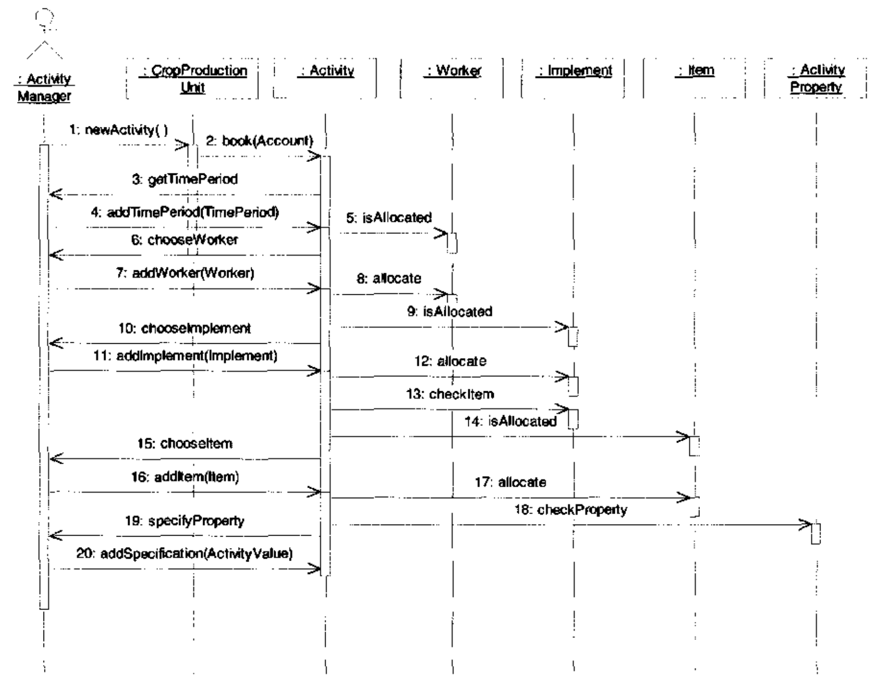

Fig. 5.12. Sequence diagram for the use case 'Formulate activity'

production unit based on previously collected logfiles. The control flow is to select the harvest activity from the crop production unit, retrieve the associated logfiles and start a yield post processor to calculate the yield. It is the responsibility of the yield post processor to use the valid calibrations and process the logfiles. After processing, the yieldmap is presented to the crop consultant and can be added as a specification to the crop production unit.

5.6. Discussion

5.6.1. *Information model*

Modelling in general is to find a suitable level of abstraction while not throwing away too much detail. In information modelling this is no different. In the structured analysis part, it is therefore arguable which entity types must be distinguished and which entity types can be generalised to another level of abstraction. The more abstract entity types, like the

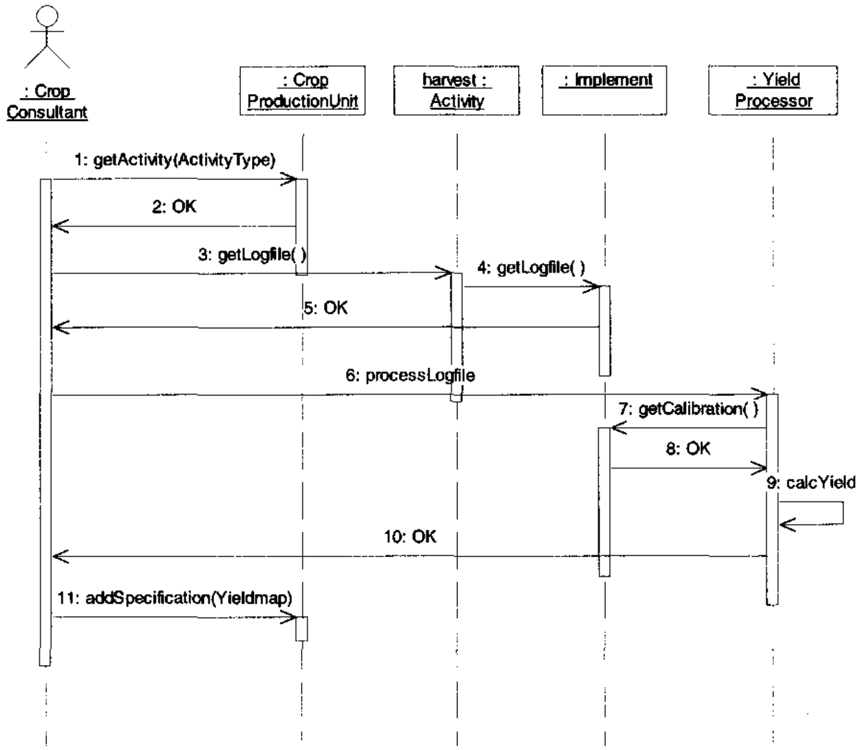

Fig. 5.13. Sequence diagram for the use case 'Create yieldmap'

entities for the specification pattern, require additional information, for instance a table of properties, before an implementation is possible. On the other hand, a too rigid information model with few abstract entity types reduces flexibility of the information system. This dilemma is partly solved by the object oriented approach, where the level of abstraction can vary with the different inheritance levels. Still, an extensible system requires a flexible way of specifying new properties and new data types but the benefit of object orientation is that the common behaviour can be modelled once by means of a superclass implementation or interface definition.

Another discussion item regarding the specification of properties as implemented in this model is how exchangeable the information is. Two information systems, both implemented according to this model, but populated with a different set of property definitions can hardly exchange information anymore. It would therefore be essential to create common coding lists for properties when separate implementations must exchange information.

The OpenGIS geometry specification for SQL adds some constraints to the application entity types that were not present in a previous model (Goense *et al.*, 1996). According to the OpenGIS model, an entire geometry column in a feature table must refer to a single spatial reference system. The reason behind this is that a spatial search only works correctly when the spatial units for all tuples in a table are the same. The consequence is that when an application uses a local coordinate system different to the spatial reference system defined for the persistent geometry, a coordinate conversion is needed. Another difference is the definition of a grid. Previously, a grid was defined by a reference point located in a spatial reference system combined with a number of cells relative to that reference point. In the OpenGIS model this approach is not available, an alternative depicted in this model is to treat a grid as a data type for the specification pattern. The benefit of the use of the OpenGIS geometry definition is that the implementation is available from GIS and database systems manufacturers. An implementation of this information model in such a system does not have to implement the geometry model itself but can extend the GIS or database.

5.6.2. *Implementation aspects*

The entities and classes discussed in previous sections model just the application domain. For a prototype implementation, interaction with a computer operating system, with the user interface facilities and with the required network protocols has to be added. Several programming environments provide these components for different platforms and for various methods of distributing the components of an information system. The first prototype, build with a rapid application development tool, did use relational database components for the ODBC database connection facilities available on the ms-windows operating system. This resulted in a system with a clear distinction between the data persistency functionality and the application. But while this approach follows a two-tier architecture it was difficult to create reusable classes and components that are not obscured by for instance implementation details for a specific user interface.

One of the requirements of the information system was that is has to be extensible. The question that follows is where to design and how to implement the interface for applications that want to extend the system. When a relational database is used for persistency the interface might be described by the entity definitions and an extension is possible by using SQL queries. For a not too complex data model this will work but in this model additional constraints and stored procedures would be required to maintain database integrity. Another option would be to define the interface at the level of classes that encapsulate the persistency rules and application logic. These classes should hide the details of persistency and provide well-defined interfaces to build additional applications with.

The ideal case would be to implement classes that clearly represent application logic and are not cluttered by the overall system implementation aspects. One method to accomplish this is to use a framework that implements the 'low level' functionality and can be extended by the application classes. Examples are the DCOM components on the ms-windows platform and the Java 2 Enterprise Edition (J2EE) for the Java virtual machine. A benefit from the J2EE framework is that it combines the use of the Java virtual machine to hide differences between hardware platforms with the definition of mechanisms for the distribution of entities and applications over networks.

5.7. Conclusion

To support precision agriculture research, an information model was implemented for the storage and the distribution of field management information. The interface to this information system had to be differentiated for several types of users. The use case diagram and sequence diagram, both UML diagrams, were suitable to specify the interaction between a user and the information system. A multi tier implementation architecture was made to distinguish persistency, application and user interface components. For the persistency component, the structured analysis method was applied to implement a relational database. The application and interface components were modelled using the UML use case, class and interaction diagrams. Reuse of application and interface components benefits from a multi-tier approach were a clear distinction between the responsibilities of the application components and the implementation of the user interface is made. Care must be taken not to embed application logic in the user interface components, which is tempting when a rapid application development tool is used. Instead, a framework for distributed software systems should be used to ensure that the information system meets the requirements of access to the system by farm personnel, mobile implements and research applications.

The combination of the structured analysis method and the object oriented approach to implement an information system is suitable for an environment where different applications have to exchange information. In this approach, structured analysis is used to model the data storage component for implementation in a relational database. The data access functionality and application components are modelled by an object oriented approach. The use of a CASE tool that supports both object programming language code generation and relational database definition generation is an advantage, while a single model can be used for the persistent classes and application modules. The CASE tool should go further than just model the information system according the UML diagrams. Simulations of modelled components are a promising method to test components before actual implementation and code generation is important to synchronise documentation and implementation.

