Department of Automation and Systems Technology

Automated control of compliance with production standards in precision agriculture

Raimo Nikkilä

Aalto University

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Automated control of compliance with production standards in precision agriculture

Raimo Nikkilä

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Abstract

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Abstract

Significant manual effort is currently involved in monitoring the compliance of agricultural production with legislation. While this administrative effort has little actual benefit for farms, compliance with legislation, or more generally production standards, is tied to the payout of economically vital farm subsidies. Information technology, together with the data collected automatically in precision agriculture, could alleviate this problem by automatically determining compliance with a significant portion of agricultural production standards. This thesis identifies the technical requirements of automated compliance control, formulates a design that conforms with the requirements of the stakeholders in precision agriculture and evaluates this design. The primary research objective can be further subdivided into three information systems: a farm management information system (FMIS) for precision agriculture, an infrastructure of Web services for automated compliance control and finally, spatial computer inference. These research objectives are addressed with the methodology of design science, using the agricultural field operation of precise fertilisation as the principal use case for automated compliance control. The results consist of information system designs and evaluation of these designs for functionality and feasibility. This thesis contributes the designs for three information systems: a software architecture for an FMIS in precision agriculture, a service infrastructure for automated compliance control and spatial computer inference with an interchangeable rule format. Through their prototype implementations, these are evaluated to constitute the necessary framework for automated compliance control. While technically demanding, automated compliance control with pertinent agricultural legislation is attainable, given the functionality of precision agriculture and the information systems presented in this thesis. However, the feasibility of the process relies on a degree of data interchange, which due to the lack of established data formats is currently difficult in agriculture. On the other hand, parts of the proposed solution can be applicable on a shorter time frame in agriculture or other domains.

Keywords FMIS, RIF, spatial inference, precision agriculture

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Tiivistelmä

Maatalouden tuotantosäännöstöjen valvontaan käytetään nykyisin huomattava määrä ihmistyötä. Tuotantosäännöstöjen noudattaminen on edellytyksenä maatiloille maksettavista ja taloudellisesti elintärkeistä maataloustuista, vaikka maksatuksen edellyttämä hallinnollinen työ ei juurikaan hyödytä tiloja. Edellä mainittua työmäärää olisi kuitenkin mahdollista vähentää ja työtä helpottaa informaatiotekniikalla käyttäen täsmäviljelyssä automaattisesti kerättyä tietoa konepäättelyssä. Tämä väitöstutkimus kattaa automaattisen tuotantosäännöstöjen valvonnan teknisen toteutuksen. Järjestelmän vaatimukset ja rakenne perustuvat täsmäviljelyn tunnistettuihin sidosryhmiin. Mainittu tavoite jakautuu kolmeen keskeiseen tietojärjestelmään: yleiseen täsmäviljelyn tiedonhallintajärjestelmään, verkkopalveluarkkitehtuuriin tuotantosäännöstöille sekä konepäättelyyn paikkatiedolla. Näihin tavoitteisiin pyritään suunnittelutieteen metodein käyttäen täsmälannoitusta tuotantosäännöstöjen automaattisen valvonnan pääasiallisena käyttötapauksena. Väitöstutkimukseen sisältyy tietojärjestelmien suunnittelu ja niiden toiminnallisuuden sekä toteutuksen mielekkyyden arviointi. Väitöstutkimuksen tuloksina esitetään kolme tietojärjestelmää: yleinen tiedonhallintajärjestelmä täsmäviljelyyn, verkkopalveluarkkitehtuuri tuotantosäännöstöjen valvontaan sekä paikkatietoa käsittelevä konepäättelijä, joka tukee järjestelmien välillä vaihdettavaa sääntöesitysmuotoa. Edellä mainittujen tietojärjestelmien prototyyppitoteutusten perusteella on todettavissa niiden yhdessä muodostavan riittävän tietoinfrastruktuurin tuotantosäännöstöjen automaattiseen valvontaan. Automaattinen tuotantosäännöstöjen valvonta on teknisesti haastavaa, mutta täsmäviljelyssä kerätyn tiedon ja esitettyjen tietojärjestelmien avulla sillä pystytään kattamaan suurin osa tuotantosäännöstöistä. Sen tekninen ratkaisu ei kuitenkaan ole ongelmaton, sillä maatalouden standardoimattomat ja vakiintumattomat tiedon esitysmuodot edellyttävät huomattavaa ja usein epäkäytännöllistä tietointegraatiota. Osia esitetystä ratkaisusta voitaisiin toisaalta hyödyntää sellaisenaan lyhyehköllä aikavälillä, sekä mahdollisesti myös muilla sovellusalueilla kuin maataloudessa.