There exists a trade-off between the flexibility of an information system and the exchangeability of the contained information. When all properties that can be specified for the entities are defined as fixed attributes, these specifications can easily be exchanged. However, such a system would not be able to host new properties, so a more abstract method was used for specifications. The drawback is that this method requires a common or standard definition for the properties that can be specified in order to exchange information with other systems. Regarding the definition of the farm structure there is less need for flexibility. The current definitions for the different types of accounts and for their relations are fixed. These entities are implemented more or less similar in current farm management systems, designed for management at field level detail. The extensions implemented in this information system make it suitable for precision agriculture related topics like spatial data handling, storage of large data files and on-farm research.

5.8. Recommendations

A number of recommendations for further research on information systems for precision agriculture remain. Regarding the information modelling tools an improvement of model simulation and generation of code (C++ or Java) based on the UML diagrams is necessary. The information system itself relies for the spatial components on the OpenGIS specifications. An overview of OpenGIS conform products lacks and more experience regarding the implications of using these products for an information system would be useful in order to decide whether implementation of the OpenGIS documents should be followed. The distribution of components over networks to serve different types of users is a topic encountered in many information systems today. A comparison off different approaches, from for instance lightweight 'web' clients to applications that share many objects over different networks, is needed to be able to specify the communication methods that are essential for a distributed farm information system. With the increased use of the extensible markup language (XML) for information exchange it is recommended to create an XML conform interface to this information system. This will also be a start to define standard lists of properties that can be specified for the farm structure elements. A last recommendation is to have a closer look at the definition of frameworks for distributed systems. As systems become more complex, choosing or building the right tools to design and implement them becomes even more important.

References

anonymous (1999). The Cloudscape Documents, cloudscape version 3.0.

anonymous (2000). The JAVA 2 Enterprise Edition Developers Guide, version 1.2.1. Sun microsystems, http://java.sun.com/. Palo Alto.

Booltink H W G; Verhagen A (1997). Using decision support systems to optimise barley management on spatial variable soil. In: Applications of systems approaches at the field level (Kropff M J; Teng P S; Aggarwal P K; Bouma J; Bouman B A M; Jones J W; van Laar H H eds), pp 219-233, Kluwer, Dordrecht, The Netherlands

Burrough P A (1986). Principles of Geographical Information Systems for Land Resource Assessment. Oxford.

Caldeira C P; Pinto P A (1998). Linking DSSAT V3 to a relational database: the AGROSYS-DSSAT interface. Computers and electronics in agriculture, 21, 69-77

Fowler M; Scott K (1997). UML Distilled: Applying the Standard Object Modeling Language. Addison-Wesley.

Gauthier L; Guay R (1998). Using object-oriented database management technology in agricultural decision support software. Canadian agricultural engineering, 40(3), 219-226

Goense D; Hofstee J W; van Bergeijk J (1996). An information model to describe systems for spatially variable field operations. Computers and Electronics in Agriculture, 14, 197-214

Jacobson I; Christerson M; Jonsson P; Övergaard G (1992). Object-Oriented Software Engineering: A Use Case Driven Approach. Addison-Wesley.

Jones J W (1993). Decision support systems for agricultural development. In: Systems approaches for Agricultural Development (Penning de Vries F W T; Teng P S; Metselaar K eds), pp 459-471, Kluwer, Dordrecht

McCown R L; Hammer G L; Hargreaves J N G; Holzworth D P; Freebairn D M (1994). APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agricultural Systems, 50, 255-271

OpenGIS (1998). Simple Features Specification For CORBA, Revision 1.0. Open GIS Consortium.

OpenGIS (1999). Simple Features Specification For SQL, Revision 1.1. OpenGIS Project Document 99-049. OpenGIS consortium.

Pan X; Hesketh J D; Huck M G (1998). A web interface to databases associated with a plant growth simulator. Computers and Electronics in Agriculture, 21, 207-217

Saraiva M; Massola A M A; Cugnasca C E (1998). An object model for information systems for precision agriculture. Fourth international conference on precision agriculture, St.Paul, Minnesota, Vol. 2, pp 1355-1366, ASA-CSSA-SSSA

Shlaer S; Mellor S J (1991). Object lifecycles: Modeling the world in states. Yourdon.

Uehara G; Tsuji G Y (1993). The IBSNAT project. In: Systems approaches for Agricultural Development (Penning de Vries F W T; Teng P S; Metselaar K eds), pp 504-514, Kluwer, Dordrecht

Zeiler M (1999). Modeling Our World, the ESRI guide to geodatabase design. Environmental Systems Research Institute. Redlands.

Chapter 6

Discussion and conclusions

6.1. Introduction

Farming methods have changed considerably during the last century. As in other areas of society, the expansion and application of fundamental knowledge led to farming methods that are based on rational approaches. In western society, where labour is expensive and technology development is continuing to mechanize and automate processes, farming has become like an industrial production process. Characteristic of this approach is the use of primarily economic criteria to allocate production resources and the tendency to exercise complete control over the production process by technological means. Although this farming method provides sufficient cheap food, the negative aspects of such a narrow focus on productivity are becoming apparent. Hence, farming methods will evolve further such that food production itself has no mineral emissions to, or chemical pollution of, the environment. Other goals such as maintenance of the rural area and minimization of fossil energy consumption are also becoming part of the farming strategy.

Some of these new requirements for farming are contradictory when applied to current farming methods. For instance, to maintain high production quantity and quality combined with less intensive farming, though possible in some cases, is not generally an easy task. Similarly, reduced use of fertilizers and agrochemicals in order to minimize fertilizer losses and minimize leaching of agrochemicals can lead to a higher risk of harvest losses or can result in loss of control over certain diseases. Another example is the preservation of the rural area. The scale at which machinery operates efficiently requires large, preferably rectangular shaped, fields. Modification of the rural landscape in such a way that it looks more natural for recreational purposes or emphasizes former landscape characteristics, effects the type and use of mechanization.

Some of these contradictions can be resolved by the implementation of recently acquired knowledge and the use of new technologies. For instance, improved positioning instruments and automated implement control systems may lead to a new generation of farming machinery that is able to follow curved field boundaries and avoid obstacles or other predefined areas. Improved insight into the way that biological systems work should help to reduce negative side effects of human intervention. In practice, the complexity encountered in understanding and modelling biological systems makes it difficult to forecast what the effect of a certain farm operation might be. Combined with the relatively long time span of a growing season and the difficulty of forecasting weather conditions, it would appear almost impossible to control crop growth on a detailed scale. Should therefore a farming system, with the objective to maximise crop production whilst keeping emissions just within defined environmental limits, be abandoned? Or is an intuitively implemented and more on internal regulating principles based growing system a better alternative? Whatever the answer to these questions is, explicit knowledge on the effect of farm operations will be necessary to meet the requirements imposed on food production. Therefore, instead of trying to optimize a single farm system, agricultural research should benefit from the diversity of farm systems and monitor these in order to expand agronomic knowledge and improve understanding of biological systems. It is here that precision agriculture can particularly contribute. Precision agriculture components such as information systems to document field production, implements that carry out measurements and a positioning system to tag crop observations to specific locations are essential for the application and validation of agronomic knowledge.

6.2. Components for precision agriculture

Previous chapters have described several components necessary for the application of precision agriculture in farm practice. In the following sections, the contribution of these components to a precision agriculture farming system will be discussed.

6.2.1. *Digital filters to integrate global positioning system with dead reckoning*

Positioning is one of the basic technologies of precision agriculture. Both data acquisition

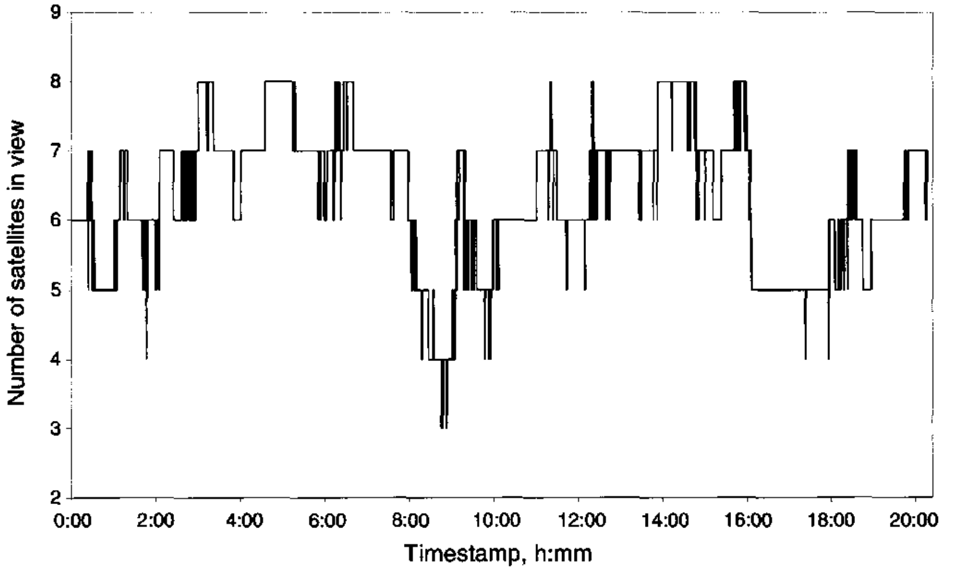

Fig. 6.1. Number of satellites in view for a location at 52 degrees latitude, measured on 31 December 2000

systems and site specific implement control rely on positioning systems in order to link measurements to spatial units and to address specific areas in a field. The major criteria for the suitability of a positioning system for a certain application are the accuracy and the reliability of the position measurements. The required accuracy depends on the type of application, ranging from an allowable 10 m deviation for data acquisition on wide implements down to less than a single centimetre deviation for control of implements in row cropping systems and for digital terrain model measurements. Although these accuracy requirements can nowadays be met by different types of satellite based positioning systems, reliability is still a problem. Even with the full constellation of satellites available, there are short periods during the day when there are only 3 or 4 satellites in view for a receiver operating at 52 degrees latitude (*Fig. 6.1*). A method to avoid these periods of poor satellite visibility is to use the satellite constellation forecast for a certain area and avoid site specific operations that require accurate positioning during these periods. However, for agricultural activities this is not an option because work hours are already restricted by the weather. A better solution, therefore, is to augment the satellite based positioning system with alternate methods that increase the reliability of the position measurement. This will also improve positioning at the locations where there are trees near or, sometimes, in fields.

The results obtained in chapter 2 indicated that positioning reliability can be improved when a dead reckoning system is combined with a satellite based positioning system. The weakest points in this system were the flux gate heading sensor and, for real time implementation, limited computing power for the digital filtering technique. Recent developments in solid state gyros, improved GPS signal processing and faster digital signal processors can further improve the positioning device. It is worth mentioning integration of different sensors in a positioning system in other industry segments. For instance, vehicle navigation systems that have to operate in so called 'urban canyons, (areas with poor satellite visibility) have been developed using similar techniques in order to provide continuous position information.

The specification of the actual positioning accuracy has been addressed only briefly. The specification of position errors for positioning equipment is usually expressed as a standard deviation over a large number of static position measurements. At a given moment, the actual accuracy might be better or worse, depending, for instance, on the satellite constellation. When measuring position on a moving vehicle, accuracy might degrade when the satellite receiver's internal filter implemented an incorrect model of the actual vehicle dynamic behaviour. Integration of different sensors in one positioning system would allow a more accurate computation of the vehicle dynamics and redundancy in the measurements would enable cross checking against sensor failures and estimation of the actual positioning accuracy. As will be discussed later, information on positioning accuracy of spatially distributed measurements is important for the construction of field maps for precision agriculture.

6.2.2. *Soil tillage resistance as a tool to map soil type differences*

Spatial variability in soils is a major factor driving crop spatial variability. Therefore, mapping of soil types is essential for the implementation of precision agriculture crop management. From a farm economic point of view, this is a weakness in precision agriculture. A soil survey is costly when many soil samples are required to describe soil spatial variability correctly. Methods to reduce the number of soil samples, while maintaining spatial resolution and quality of the soil map, often incorporate additional information such as remote sensing images and yield maps from the same area. The assumption is that spatial correlation between these information sources and soil type differences allows the number of soil samples to be reduced. Soil samples are only taken in those areas that are significantly different and an interpolation technique is used to

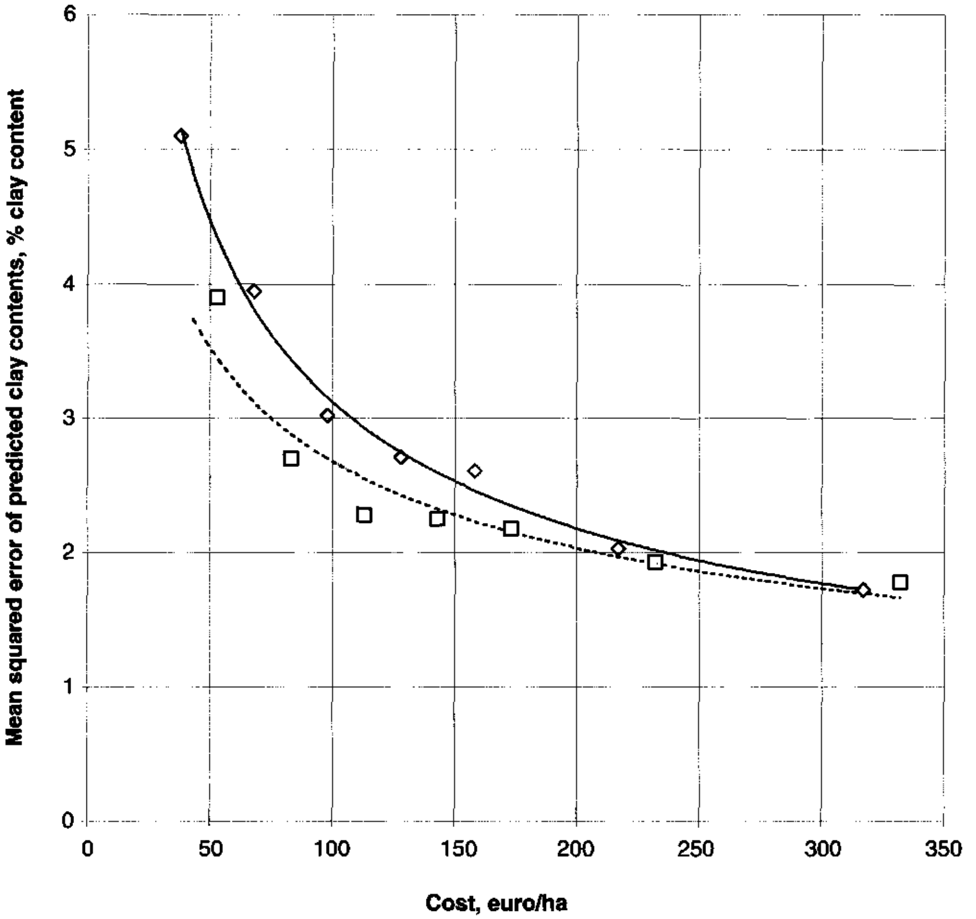

Fig. 6.2. Mean squared error of predicted clay content in % against costs of two data acquisition methods. (◇) air-dry method, (□) air-dry method with plough draught measurement.

estimate the soil type data at non visited locations, based on correlation with the additional information sources.

In chapter 3, a similar approach was followed, but instead of remote sensing images or yield maps, plough draught was used as an additional information source. On the fields investigated, spatial correlation with top soil clay content was positive and therefore a reduction in number of top soil samples was possible. Given the costs of both soil sampling and plough draught measurement, calculation of the economic value of plough draught measurement to map soil type differences can be made. For an approximate calculation, Table 6.1 lists the costs of the air-dry top soil clay content determination method (Perdok *et al.*, 1997), and of the plough draught measurement method.

Table 6.1

Cost comparison of air-dry moisture detection and plough draught measurement

Method	*Sample density, samples/ha*	*Cost[1], euro/ha*
Air-dry moisture detection	6	38
Air-dry moisture detection	12	68
Air-dry moisture detection	18	98
Air-dry moisture detection	24	128
Air-dry moisture detection	30	158
Air-dry moisture detection	40	217
Air-dry moisture detection	60	317
Plough draught measurement	1000	15

[1] soil sample acquisition labour, equipment cost and data processing labour.

Combination of the air-dry moisture detection method with the plough draught measurement results in a lower top soil clay content determination error at lower cost level (Fig. 6.2). The lower cost levels correspondent to the lower sample densities specified in Table 6.1. At a sample density of 24 samples/ha for the air-dry moisture detection method only, the mean squared error of predicted clay content is 2.7% and the cost of the measurement method is 128 euro/ha. Combination with plough draught measurements can either reduce cost to 90 euro/ha when the clay content prediction error is kept constant or can reduce clay content prediction error to 2.3% when the costs remain the same.

This cost calculation illustrates how a combination of different types of measurements can reduce cost of data collection for precision agriculture. However, the relevance of this data to precision agriculture requires further discussion. Precision agriculture uses information from many different sources. However, calculating the cost of a soil survey is difficult because the relevance of a certain type of information is not constant from season to season. For instance, in a wet season, information on soil profile differences might be less important to crop management than the same information in a dry season.

Although the working depth of a plough is limited to the top soil layer, the use of plough draught as a co-variable to assist characterization of soil below the top soil layer is also possible. In this case, the top soil characteristics that influence plough draught should be sufficiently correlated with the deeper soil layer characteristics to be determined.

6.2.3. *Dynamic weighing for accurate fertilizer application*

Field operations to manage crops are also a source of information. Most activities, from soil tillage and seed bed preparation to harvest, have to take into account spatial variations in crop and soil. These spatial variations can result in different set point values for operational quantities such as tillage depth and application rates or to different areas to be treated. In chapter 4, the implications for fertilizer application according to a collection of site specific set points, was described. Although this is only one implement from the range of implements used during a growing season, the principles of making this implement suitable for precision agriculture also apply to other implements. Basically, these implements should comply with the following requirements:

(1) The implement should be able to vary operation at a specified spatial scale.
(2) The implement should operate with a prescribed or known accuracy.
(3) Collect data on actual operation of the implement

Regarding the first point, an implement has to be able to achieve a given site specific application rate at a given spatial resolution. It has been shown that the effective working width of an implement and the response time to achieve different application rates should have similar spatial dimensions to the site specific information of the set point values (Goense, 1997). This requirement implies that the implement must be modified to be able to vary application rates at smaller distances and working widths when detailed information on crop and soil status is available. In contrast, detailed information is useless whilst farm machinery is not able to operate at the same resolution. Although farmers still invest in larger machinery with increased working widths, the need to develop implements that can address smaller areas can only be justified when it is clear that crop and soil differences have to be managed at a more detailed scale.

The second point (operation accuracy) states, when applied to a fertilizer spreader, that the actual application rate should not differ from the set point application rate. On a fertilizer spreader, application rate errors originate from speed measurement errors and material flow calibration errors. A method to detect and eliminate speed calibration errors was discussed in chapter 2. Based on the same principle, i.e. measurement of another quantity to construct a redundant sensor setup, chapter 4 discussed dynamic weighing. Under ideal circumstances, i.e. when calibration would not change over time, a single feedback control of the rate control actuator would be sufficient to follow application rate set point values. When calibration varies in time, dynamic weighing can be used to adjust the material flow calibration of the application device automatically.