Avainsanat FMIS, RIF, konepäättely paikkatiedolla, täsmäviljely

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Preface

I would like to thank all my friends and colleagues who have been helpful along the arduous six year path to this thesis. Particularly, I would like to thank my supervisor, professor Kari Koskinen, for his diligent support. You were always the optimist, finding solutions and workarounds amid all the bewilderment. And whenever the chairs on the Titanic were being rearranged, you always made sure your research group got good seats. Additionally, I would like to thank my outstanding advisor docent Ilkka Seilonen. I did my master's thesis under Ilkka and proceeded to became his first graduate student. Ilkka, thanks for everything and I hope I wasn't too much of a bother to you. And finally, thanks to all my other colleagues, without whom I wouldn't have managed with all the teaching and research over these years. Whether or not all this turns out to have been worth the effort, I honestly don't know, but certainly do hope so. Anyhow, they should really have a pet lemur award option available for completed doctoral theses.

Espoo, April 24, 2013,

Raimo Nikkilä

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List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Raimo Nikkilä, Ilkka Seilonen, Kari Koskinen. Software architecture for farm management information systems in precision agriculture. *Computers and Electronics in Agriculture*, 70, 328-336, March 2010.

II Edward Nash, Jens Wiebensohn, Raimo Nikkilä, Anna Vatsanidou, Spyros Fountas, Ralf Bill. Towards automated compliance checking based on a formal representation of agricultural production standards. *Computers and Electronics in Agriculture*, 78, 28-37, August 2011.

III Edward Nash, Raimo Nikkilä, Jens Wiebensohn, Kai Walter, Ralf Bill. Interchange of geospatial rules - towards georules interchange format (GeoRIF)?. *GIS.Science*, 24, 82-94, 2011.

IV Raimo Nikkilä, Jens Wiebensohn, Edward Nash, Ilkka Seilonen, Kari Koskinen. A service infrastructure for the representation, discovery, distribution and evaluation of agricultural production standards for automated compliance control. *Computers and Electronics in Agriculture*, 80, 80-88, January 2012.

V Raimo Nikkilä, Jens Wiebensohn, Edward Nash, Ilkka Seilonen, Kari Koskinen. Spatial inference with an interchangeable rule format. *International Journal of Geographical Information Science*, DOI: 10.1080/13658816.2012.750323, 2013.

Author's Contribution

Publication I: "Software architecture for farm management information systems in precision agriculture"

This journal article presents research by the author, who designed the software architecture, implemented the prototype system and wrote the bulk of the publication.

Publication II: "Towards automated compliance checking based on a formal representation of agricultural production standards"

This journal article presents collaboratory research where the author was party to designing the formal representation and computer encoding of agricultural production standards and the technical basis for the overall procedure and workflow of automated compliance control. Co-authors evaluated the corpus of agricultural legislation, formulated the XML container for the GeoRIF rules and wrote the bulk of the publication.

Publication III: "Interchange of geospatial rules - towards georules interchange format (GeoRIF)?"

This journal article presents collaboratory research where the author was involved in the design and formulation of the interchangeable GeoRIF rule format, particularly in aspects related to computer inference with GeoRIF. Co-authors formulated the proposed use cases for GeoRIF, collected the functionality from OGC-SFA (Open Geospatial Consortium - Simple feature access) and wrote the bulk of the publication.

Publication IV: "A service infrastructure for the representation, discovery, distribution and evaluation of agricultural production standards for automated compliance control"

This journal article presents collaboratory research, where the author designed and specified the service infrastructure, provided the prototype implementations and wrote the bulk of the publication.

Publication V: "Spatial inference with an interchangeable rule format"

This journal article presents research by the author, who designed and implemented the prototype spatial inference system for GeoRIF and wrote the bulk of the publication.