Collection of data about the operation of implements serves several purposes. Ona fertilizer spreader, this is necessary for correct calculation of future application rates and to evaluate fertilizer efficiency of a crop. Even when calibration errors are minimised automatically during operation, reporting back dynamic weighing data and material flow controller data is important to track initial calibration errors or trace back material flow controller set point errors. On other implements, collection of data might be done primarily for precision agriculture purposes. Examples of these systems are yield mapping systems and the plough draught measurement system discussed in chapter 3.

6.2.4. *An information system for spatially variable field management*

The purpose of an information system is to support the handling of large amounts of data. When the scale at which fields are managed decreases, i.e. smaller spatial units are treated individually or crop activities are split up into more actions per season, a larger amount of data is generated and more decisions are required. As well as to the availability of denser spatial data, more variables that quantify soil and crop status might be measured. Hence, field operational decisions become more complex and without an adequate information system the time to manage crop production, on an area basis, increases.

Another important aspect of an information system is the ability to exchange data with other participants. As depicted in figure 1.5, different research disciplines are involved in precision agriculture. Cooperation will be easier when observations and results are available in a well described format, for instance as structured in an information system. As is the case with most information systems, the exchange of data can easily be made worthless when no precautions to enforce data integrity and data quality are taken. It is therefore important that as well as the data itself, the source of the data, the method of data acquisition and the validity ranges are recorded. When used correctly this will prevent the other parties from drawing erroneous conclusions due to, for instance, error propagation or misinterpretation of data. Two cases where data exchange is involved and data credibility is important are the enforcement of environmental legislation and the concept of on-farm research to validate and deduce generic agronomic principles. In the first case, uncertainty in measurement of crop yields, soil status and field operations for instance can lead to a different figure for nitrate efficiency and leaching and affects the evaluation of the environmental effects of a cropping method. The second case requires additional constraints, for instance generation and implementation of field trial patterns, in order to determine cause and effect relations in a statistically sound manner. Although it is disputable whether the on-farm research approach is an alternative to plot trials on specialized farms (Adams & Cook, 2000), the requirements of the information system are, to a large extent, the same, both for ordinary farms and for research stations.

The information system discussed in chapter 5 is also intended to be used both for the site specific crop management on a farm and as a tool in agronomic research. Although a full implementation was beyond the scope of this research, the data storage component and some of the (geo-statistical) data processing algorithms and user interface components were implemented and supported the processing of spatial data presented in chapter 3. Other examples of similar efforts to construct an information system for spatially variable field management exist (Linseisen *et al.*, 2000; Lütticken, 2000) but the common problem is that the impact of each of these initiatives is not large enough to build up a sufficiently large database for research purposes. This might change when the main interest in this type of information system moves from research and early adopters among the farmers to the agricultural product processors or other parties along the agricultural production chain.

6.3. Practical applications

The components described for precision agriculture were put into practice at two different types of farms. Initially, the precision agriculture research activities took place on a single field on the experimental farm "prof. J.M. van Bemmelenhoeve" in the northwestern part of the Netherlands. At this site, the research objective was to determine whether site specific field management can improve nitrate efficiency of crops. The results of these studies were positive and resulted in an approach to incorporate crop growth simulations in field management (Finke & Goense, 1993; Booltink & Verhagen, 1997; Verhagen, 1997).The studies mainly evaluated alternative scenarios for the past growing season. After two years, a second site was used to convert this system into a decision support system capable of supporting farmers with a nitrate management system during the current growing season. This second site was located in the southwest of the Netherlands and consisted of approximately 60 ha divided over 9 fields on a conventional farm (Booltink *et al.*, 1999).

The most important difference between the farm mechanization used on site 1 and on site 2 was the scale of operation. On the experimental site, the fertilizer application was able to target 12 m working width. Operation at this scale was necessary while both soil samples and yield measurements, taken at a higher spatial density, revealed soil and crop variations over these short distances (Figs. 3.11 & 3.14). However, this scale could only be justified when all information necessary for nitrate management is available at least at the same density as the effective working width of the individually controllable implement sections (Goense, 1997). On site 2, a less detailed soil survey was conducted and, in order to reduce data processing requirements of the decision support system, the concept of management units was introduced (van Alphen & Stoorvogel, in press). For example, the classification into management units of a 16 ha field, based on soil water and soil nitrate dynamics, resulted in just 4 distinguishable management units of which 3 covered more than 90% of the area (Booltink *et al.*, 2001). As a consequence, the required spatial accuracy of the implements was lower and a conventional centrifugal fertilizer spreader operating at 32 m working width could be used in the field trials. However, for data acquisition on harvesting equipment the commercially available systems smoothed data over several times the working width of the implement and therefore special processing such as weighing of individual harvested strips in treatment trials was necessary to improve the spatial resolution of the yield maps. Hence, more accurate yield measurement and processing methods are needed for on-farm research. When fertilizer response and efficiency is studied, it is questionable whether this specific scale should be used. In farm practice, the tendency is to move towards wider effective working widths (36 - 54 m) and hence a decision support system which can operate at a low spatial resolution. However, other literature defends the use of a higher spatial resolution to obtain data on local response curves for fertilizers (Haapala, 1995). A more detailed measurement setup would be of benefit to the quality of fertilizer recommendations but it is hard to predict whether they can be implemented in practice without control over other growing factors such as water supply. Therefore, the approach to adapt the current fertilizer recommendations, that are based on average responses, to local circumstances by means of a decision support model is more easily implemented on conventional farms.

Other lessons learned in the on-farm part of the research project were that a correct interpretation of the experiments is not guaranteed by just a good experimental design and the evaluation of a number of observations or measurements from sensor systems. On fields, other factors such as crop damage due to animals and the occurrence of diseases, of which the severity is difficult to quantify, can disturb the experiments. After the use of precise technology for implementing on-farm research, it is therefore important that the results of trials are screened for exceptions before incorrect conclusions are drawn.

6.4. Evaluation of research objectives

In section 1.6, the following research objectives were formulated:

(1) development of the essential components for a site specific N-fertilizer system;
(2) evaluation of the accuracy of the measurement systems and application components;
(3) determination of the required spatial resolution required of the components.

6.4.1. *Development of the essential components for a site specific N-fertilizer system*

Within this thesis, three components are described that were developed for the site specific N-fertilizer system. Chapter 2 discussed a positioning device, chapter 4 described modification and enhancements to a fertilizer spreader and in chapter 5, an information system for precision agriculture was presented. These components were part of a study on N-fertilizer efficiency with participants in France, Belgium, United Kingdom and the Netherlands. Field validations were carried out by the participating institutes in each country. In the Netherlands, a field in the north west part was chosen. During three years, both soil and crop status and fertilizer applications were monitored. In one of these years, the N-fertilizer application rate was spatially varied according to a strategy aimed at minimization of N-leaching (Booltink & Verhagen, 1997). Of the technical components, yield mapping has not been discussed in this thesis but was carried out by a system developed at the Catholic University Leuven, Belgium (Missotten, 1998) and processed in the information system presented in chapter 5.

6.4.2. *Evaluation of the accuracy of measurement systems and application components*

Regarding the accuracy of the positioning system, both the spatial accuracy and the reliability have to be taken into account. For the yield and plough draught measurements and for the fertilizer application operations, a differential coarse/acquisition code GPS receiver was used. The horizontal accuracy of this receiver was between 1 to 5 m when at least four satellites were in view. In the yield mapping data, the distance between adjacent lanes varied by several meters but the lanes never crossed each other at a working width of 5.1 m. Both during plough draught measurements and fertilizer application, occasionally too few satellites were in view of the receiver. For the plough draught measurements, positions were corrected by a post-processing operation based on the knowledge that a certain area can only be ploughed once. The fertilizer application operation required real time positioning and therefore a Kalman filter (chapter 2, filter A) that integrated GPS position readings with radar and wheel speed and compass heading measurements had to be implemented on the board computer of the tractor.

The variable rate fertilizer application was carried out according to a map with 12 by 12 m grid cells. Each grid cell represented a set point application rate. The grid cells were positioned along the tramlines in order to minimize set point lookup errors due to positioning deviations. Drive speed was kept constant at 1.6 m/s and the reported actual fertilizer rates deviated on average 0.5 % from the set point values with a standard deviation of 1.9 %. Although application rates were varied in small steps, 4 - 8 kg/ha for adjacent grid cells, and over a small total range of 252 - 289 kg/ha, the fertilizer applicator was capable of adjusting material flow according to these set point values.

6.4.3. *Determination of the required spatial resolution of the components*

The data with the highest resolution available for the validation field originated from the plough draught mapping and from the straw yield mapping. Visualisation of either the original sampled data or the processed data on a 5 by 5 m grid showed soil texture differences that resulted in crop growth variations. If the spatial scale of N-application had to be of the same size as the soil texture differences, the smallest addressable spatial unit for the fertilizer application system had to be 5 by 5 m too. In the current setup, the fertilizer application rate could only be varied for the total working width of 12 m. Apparently, for this field, a fertilizer spreader with at least a factor 2 higher working resolution is needed in order to address the soil texture spatial variations. As this was based on a single field only, care has to be taken when generalizing these operation resolution requirements to other areas.

6.5. Conclusions

- Integration of a Global Positioning System (GPS) receiver with radar speed, wheel speed and compass heading improved positioning accuracy and reliability. The integrated positioning device, based on a Kalman filter, maintained position updates during short periods of missing or wrong GPS position measurements.

- Addition of extra states to the system model of the integrated positioning device to model autocorrelation was necessary for both the GPS and the dead reckoning sensors. Temporary calibration errors of the speed sensors can be modelled by autocorrelation states in the system model. The heading sensor was the weakest part of the positioning system and requires replacement by another type of sensor.

- Specific plough draught can be measured with the combination of a tractor, equipped with accurate speed measurement and an electronic hitch system, and a plough, with at least an accurate working depth sensor and working width indicator.

- Specific plough draught maps, obtained from two successive years on the same field, showed a similar pattern and corresponded well with a manually conducted soil survey. Co-kriging of specific plough draught data with top soil clay content samples can decrease the required amount of samples to sufficiently cover the variation present in a field.

- Determination of spreader weight during fertilizer application can be used to reduce application rate errors due to material flow calibration errors. Dynamic weighing requires the use of an acceleration sensor to compensate for weight force fluctuations under field conditions.

- When accurate dynamic weight measurements are available, the calibration of the material flow controller can be adjusted, based on a criterion for both the calibration error and the weighing accuracy. A simulation study resulted in the possibility of decreasing the calibration error to 1% with 99% reliability after application of 160 kg of fertilizer.

- Site specific application of fertilizer requires both a task controller capable of generating application rate set point values, according to the implement position on a map, and a data logger to report back the actual applied amount of fertilizer.

- The amount of information, originating from many different sources, in a precision agriculture system can only be handled by an information system. Essential parts of this information system are data storage, interfacing to other systems such as external databases, weather forecasts and mobile equipment and a user interface that can be tailored for different types of users. The information system must have the capability to handle geographical and temporal data entities. Another important requirement is that it has to be extensible and has a means for processing and storage of future data entities.

- The Unified Modelling Language (UML) is a suitable tool to model an information system. Both for the design of the data storage component in a conventional multi-tier system and for the design of an object orientated system, case tools exist that can be used to document the information system or generate the appropriate code.

- A system for site specific field operations should have a spatial resolution similar to the spatial scale of factors that determine crop growth variations. Therefore, both the field management information system has to be able to process data of this resolution and the implements have to be able to vary operation or record data at that scale.

References

Adams M L; Cook S E (2000). On-farm experimentation: application of different analytical techniques for interpretation. Proceedings (CD) of the Fifth International Conference on Precision Agriculture, Minneapolis, MN, USA, ASA, CSSA, SSSA, Madison, WI, USA

Booltink H W G; van Alphen B J; Epinat V; Peters P D; van Bergeijk J; Booij R; Grashoff C; van Persie M; Brokx W; Tiemissen T G M (2001). Operational remote sensing for precision agriculture. code 3.2 DE-05. Netherlands Remote Sensing Board (BCRS), Delft

Booltink H W G; van Alphen B J; Finke P A; van Kraalingen D W G; van Persie M; van Bergeijk J (1999). Remote sensing for precision agriculture. report 98-13.

Netherlands Remote Sensing Board (BCRS), Delft

Booltink H W G; Verhagen A (1997). Using decision support systems to optimise barley management on spatial variable soil. In: Applications of systems approaches at the field level (Kropff M J; Teng P S; Aggarwal P K; Bouma J; Bouman B A M; Jones J W; van Laar H H eds), pp 219-233, Kluwer, Dordrecht, The Netherlands

Finke P A; Goense D (1993). Differences in barley grain yields as a result of soil variability. Journal of Agricultural Science, 120, 171-180

Goense D (1997). The accuracy of farm machinery for precision agriculture: a case for fertilizer application. Netherlands journal of agricultural science, 45, 199-215

Haapala H E S (1995).Position Dependent Control (PDC) of plant production. PhD thesis, University of Helsinki, Helsinki, Finland

Linseisen H; Spangler A; Hank K; Wagner P; Steinmayr T; Demmel M; Auernhammer H; Manakos I; Schneider T; Liebler J (2000). Daten, Datenströme und Software in einem Informationssystem zur teilflächenspezifischen pflanzenproduktion (Data, data flow and software in an information system for site-specific plant production). Zeitschrift für Agrarinformatik, 8(2), 36-43

Lütticken R E (2000). Development of an internet-based communication and information network to progress the implementation of precision agriculture. Proceedings (CD) of the Fifth International Conference on Precision Agriculture, Minneapolis, MN, USA, ASA, CSSA, SSSA, Madison, WI, USA

Missotten B (1998).Measurement systems for the mapping and the evaluation of crop production performance. PhD thesis, Katholieke Universiteit, Leuven

Perdok U D; Kroesbergen B; Kurstjens D A G (1997). Soil mapping at field level by air-dry moisture detection. Proceedings of the 14th Conference of ISTRO, Pulawny, Poland, pp 517-520

van Alphen B J; Stoorvogel J J (in press). A methodology for precision nitrogen fertilization in high-input farming systems. Precision Agriculture,,

Verhagen A (1997). Site specific fertilizer application for potato production and effects on N-leaching using dynamic simulation modelling. Agricultural Ecosystems & Environment, 66, 165-175

Summary

The spatial and temporal variability, as present in soil, crop and climate, results in differences in utilization of nutrients and in the need for cultivation activities. Traditionally, the spatial resolution for cultivation activities is equal to the size of the fields. With recent technological developments such as satellite based positioning and automated control systems it is possible to increase the spatial resolution. In this approach, within-field variability is not neglected but instead used as a source of information. The concept behind this approach is that the availability of more detailed information leads to a more accurate farming method resulting in no or minimal emission of minerals and agrochemicals to the environment. The abstract formulation of this concept already shows that for a successful implementation, cooperation between several disciplines is necessary. It might start with technology that offers certain tools or possibilities but the applications depend on the knowledge on the interactions between soil, crop and climate and of the ability in the farming system to utilize this knowledge.

This research focuses on the development and evaluation of a system for site specific application of fertilizer. A number of components that are required for the definition of a site specific fertilizer advice and for the evaluation of crop nutrient efficiency and leaching are: positioning systems, soil characterization, crop status monitoring and crop yield determination, control of fertilizer application and processing of spatial and temporal data. The central issue with several of these components is: "what spatial resolution is required to describe and address the variability correctly?".

Positioning systems that combine a number of distance to beacon measurements are common practice. When satellites are used as beacons it might happen that calculation of a location fails when satellites are not in line of sight or that the accuracy degrades when satellite constellation is not optimal. It is therefore important that a positioning system that has to guarantee continuous position updates also uses information from other sensors. The reliability and the accuracy of the position measurements increase when driving speed and heading are combined with distance to satellite measurements

by means of a Kalman filter.

Determination of the spatial variability in soil characteristics requires a large number of soil samples. This number can be reduced when correlated measurements with a large resolution are available with less effort. An example is the correlation between specific plough draught and clay content in the top soil layer. On a 6 ha size research field, information on specific plough draught could reduce the number of soil samples from 60 per ha to 18 per ha while the prediction error for clay content increased by 20%.

One of the causes of inaccurate application of fertilizer are application errors due to incorrect calibration of the fertilizer flow control device. Adjustment of this calibration can be automated by means of dynamic weighing of the fertilizer decrease during fertilizer spreading. Another benefit of this system is that the actual applied amount of fertilizer can be logged. In case of incorrect dosing, this can be corrected during succeeding applications.

Processing of a large amount of data is currently one of the major bottlenecks in the precision agriculture concept. Combination of basic structures from geographic information systems (GIS) with entities valid for farm management are required to build an information system capable of both handling spatial data and processing data from farm activities. Using the unified modelling language (UML) a prototype of an information system is presented.

A number of factors play a role when the spatial resolution and accuracy is determined. A practical consideration is the accuracy of available positioning systems and the working width of the available implements. With regard to positioning systems 1 to 5 m deviation is common practice although technically a deviation of maximally a couple of centimeters is achievable. The working width of implement tends to be larger. Nevertheless, for precision agriculture, smaller, individually controllable sections are necessary. The developments in implement automation go in this direction. The more fundamental determination of spatial resolution should be based upon soil and crop analysis. Measurements carried out on the research field indicated that a spatial resolution of 5 by 5 meter was adequate to describe the variation.

Samenvatting

De ruimtelijke en temporele variabiliteit, aanwezig in bodem, gewas en klimaat, resulteerd in verschillen in de benutting van meststoffen en in de behoefte aan gewasverzorgende maatregelen. Traditioneel is de ruimtelijke resolutie waarmee gewasverzorgende maatregelen uitgevoerd worden gelijk aan de grootte van de percelen. Met behulp van technische ontwikkelingen zoals plaatsbepaling op basis van satellietsignalen en het toepassen van geautomatiseerde regelsystemen is het mogelijk de ruimtelijke resolutie te verhogen. Met deze aanpak wordt de variabiliteit binnen percelen *niet genegeerd maar juist als informatiebron* benut. Het idee achter deze aanpak is dat met gedetailleerdere informatie de bedrijfsvoering nauwkeuriger uitgevoerd kan worden en dat hierdoor uitspoeling of emissie van mineralen en gewasbeschermingsmiddelen te minimaliseren is. De brede formulering van deze gedachte geeft al aan dat voor een succesvolle uitwerking een geïntegreerde aanpak noodzakelijk is. Enerzijds is het technologie die bepaalde mogelijkheden biedt maar anderzijds is de toepassing afhankelijk van kennis van de interacties tussen bodem, gewas en klimaat en van de ruimte binnen de bedrijfsvoering om deze kennis te benutten.