List of Acronyms

DSS	Decision support system
FMIS	Farm management information system
GeoRIF	Geospatial RIF
GIS	Geographic information system
GML	Geographic markup language
ISO	International Organization for Standardization
ISOBUS	ISO 11783: Tractors and machinery for agriculture and forestry - Serial control and communications data network
MGU	Most general unifier
MVC	Model-view-controller (software architecture pattern)
NUTS	(European) Nomenclature of territorial units for statistic
OGC	Open Geospatial Consortium
RDBMS	Relational database management system
RDF	Resource description framework
REST	Representational state transfer
RFID	Radio-frequency identification
RIF	Rule interchange format
RIF BLD	RIF basic logic dialect
RIF PRD	RIF production rule dialect
SDI	Spatial data infrastructure
SFA	Simple feature access
SOA	Service-oriented architecture
SOAP	Simple object access protocol
SWIG	Simplified wrapper and interface generator
TC	Task controller (ISO 11783)
VT	Virtual terminal (ISO 11783)
XML	Extensible markup language
XSD	XML schema definition
XSLT	Extensible stylesheet transformation

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1. Introduction

Agriculture has undergone technological shifts through adopting new technologies as they have become available. One such major technological shift was the adoption of mechanised farming equipment, which largely replaced labour animals over the last century. The currently ongoing shift is the adoption of information technology, which enhances farming equipment and enables new approaches in agriculture (Bill et al. 2012). One such approach is precision agriculture, which has only recently become technologically feasible (Stafford 2000). Agriculture in the Western world is also facing new challenges; the average farm size is on an increase and farms are becoming increasingly more multifunctional (Jongeneel et al. 2008). In addition to the agricultural produce proper, farms can produce bioenergy, act as on-site vendors for their produce or even entertain tourists. Such diversity of activities necessitates flexibility from the farm management information system (FMIS), which is expected to act as the central information system for the farm. These FMIS are becoming complicated and interconnected systems, with numerous requirements on their functionality, as they slowly transition from simple on-site software to industrial information systems (Sørensen et al. 2011).

This thesis is motivated by the recognised current and future role of information technology in agriculture (Cox 2002, Kuhlmann & Brodersen 2001). Contemporary FMIS are generally diverse and uncomplicated small-scale systems operating as on-site software. However, with the increasing quantity and complexity of information exchange in agriculture (Sørensen, Pesonen et al. 2010), this approach should be reconsidered. The design of agricultural information systems should reflect the increased need of information exchange. This need of information exchange is particularly demanding in precision agriculture. Moreover, precision agriculture also produces significant quantities of information (Steinberger et al. 2009), which properly utilised, can benefit the stakeholders in agriculture through new applications and services.

This thesis focuses on the technical solutions of information systems in precision agriculture, particularly for the task of automated compliance control with production standards. Automated compliance control is a technologically challenging objective, described in Publication II of this thesis, which requires extensive interoperability between information systems, a formal encoding of agricultural production standards and spatial computer inference. Thus, both general-purpose FMIS and Web services for precision agriculture are within the scope of this thesis. Furthermore, the technical solutions and designs for these systems and services should be feasible with existing and emerging technologies. A simplified workflow of automated compliance control can be seen in Figure 1.1, together with the systems relevant to the process and this thesis. The workflow is illustrated from the generation of a field operation plan to the eventual validation of compliance based on automatically recorded operation documents.

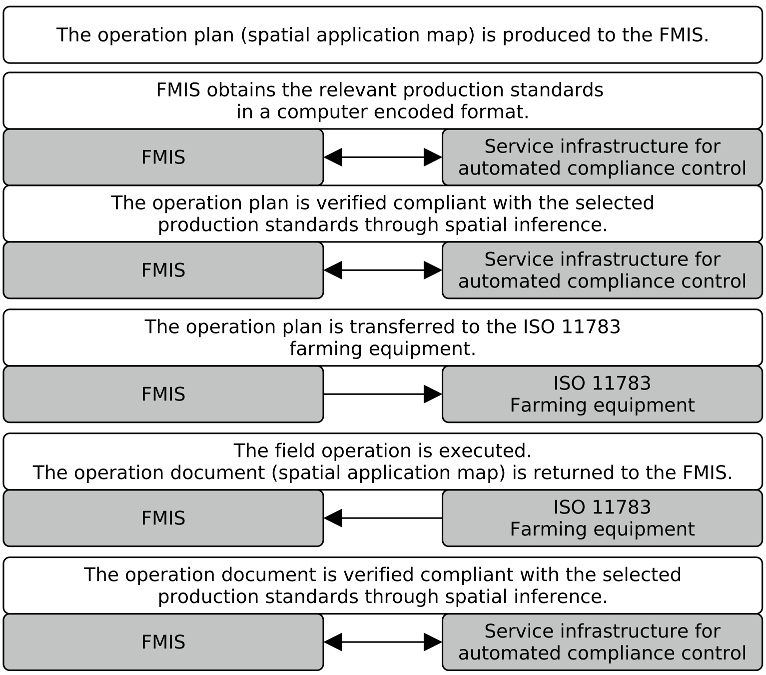

Figure 1.1. A simplified workflow of automated compliance control.

Of the systems shown in Figure 1.1, only the ISOBUS (ISO 11783: Tractors and machinery for agriculture and forestry - Serial control and communications data network) equipment are not considered in any detail by this thesis. ISOBUS is a family of automation and communication standards for agricultural equipment. As such, ISOBUS spans from low-level device control signals to virtual terminals (VT), which are the user interface for ISOBUS tractors. ISOBUS also specifies data formats for communication between the tractor and other information systems, particularly with the FMIS. Consequently, consideration of ISOBUS is restricted to this communication between the FMIS and ISOBUS in this thesis.

The use of spatial information in Figure 1.1, in the form of planned application maps and documents, implies precision agriculture. While the overall objective of automated compliance control is considered in the context of precision agriculture, parts of the necessary functionality are still applicable in traditional agriculture. Precision agriculture is not only a technical challenge, but rather, includes several important topics that lie outside the technical scope of this thesis. Many of these topics involve the socio-economic foundations and consequences of precision agriculture, as well as the effects of precision agriculture on a larger scale. Thus, important non-technical topics such as the effects of precision agriculture on sustainability (Bongiovanni & Lowenberg-Deboer 2004), the education of farmers in the use of the necessary technology (Kitchen et al. 2002) or the economic issues involved in precision agriculture (Bullock & Bullock 2000), are not considered in this thesis.

1.1 Research objectives

The overall objective of automated compliance control can be subdivided into three components: a suitable central information system, a service infrastructure for information exchange and spatial inference to determine compliance. These three components must be designed and evaluated. Functionality will be demonstrated through prototype implementations, which are further used to assess the overall feasibility of the designs.

Architecture of an FMIS for precision agriculture

The first research objective concerns FMIS for precision agriculture, which as the central information system in agriculture is essential to automated compliance control. Compared to FMIS for traditional agriculture, these have a wider base of stakeholders with additional requirements and design criteria. The information intensive nature of precision agriculture establishes requirements that drive most designs towards Web-based solutions. Web-based approaches, however, are infrequent in the literature as well as in existing agricultural information systems. Moreover, existing information systems for precision agriculture are scarce and commonly, as the results of academic research projects, focus on some particular task rather than general use. Hence, the objective of research is to identify the requirements and design for a general-purpose FMIS through the stakeholders in precision agriculture.

Service infrastructure for information exchange in automated compliance control

The second research objective concerns Web services for precision agriculture, particularly for the task of automated compliance control. Various services are already an inherent element of modern agriculture, extending from soil sample analyses and weather forecasts to contracted field work. Many of these services, or the information exchange of these services, could be developed into Web services and hence utilised conveniently through the FMIS (Thysen 2000). Web services for agriculture have started to appear in the literature and some systems are already available for commercial use. Furthermore, Web services have been found beneficial for system interoperability in agriculture (Wolfert et al. 2010). Since automated compliance control necessitates significant communication and interoperability between information systems, service-based technologies are a reasonable design approach. Thus, the objective is to identify, design and evaluate services which can form the communication framework for automated compliance control.

Spatial inference for automated compliance control with production standards

In the end, automated compliance control is achieved through spatial computer inference, which can be applied on information recorded automatically as documentation by the farming equipment. Alternatively, the operation plan can be proactively subjected to automated compliance control. This final research objective addresses the technology of spatial inference. Computer inference requires the agricultural production standards encoded in a logical rule format. The discovery and distribution of these rules is achieved with the service architecture of the preceding research objective. However, the actual process of spatial inference lacks mature solutions, particularly for interchangeable rule formats which are indicated in automated compliance control. Hence, the objective of research is to design and evaluate a spatial inference system, which together with agricultural data and production standards encoded as rules, can provide automated compliance control.

1.2 Contributions

This thesis makes three contributions, drawn from the results presented in Chapter 3; one for each of the previously stated research objectives. These are presented in the same order as the research objectives and thus thematically in an increasing focus; from general-purpose FMIS to the internal technical structure of a single service within a larger service architecture. The functionality of these designs is demonstrated with prototype implementations, which are also used to assess the feasibility of the designs.