In dit onderzoek ligt de nadruk op de ontwikkeling en evaluatie van een systeem voor het plaats specifiek toedienen van kunstmest. Enkele componenten die noodzakelijk zijn voor het opstellen van een plaats specifiek stikstof bemestingsadvies en het kunnen evalueren van de stikstof benutting c.q. uitspoeling zijn: plaatsbepaling, bodemkarakterisering, gewastoestandsbepaling en gewasopbrengstmeting, regeling van kunstmestdosering en het verwerken van ruimtelijke en temporele gegevens. De centrale vraag bij diverse componenten is: "welke ruimtelijke resolutie is noodzakelijk om de variatie correct te beschrijven?".

Voor plaatsbepaling is het combineren van afstanden ten opzichte van meerdere bakens een gangbare methode. Wanneer satellieten als bakens gebruikt worden kan het voorkomen dat berekening van een positie faalt doordat satellieten niet 'in zicht' zijn of dat de nauwkeurigheid afneemt doordat de satelliet constellatie niet optimaal is. Voor gebruik bij bewerkingen die een gegarandeerde plaatsbepaling nodig hebben is het daarom van belang informatie van andere sensoren te benutten. De betrouwbaarheid en de nauwkeurigheid van de plaatsbepaling verbeteren wanneer de rijsnelheid en de rijrichting van het werktuig door middel van een Kalman filter gecombineerd wordt met de afstandmeting tot satellieten.

Bepaling van ruimtelijke variatie in bodemkarakteristieken vergt een groot aantal bodemmonsters. Dit aantal is te reduceren wanneer gecorreleerde gegevens eenvoudiger en met hogere resolutie te verkrijgen zijn. Een voorbeeld is de correlatie tussen de trekkracht tijdens het ploegen en het kleigehalte in de bouwvoor. Op een 6 ha groot onderzoeksperceel kon met informatie over de ploegweerstand het aantal bodemmonsters van 60 per ha tot 18 per ha gereduceerd worden waarbij de kleigehalte voorspellingsfout met 20% toenam.

Eén van de oorzaken van het onnauwkeurig toedienen van kunstmest zijn doseringsfouten door onjuiste calibratie van het doseermechanisme van de kunstmeststrooier. Deze calibratie is te automatiseren door dynamisch, tijdens het strooien, de gewichtsafname de bepalen. Bijkomend voordeel is dat de daadwerkelijk verstrooide hoeveelheid vastgelegd kan worden zodat eventuele afwijkingen bij een volgende bemesting te corrigeren zijn.

Het verwerken van de grotere hoeveelheid gegevens is op dit moment één van de lastigste punten aan het precisie landbouw concept. Het combineren van de technologie achter geografische informatie systemen (GIS) met entiteiten uit de bedrijfsvoering van een landbouwbedrijf is noodzakelijk om een informatie systeem te bouwen dat zowel met ruimtelijke gegevens om kan gaan als data van de bewerkingen kan verwerken. Met behulp van de modelleertaal UML (Unified Modelling Language) is een concept van een dergelijk informatie systeem uitgewerkt.

Bij de bepaling van de ruimtelijke resolutie en nauwkeurigheid van deze componenten spelen een aantal factoren een rol. Een praktische beperking is in eerste instantie de nauwkeurigheid van beschikbare plaatsbepalingstechnieken en de werkbreedte van de gebruikte werktuigen. Voor de plaatsbepaling geldt dat 1 tot 5 meter afwijking standaard is maar dat technisch een afwijking van maximaal enkele centimeters haalbaar is. De werkbreedte van werktuigen tendeert breder te worden. Voor precisie landbouw is echter het aantal en de breedte van de individueel aan te sturen elementen van belang. Hiervoor geldt dat door de toenemende werktuig automatisering de mogelijkheden voor een hogere ruimtelijke resolutie toenemen. De meer fundamentele bepaling van de vereiste ruimtelijke variatie moet vanuit de bodem en gewas analyses komen. Voor metingen uitgevoerd op het onderzoeksperceel bleek een ruimtelijke resolutie van 5 bij 5 m voldoende om de variatie te beschrijven.

Curriculum vitae

Jacob van Bergeijk werd op 31 juli 1969 geboren te Zuidland. Hij behaalde in 1987 het VWO diploma aan de Reformatorische Scholengemeenschap Guido de Brès te Rotterdam. Aansluitend studeerde hij Landbouwtechniek aan de toenmalige Landbouwuniversiteit Wageningen. Het doctoraal examen in de oriëntatie landbouwsysteemtechniek van deze studie werd in 1993 met lof behaald. In de afstudeeronderwerpen lag de nadruk op de vakgebieden Landbouwwerktuigkunde, Informatica en Meet-, Regel- en Systeemtechniek.

Van 7 oktober 1993 tot 7 oktober 1997 was hij aangesteld als Assistent in Opleiding bij de vakgroep Agrotechniek en -fysica. Het promotie onderzoek begon als onderdeel van het project 'Reduced fertilizer input by an integrated location specific support, monitoring and application system' (EU-AIR 92 1204). Aansluitend volgde een aanstelling als toegevoegd onderzoeker precisie landbouw. Deze functie is vanaf 1 januari 1999 tot 1 september 2000 deels op het instituut voor Milieu- en Agritechniek (IMAG) en deels op de vakgroep Agrotechniek en -fysica ingevuld. De resultaten van onderzoek gedurende deze aanstellingen zijn terug te vinden in dit proefschrift.

Vanaf 1 september 2001 is hij werkzaam binnen de R&D groep van de afdeling Mechatronica van landbouwwerktuigenfabrikant Kverneland te Nieuw-Vennep. De funktie omvat het ontwikkelen van besturingen voor landbouwwerktuigen en het doorvoeren van internationale standaardisering voor het koppelen van de elektronische componenten die hiervoor worden gebruikt.