Architecture of a general-purpose information system for precision agriculture

Publication I presents a design for a complete FMIS for precision agriculture operating as a Web application. The requirements of the design are based on the concerns and requirements of the identified stakeholders in precision agriculture, drawn from agricultural use cases. The design is presented from alternating viewpoints, with a technical structure following a layered model-view-controller (MVC) architecture.

Compared to published and established agricultural information systems, the design is a complete non-specialised FMIS for precision agriculture with foundation in the stakeholders in precision agriculture. The design also considers interfaces to all necessary systems and stakeholders, spanning from ISOBUS farming equipment to farmers and agricultural advisors. Communication with ISOBUS equipment in this design was demonstrated with a precise fertilisation operation described in Publication I. This evaluation covered information exchange in precision agriculture, consisting of the transfer of operation plans and documents between the FMIS and the ISOBUS task controller (TC). Based on this evaluation, the necessary communication between the FMIS and ISOBUS equipment can be feasibly provided through the proposed architecture, with uncomplicated protocols and implementations for both the FMIS and the tractor TC. Same communication design could be extended to other operations in agriculture which necessitate communication between the FMIS and the tractor. However, operations which require real-time communication may require a different design, as the requirements of real-time communication are largely incompatible with mobile networks.

A service infrastructure for automated compliance control

Publication IV presents a complete service infrastructure for automated compliance control, the feasibility of which is discussed more thoroughly in Publication II. The design extends the general-purpose FMIS for precision agriculture and is based on the requirements of the stakeholders in automated compliance control, which are a subset of the stakeholders in the general-purpose FMIS. The functionality required by automated compliance control was divided across individual services according to their corresponding stakeholders.

Automated compliance control involves significant data interchange and processing, relying primarily on data recorded by the farming equipment in precision agriculture. This interoperability is delivered through the specified service architecture, using lightweight service interfaces based on representational state transfer (REST). The functionality of the service infrastructure was evaluated with a client implementation by a German commercial FMIS provider, which demonstrated the full workflow of automated compliance control through a Web-based FMIS. On the strength of this evaluation, the structure and interfaces of the service infrastructure appear suitable and sufficient for automated compliance control.

Design and evaluation of a spatial inference engine for automated compliance control

The service infrastructure presented in Publication IV provides the information flows for automated compliance control. Publication V covers a system capable of performing the necessary spatial inference, given the required input information and the production standards encoded in GeoRIF, the spatially extended W3C rule interchange format (RIF) specified in Publication III. The functionality of spatial inference with an interchangeable rule format is not readily available. Existing spatial inference systems generally do not support rule interchange or lack the necessary facilities for data integration. The system described in Publication V operates natively on the interchangeable rule format and provides facilities for the data integration of geographic markup language (GML), without preference to any GML Application Schema. Encapsulated within a Web service, this system provides the spatial inference for automated compliance control. The functionality and computational efficiency of the inference engine were evaluated in Publication V. Based on this evaluation, spatial data can be provided for inference as a fully-functional data type comparable to other RIF data types, with a computational efficiency depending predominantly on spatial operations. Lacking agriculture specific functionality, this result is applicable in other domains where rule interchange and spatial inference are indicated.

1.3 Research methodology

This thesis approaches the objectives of automated compliance control through design science. Design science (Peffers et al. 2007), provides a framework of quantitative and qualitative research methods for the evaluation of artefacts, which in the context of this thesis are designs of information system and their corresponding prototype implementations.

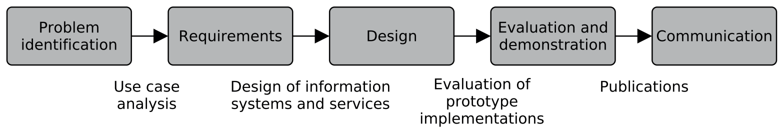

Figure 1.2. Design science in this thesis.

Since design science is a methodology framework, the actual process of research in design science varies between different domains and authors (Peffers et al. 2006). Figure 1.2 shows the five-step research process of design science in this thesis. Starting with the identified research problem, the requirements for the technical solution are formulated through use case analysis. These requirements are then fulfilled in design, which is shown functional and feasible through prototype implementations. Communication, an essential constituent of research, is included as an explicit last step. This section covers the relevant methods of design science and their application in this thesis. These correspond to the actitivies shown at the base of Figure 1.2 that transition between the steps of the research process.

1.3.1 Use case analysis - precise fertilisation

Use case analysis is a method of engineering, and consequently of technical research, for deriving the requirements and information flows for a system or process. In agriculture, agricultural field operations constitute a significant group of use cases for information systems. Hence, the relevant information flows and stakeholders in precision agriculture can be identified through use case analysis of agricultural field operations.

Particularly, the case of precise fertilisation and the information flows involved therein (Sørensen, Pesonen et al. 2010), encompasses the domain of precision agriculture to such an extent that it is considered throughout this thesis. This use case represents the near future of precision agriculture, consolidating existing and conceived future information flows. The use case of precise fertilisation involves planning, which requires information from several sources, produces digital documentation of the operation, entails economic aspects and is restricted by legislation. On an abstract level, the information flows for most field operations can be considered as variations of precise fertilisation (Sørensen et al. 2011). While the necessary amount of fertiliser is calculated differently from the amount of e.g. pesticide, both operations require similar input information and produce similar results. Furthermore, precise fertilisation can be simulated on fields using an inert substance, i.e. water, instead of the actual fertiliser with little restrictions or ill-effects. Therefore, the case of precise fertilisation is used for deriving the stakeholders and requirements in agriculture for the technical solutions considered in this thesis.

1.3.2 Design of information systems and services

Design science is inherently intertwined with artefacts, which in their widest sense can include most constructs of human origin. In the context of information technology, these artefacts consist of designs and implementations of information systems. Scientific contributions through design science in information technology are manyfold, spanning from the construction of these system to theoretical modelling (March & Smith 1995).

This thesis exercises design science by providing artefacts in the form of designs and prototype implementations for information systems. The designs of these information systems are based on the requirements drawn from the identified stakeholders in the systems within the use case described in Section 1.3.1. The actual process of designing information systems from these requirements falls within the domain of software engineering, which is outside the scope of this thesis. The prototype implementations, likewise products of software engineering, are proof-of-concept implementations intended to provide and demonstrate the core functionality of the designs. Both the designs and prototypes are evaluated through the qualitative and quantitative methods of design science.

1.3.3 Evaluation of prototype implementations

Qualitative methods of evaluation in design science include static analyses and proof-of-concept implementations. Many of these qualitative methods are available to information system designs, which given their abstract nature are largely unfit for quantitative research methods. Implementations of these designs, on the other hand, can be subjected to quantitative evaluation. While prototype implementations are commonly unbefitting for wide-scale deployments and testing by the intended user base, the designs can still be evaluated based on the performance and complexity of these prototypes.

The designs presented in thesis are evaluated with static analysis, comparison to other systems in the literature and prototype implementations. These implementations are evaluated qualitatively by demonstrating that the design fulfils set requirements or performs a designated function; and quantitatively where computational performance is a concern in the design.

1.4 Structure of the thesis

The rest of this thesis is structured so that following this introductory chapter, there is a review of the relevant literature in Chapter 2, focusing on the application domain of precision agriculture. This chapter provides background information on agriculture and the information systems used in agriculture. The results of this thesis are then presented in Chapter 3, grouped according to the previously stated research objectives. The thesis is concluded in Chapter 4, followed by a short discussion on the implications and applications of the results in both practice and research. These are followed by the bibliography and the publications in chronological order.

2. Information systems in agriculture

This chapter provides an overview of the literature, including some background information on both agriculture and the technologies relevant to this thesis. Stakeholders in modern agricultural production are used to introduce agriculture as an application domain. The science and practice of agricultural engineering are intertwined to such an extent that they are considered together in this chapter, without a significant distinction made between the two. This is followed by a review of FMIS and the technologies used in FMIS and related systems, such as Web services. The last sections of this chapter cover technologies, including computer inference and the management and integration of spatial data.

2.1 Stakeholders in agricultural information systems

Following is an abridged list of stakeholders in the agricultural information systems considered in this thesis. The complete list for a general FMIS can be found in Publication I. These stakeholders are considered in the context of precision agriculture, where much of the information exchange between the stakeholders includes spatial data. The roles and concerns of these stakeholders are considered and grouped by the three primary foci of this thesis: general FMIS, agricultural services and automated compliance control.