Appendix A: SQL data definition script farm resources

```
CREATE TABLE WorkLogTimeTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    WorkLogTimeTypesID INTEGER,
    PRIMARY KEY(WorkLogTimeTypesID));

CREATE TABLE ImplementLogTimeTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    ImplementLogTimeTypesID INTEGER,
    PRIMARY KEY(ImplementLogTimeTypesID));

CREATE TABLE ActivityTimeTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    ActivityTimeTypesID INTEGER,
    PRIMARY KEY(ActivityTimeTypesID));

CREATE TABLE ISO11783ImplementGroups(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    ISO11783ImplementGroupsID INTEGER,
    PRIMARY KEY(ISO11783ImplementGroupsID));

CREATE TABLE ImplementTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    ISO11783ImplementGroupsID INTEGER REFERENCES
ISO11783ImplementGroups(ISO11783ImplementGroupsID),
    ImplementTypesID INTEGER,
    PRIMARY KEY(ImplementTypesID));

CREATE TABLE Addresses(
    Street VARCHAR(64),
    ZipCode VARCHAR(16),
    City VARCHAR(64),
    State VARCHAR(64),
    Country VARCHAR(64),
    AddressesID INTEGER,
    PRIMARY KEY(AddressesID));

CREATE TABLE Organizations(
    Name VARCHAR(64) NOT NULL UNIQUE,
    Phone VARCHAR(16),
    Fax VARCHAR(16),
    Email VARCHAR(64),
    WebPage VARCHAR(64),
    VatNumber VARCHAR(16) UNIQUE,
    RegNumber VARCHAR(16) UNIQUE,
    AddressesID INTEGER REFERENCES Addresses(AddressesID),
    OrganizationsID INTEGER,
    PRIMARY KEY(OrganizationsID));

CREATE TABLE Accounts(
    BeginDate TIMESTAMP,
    EndDate TIMESTAMP,
    Code VARCHAR(16),
    Designator VARCHAR(64) NOT NULL,
    OrganizationsID INTEGER REFERENCES Organizations(OrganizationsID),
    AccountsID INTEGER,
    PRIMARY KEY(AccountsID),
    UNIQUE(OrganizationsID,Designator),
    UNIQUE(OrganizationsID,Code)) ;

CREATE TABLE Persons(
    Name VARCHAR(64) NOT NULL,
    Phone VARCHAR(16),
    Fax VARCHAR(16),
    Mobile VARCHAR(16),
    Email VARCHAR(64),
    TaxNumber VARCHAR(16) UNIQUE,
    DateOfBirth TIMESTAMP,
    PlaceOfBirth VARCHAR(64) NOT NULL,
    AddressesID INTEGER REFERENCES Addresses(AddressesID),
    PersonsID INTEGER,
    PRIMARY KEY(PersonsID),
    UNIQUE( Name,DateOfBirth,PlaceOfBirth));
```

```
CREATE TABLE Customers(
    OrganizationsID INTEGER REFERENCES Organizations(OrganizationsID),
    PersonsID INTEGER REFERENCES Persons(PersonsID)) ;

CREATE TABLE ActivityTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    ActivityTypesID INTEGER,
    PRIMARY KEY(ActivityTypesID));

CREATE TABLE ItemTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    ItemTypesID INTEGER,
    PRIMARY KEY(ItemTypesID));

CREATE TABLE CropTypes(
    Code VARCHAR(16) UNIQUE,
    Designator VARCHAR(64) NOT NULL UNIQUE,
    CropTypesID INTEGER,
    PRIMARY KEY(CropTypesID));

CREATE TABLE CropGoals(
    Designator VARCHAR(64) NOT NULL,
    CropTypesID INTEGER REFERENCES CropTypes(CropTypesID),
    CropGoalsID INTEGER,
    PRIMARY KEY(CropGoalsID),
    UNIQUE( Designator, CropTypesID));

CREATE TABLE CropVarieties(
    Code VARCHAR(16),
    Designator VARCHAR(64) NOT NULL,
    CropTypesID INTEGER REFERENCES CropTypes(CropTypesID),
    CropVarietiesID INTEGER,
    PRIMARY KEY(CropVarietiesID),
    UNIQUE( Designator, CropTypesID));

CREATE TABLE ISO11783DataModifiers(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    ISO11783DataModifiersID INTEGER,
    PRIMARY KEY(ISO11783DataModifiersID));

CREATE TABLE SpecificationTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    SpecificationTypesID INTEGER,
    PRIMARY KEY(SpecificationTypesID));

CREATE TABLE Specifications(
    EntryDate TIMESTAMP,
    SpecificationTypesID INTEGER REFERENCES SpecificationTypes(SpecificationTypesID),
    SpecificationsID INTEGER,
    PRIMARY KEY(SpecificationsID));

CREATE TABLE DataTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    DataTypesID INTEGER,
    PRIMARY KEY(DataTypesID));

CREATE TABLE DataTables(
    EntityTableName VARCHAR(64),
    DataTableName VARCHAR(64) NOT NULL UNIQUE,
    DataTypesID INTEGER REFERENCES DataTypes(DataTypesID),
    DataTablesID INTEGER,
    PRIMARY KEY(DataTablesID));

CREATE TABLE Units(
    Designator VARCHAR(64),
    Symbol VARCHAR(16) NOT NULL UNIQUE,
    Status INTEGER,
    ISO11783Code INTEGER,
    UnitsID INTEGER,
    PRIMARY KEY(UnitsID));

CREATE TABLE ImplementLogProperties(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    ImplementLogPropertiesID INTEGER,
    PRIMARY KEY(ImplementLogPropertiesID));

CREATE TABLE ActivityProperties(
```

```
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    ActivityPropertiesID INTEGER,
    PRIMARY KEY(ActivityPropertiesID));

CREATE TABLE ItemTypeProperties(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    ItemTypePropertiesID INTEGER,
    PRIMARY KEY(ItemTypePropertiesID));

CREATE TABLE CropProdUnitProperties(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    CropProdUnitPropertiesID INTEGER,
    PRIMARY KEY(CropProdUnitPropertiesID));

CREATE TABLE SoilBlockProperties(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    SoilBlockPropertiesID INTEGER,
    PRIMARY KEY(SoilBlockPropertiesID));

CREATE TABLE SoilProperties(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    SoilPropertiesID INTEGER,
    PRIMARY KEY(SoilPropertiesID));

CREATE TABLE ImplementProperties(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    ImplementPropertiesID INTEGER,
    PRIMARY KEY(ImplementPropertiesID));

CREATE TABLE ImplementTypeProperties(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    Comment VARCHAR(64),
    ImplementTypePropertiesID INTEGER,
    PRIMARY KEY(ImplementTypePropertiesID));

CREATE TABLE FieldBoundaries(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE Fields(
    Area FLOAT(52),
    FieldsID INTEGER REFERENCES Accounts(AccountsID),
    Parent INTEGER REFERENCES Fields(FieldsID),
    GID INTEGER REFERENCES FieldBoundaries(GID),
    PRIMARY KEY(FieldsID));

CREATE TABLE CropProdUnits(
    CropProdUnitsID INTEGER REFERENCES Accounts(AccountsID),
    FieldsID INTEGER REFERENCES Fields(FieldsID),
    CropTypesID INTEGER REFERENCES CropTypes(CropTypesID),
    CropVarietiesID INTEGER REFERENCES CropVarieties(CropVarietiesID),
    CropGoalsID INTEGER REFERENCES CropGoals(CropGoalsID),
    PRIMARY KEY(CropProdUnitsID));

CREATE TABLE Implements(
    ImplementsID INTEGER REFERENCES Accounts(AccountsID),
    SerialNumber VARCHAR(64),
    Comment VARCHAR(64),
    ImplementTypesID INTEGER REFERENCES ImplementTypes(ImplementTypesID),
    PRIMARY KEY(ImplementsID));

CREATE TABLE Workers(
    WorkersID INTEGER REFERENCES Accounts(AccountsID),
    PersonsID INTEGER REFERENCES Persons(PersonsID),
    PRIMARY KEY(WorkersID));

CREATE TABLE Items(
```

```
    Balance FLOAT(52),
    ItemsID INTEGER REFERENCES Accounts(AccountsID),
    ItemTypesID INTEGER REFERENCES ItemTypes(ItemTypesID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    PRIMARY KEY(ItemsID));

CREATE TABLE Activities(
    EntryDate TIMESTAMP,
    Comment VARCHAR(64),
    Status INTEGER,
    AccountsID INTEGER REFERENCES Accounts(AccountsID),
    ActivityTypesID INTEGER REFERENCES ActivityTypes(ActivityTypesID),
    OrganizationsID INTEGER REFERENCES Organizations(OrganizationsID),
    ActivitiesID INTEGER,
    PRIMARY KEY(ActivitiesID));

CREATE TABLE ActivityLinks(
    ExternalSystem VARCHAR(64),
    ExternalKey VARCHAR(64),
    ActivitiesID INTEGER REFERENCES Activities(ActivitiesID),
    ActivityLinksID INTEGER,
    PRIMARY KEY(ActivityLinksID));

CREATE TABLE ActivityTimes(
    BeginDate TIMESTAMP,
    EndDate TIMESTAMP,
    Hours FLOAT(52),
    ActivitiesID INTEGER REFERENCES Activities(ActivitiesID),
    ActivityTimeTypesID INTEGER REFERENCES ActivityTimeTypes(ActivityTimeTypesID),
    ActivityTimesID INTEGER,
    PRIMARY KEY(ActivityTimesID));

CREATE TABLE ItemEntries(
    Amount FLOAT(52),
    CreationDate TIMESTAMP,
    ItemsID INTEGER REFERENCES Items(ItemsID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    ActivitiesID INTEGER REFERENCES Activities(ActivitiesID),
    ItemEntriesID INTEGER,
    PRIMARY KEY(ItemEntriesID));

CREATE TABLE WorkLogs(
    WorkersID INTEGER REFERENCES Workers(WorkersID),
    ActivitiesID INTEGER REFERENCES Activities(ActivitiesID),
    WorkLogsID INTEGER,
    PRIMARY KEY(WorkLogsID));

CREATE TABLE WorkLogTimes(
    BeginDate TIMESTAMP,
    EndDate TIMESTAMP,
    Hours FLOAT(52),
    WorkLogsID INTEGER REFERENCES WorkLogs(WorkLogsID),
    WorkLogTimeTypesID INTEGER REFERENCES WorkLogTimeTypes(WorkLogTimeTypesID),
    WorkLogTimesID INTEGER,
    PRIMARY KEY(WorkLogTimesID));

CREATE TABLE ImplementLogs(
    ImplementsID INTEGER REFERENCES Implements(ImplementsID),
    ActivitiesID INTEGER REFERENCES Activities(ActivitiesID),
    ImplementLogsID INTEGER,
    PRIMARY KEY(ImplementLogsID));

CREATE TABLE ImplementLogTimes(
    BeginDate TIMESTAMP,
    EndDate TIMESTAMP,
    Hours FLOAT(52),
    ImplementLogsID INTEGER REFERENCES ImplementLogs(ImplementLogsID),
    ImplementLogTimeTypesID INTEGER REFERENCES ImplementLogTimeTypes(ImplementLogTimeTypesID),
    ImplementLogTimesID INTEGER,
    PRIMARY KEY(ImplementLogTimesID));

CREATE TABLE LogFileTypes(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    LogFileTypesID INTEGER,
    PRIMARY KEY(LogFileTypesID));

CREATE TABLE LogFileVariables(
    Designator VARCHAR(64) NOT NULL UNIQUE,
```

```
    LogFileVariablesID INTEGER,
    PRIMARY KEY(LogFileVariablesID));

CREATE TABLE LogFileColumns(
    Index INTEGER,
    DataType VARCHAR(16),
    Width INTEGER,
    Decimals INTEGER,
    NAValue VARCHAR(16),
    LogFileTypesID INTEGER REFERENCES LogFileTypes(LogFileTypesID),
    LogFileVariablesID INTEGER REFERENCES LogFileVariables(LogFileVariablesID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    LogFileColumnsID INTEGER,
    PRIMARY KEY(LogFileColumnsID));

CREATE TABLE LogFiles(
    Name VARCHAR(64),
    Path VARCHAR(64),
    BeginDate TIMESTAMP,
    EndDate TIMESTAMP,
    Comment VARCHAR(64),
    LogFileTypesID INTEGER REFERENCES LogFileTypes(LogFileTypesID),
    ImplementLogsID INTEGER REFERENCES ImplementLogs(ImplementLogsID),
    LogFilesID INTEGER,
    PRIMARY KEY(LogFilesID));

CREATE TABLE SoilBlocks(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    SoilBlocksID INTEGER,
    PRIMARY KEY(SoilBlocksID));

CREATE TABLE SoilProfiles(
    Designator VARCHAR(64) NOT NULL UNIQUE,
    SoilProfilesID INTEGER,
    PRIMARY KEY(SoilProfilesID));

CREATE TABLE SoilBlockLayers(
    BeginDepth FLOAT(52),
    EndDepth FLOAT(52),
    SoilProfilesID INTEGER REFERENCES SoilProfiles(SoilProfilesID),
    SoilBlocksID INTEGER REFERENCES SoilBlocks(SoilBlocksID),
    SoilBlockLayersID INTEGER,
    PRIMARY KEY(SoilBlockLayersID));

CREATE TABLE ImplementLogValuePoints(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE ImplementLogValuePolygons(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE ImplementLogValueGeometries(
    GeometryType INTEGER,
    PointGID INTEGER REFERENCES ImplementLogValuePoints(GID),
    PolygonGID INTEGER REFERENCES ImplementLogValuePolygons(GID),
    ImplementLogValueGeometriesID INTEGER,
    PRIMARY KEY(ImplementLogValueGeometriesID));

CREATE TABLE ActivityValuePoints(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));
```

```
CREATE TABLE ActivityValuePolygons(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE ActivityValueGeometries(
    GeometryType INTEGER,
    PointGID INTEGER REFERENCES ActivityValuePoints(GID),
    PolygonGID INTEGER REFERENCES ActivityValuePolygons(GID),
    ActivityValueGeometriesID INTEGER,
    PRIMARY KEY(ActivityValueGeometriesID));

CREATE TABLE CropProdUnitValuePoints(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE CropProdUnitValuePolygons(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE CropProdUnitValueGeometries(
    GeometryType INTEGER,
    PointGID INTEGER REFERENCES CropProdUnitValuePoints(GID),
    PolygonGID INTEGER REFERENCES CropProdUnitValuePolygons(GID),
    CropProdUnitValueGeometriesID INTEGER,
    PRIMARY KEY(CropProdUnitValueGeometriesID));

CREATE TABLE SoilValuePoints(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE SoilValuePolygons(
    GID INTEGER NOT NULL,
    XMIN FLOAT(52),
    YMIN FLOAT(52),
    XMAX FLOAT(52),
    YMAX FLOAT(52),
    WKB_GEOMETRY LONG BIT VARYING,
    PRIMARY KEY(GID));

CREATE TABLE SoilValueGeometries(
    GeometryType INTEGER,
    PointGID INTEGER REFERENCES SoilValuePoints(GID),
    PolygonGID INTEGER REFERENCES SoilValuePolygons(GID),
    SoilValueGeometriesID INTEGER,
    PRIMARY KEY(SoilValueGeometriesID));

CREATE TABLE ImplementValues(
    VID INTEGER,
    TimeTag TIMESTAMP,
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    ImplementPropertiesID INTEGER REFERENCES ImplementProperties(ImplementPropertiesID),
    ImplementsID INTEGER REFERENCES Implements(ImplementsID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    ImplementValuesID INTEGER,
    PRIMARY KEY(ImplementValuesID));

CREATE TABLE ImplementTypeValues(
```

```
    VID INTEGER,
    TimeTag TIMESTAMP,
    ImplementTypePropertiesID INTEGER REFERENCES
ImplementTypeProperties(ImplementTypePropertiesID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    ImplementTypesID INTEGER REFERENCES ImplementTypes(ImplementTypesID),
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    ImplementTypeValuesID INTEGER,
    PRIMARY KEY(ImplementTypeValuesID));

CREATE TABLE ImplementLogValues(
    VID INTEGER,
    TimeTag TIMESTAMP,
    ItemTypesID INTEGER REFERENCES ItemTypes(ItemTypesID),
    ImplementLogValueGeometriesID INTEGER REFERENCES
ImplementLogValueGeometries(ImplementLogValueGeometriesID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    ImplementLogsID INTEGER REFERENCES ImplementLogs(ImplementLogsID),
    ImplementLogPropertiesID INTEGER REFERENCES
ImplementLogProperties(ImplementLogPropertiesID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    DataModifier INTEGER REFERENCES ISO11783DataModifiers(ISO11783DataModifiersID),
    ImplementLogValuesID INTEGER,
    PRIMARY KEY(ImplementLogValuesID));

CREATE TABLE ActivityValues(
    VID INTEGER,
    TimeTag TIMESTAMP,
    ActivitiesID INTEGER REFERENCES Activities(ActivitiesID),
    ItemTypesID INTEGER REFERENCES ItemTypes(ItemTypesID),
    ActivityValueGeometriesID INTEGER REFERENCES
ActivityValueGeometries(ActivityValueGeometriesID),
    ActivityPropertiesID INTEGER REFERENCES ActivityProperties(ActivityPropertiesID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    DataModifier INTEGER REFERENCES ISO11783DataModifiers(ISO11783DataModifiersID),
    ActivityValuesID INTEGER,
    PRIMARY KEY(ActivityValuesID));

CREATE TABLE ItemTypeValues(
    VID INTEGER,
    TimeTag TIMESTAMP,
    ItemTypePropertiesID INTEGER REFERENCES ItemTypeProperties(ItemTypePropertiesID),
    ItemTypesID INTEGER REFERENCES ItemTypes(ItemTypesID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    ItemTypeValuesID INTEGER,
    PRIMARY KEY(ItemTypeValuesID));

CREATE TABLE CropProdUnitValues(
    VID INTEGER,
    TimeTag TIMESTAMP,
    CropProdUnitPropertiesID INTEGER REFERENCES
CropProdUnitProperties(CropProdUnitPropertiesID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    CropProdUnitValueGeometriesID INTEGER REFERENCES
CropProdUnitValueGeometries(CropProdUnitValueGeometriesID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    DataModifier INTEGER REFERENCES ISO11783DataModifiers(ISO11783DataModifiersID),
    CropProdUnitsID INTEGER REFERENCES CropProdUnits(CropProdUnitsID),
    CropProdUnitValuesID INTEGER,
    PRIMARY KEY(CropProdUnitValuesID));

CREATE TABLE SoilBlockValues(
    VID INTEGER,
    TimeTag TIMESTAMP,
    SoilBlocksID INTEGER REFERENCES SoilBlocks(SoilBlocksID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    SoilBlockPropertiesID INTEGER REFERENCES SoilBlockProperties(SoilBlockPropertiesID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    SoilBlockValuesID INTEGER,
    PRIMARY KEY(SoilBlockValuesID));
```

```
CREATE TABLE SoilValues(
    VID INTEGER,
    TimeTag TIMESTAMP,
    BeginDepth FLOAT(52),
    EndDepth FLOAT(52),
    FieldsID INTEGER REFERENCES Fields(FieldsID),
    SoilPropertiesID INTEGER REFERENCES SoilProperties(SoilPropertiesID),
    SpecificationsID INTEGER REFERENCES Specifications(SpecificationsID),
    SoilValueGeometriesID INTEGER REFERENCES SoilValueGeometries(SoilValueGeometriesID),
    UnitsID INTEGER REFERENCES Units(UnitsID),
    DataType INTEGER REFERENCES DataTypes(DataTypesID),
    SoilValuesID INTEGER,
    PRIMARY KEY(SoilValuesID));
```

Appendix B: SQL data definition script geometry

```
CREATE TABLE SPATIAL_REF_SYS(
    SRID INTEGER NOT NULL,
    AUTH_NAME VARCHAR(255),
    AUTH_SRID INTEGER,
    SRTEXT VARCHAR(255),
    PRIMARY KEY(SRID));

CREATE TABLE GEOMETRY_COLUMNS(
    F_TABLE_CATALOG VARCHAR(255) NOT NULL,
    F_TABLE_SCHEMA VARCHAR(255) NOT NULL,
    F_TABLE_NAME VARCHAR(255) NOT NULL,
    F_GEOMETRY_COLUMN VARCHAR(255) NOT NULL,
    G_TABLE_CATALOG VARCHAR(255) NOT NULL,
    G_TABLE_SCHEMA VARCHAR(255) NOT NULL,
    G_TABLE_NAME VARCHAR(255) NOT NULL,
    STORAGE_TYPE INTEGER,
    GEOMETRY_TYPE INTEGER,
    COORD_DIMENSION INTEGER,
    MAX_PPR INTEGER,
    SRID INTEGER NOT NULL,
    FOREIGN KEY (SRID) REFERENCES SPATIAL_REF_SYS,
    PRIMARY KEY(F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN));

INSERT INTO SPATIAL_REF_SYS (SRID, AUTH_NAME, AUTH_SRID, SRTEXT) VALUES (100,'DOD',1,'WGS
1984');

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES ('','','Fields','GID','','','FieldBoundaries',1,5,2,0,100);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES ('','','ActivityValueGeometries','PointGID','','','ActivityValuePoints',1,1,2,0,100);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES
('','','ActivityValueGeometries','PolygonGID','','','ActivityValuePolygons',1,5,2,0,100);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES
('','','CropProdUnitValueGeometries','PointGID','','','CropProdUnitValuePoints',1,1,2,0,100);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES
('','','CropProdUnitValueGeometries','PolygonGID','','','CropProdUnitValuePolygons',1,5,2,0,10
0);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES
('','','ImplementLogValueGeometries','PointGID','','','ImplementLogValuePoints',1,1,2,0,100);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES
('','','ImplementLogValueGeometries','PolygonGID','','','ImplementLogValuePolygons',1,5,2,0,10
0);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES ('','','SoilValueGeometries','PointGID','','','SoilValuePoints',1,1,2,0,100);

INSERT INTO GEOMETRY_COLUMNS
  (F_TABLE_CATALOG,F_TABLE_SCHEMA,F_TABLE_NAME,F_GEOMETRY_COLUMN,G_TABLE_CATALOG,
  G_TABLE_SCHEMA,G_TABLE_NAME,STORAGE_TYPE,GEOMETRY_TYPE,COORD_DIMENSION,MAX_PPR,SRID)
VALUES ('','','SoilValueGeometries','PolygonGID','','','SoilValuePolygons',1,5,2,0,100);
```