Farmers

Farmers are the foremost stakeholders in agricultural information systems. They are the most numerous and party to almost all activities in agriculture, i.e. they are a stakeholder involved in nearly every information flow. Farmers are also the most diverse group of all stakeholders, coming from various backgrounds with significant differences in their attitudes and accustomance towards information technology. Farmers are also difficult to categorise into subgroups. In addition to their primary income from agricultural produce, farms can have additional sources of income that extend from biofuel production to tourism (Jongeneel et al. 2008).

Services are essential to the normal operation of farms. Many of these services, such as soil analyses, include information exchange between the farm and another stakeholder. As stakeholders, it is in the interest of farmers to obtain this information conveniently and efficiently.

Since all farms are subject to demonstrating their compliance with legislation and production standards, farmers form the principal stakeholder in automated compliance control. Furthermore, compliance is generally a prerequisite for farm subsidies and thus vital for the economy of the farm. Demonstrating compliance is largely work that does not actually benefit the activities of the farm in any way. Therefore, any automation of this process is in the interest of farmers given that it accumulates in a reduced administrative workload.

Authorities

Authorities are a stakeholder that monitors agriculture in terms of farming practices and compliance with agricultural production standards. Authorities also want to efficiently control the flow of restricted substances used in agriculture. These include chemicals such as ammonium nitrate which can be used in explosives or anhydrous ammonia which can be used in clandestine synthesis of methamphetamine. Authorities are one of the few stakeholders that require information from the farm, i.e. they expect the FMIS to act as an information service. Having a direct, though controlled, electronic access to farm records would reduce the overall workload of authorities. Authorities are also the second most important stakeholder in automated compliance control, as it is their responsibility to control compliance. Contemporary manual compliance control is administratively demanding for both farmers and authorities (Varela-Ortega & Calatrava 2004). Though all of compliance control can not, and should not be automated, the workload of authorities could still be significantly reduced.

Customers of farms

Customers of farms who buy the agricultural produce are rarely individual consumers, but rather, large companies who buy the produce in bulk. They are a stakeholder interested in quality and traceability (Doluschitz et al. 2010), which is an increasing trend in the market. Customers are also interested in information on the available produce and the farming practices used in its production. Both of these can be made available through the FMIS. In automated compliance control, customers can have a role comparable to authorities. That is, through mutual agreements and contracts, they can impose their own production standards on the produce and expect farms to show compliance with these.

Suppliers of farms

Suppliers of farms are the stakeholder that supplies farms with material, which includes seeds, fertilisers, pesticides and equipment. For information systems, they need to provide information on their products. This information can be made available through a Web service for the FMIS. When applying any substance on the fields, e.g. a fertiliser or pesticide, details on the composition are essential for proper use. This is particularly important in automated compliance control which requires details, in computer readable format, for any substance applied on the fields. Legislation limits quantities and restricts the application of certain chemicals, e.g. near water bodies to prevent eutrophication. Additional production standards can be even more strict, such as organic farming which forbids the use of several fertilisers and pesticides of non-organic origin.

Service providers

Service providers form another diverse group of stakeholders. They can provide concrete services, such as soil analyses or contracted field work, or only information. Other stakeholders, such as the suppliers of farms can be considered as service providers when providing information on their supply. Many agricultural services can be formulated as Web services using some suitable technology. Services with physical constituents, such as soil analysis, can still provide information exchange through Web services. Automated compliance control relies extensively on services to provide information for the process.

Providers of information systems

Providers of FMIS are the invisible stakeholder that must consider all other stakeholders. They must design their systems with everyone in mind. Interfaces need to be provided for farmers and advisors, services and other information systems. Designing new systems and services is always a challenge, especially with the contemporary lack of standardised data formats in agriculture. Therefore, considerable co-operation is required between stakeholders, particularly between different providers of information systems. For automated compliance control, the providers must provide sufficient data integration for the process to be beneficial and useful.

2.2 Requirements

To understand the large-scale operation of agricultural information systems as a whole, abstract methods, such as system analysis are required (Fountas et al. 2009). Moreover, due to the complexity and scale of agricultural information systems, any individual method is unlikely to produce a usable set of requirements. Therefore, requirements should be drawn through various methods, such as user-centric approaches to information modelling (Sørensen, Pesonen et al. 2010), or by identifying information flows between the information systems and stakeholders (Fountas et al. 2006). These information flows are further complicated by the introduction of precision agriculture (Nash, Dreger et al. 2009), which imposes additional technical requirements. While the identification of information flows and system models produces requirements for the complete system, many of the functional requirements are still drawn from the requirements of individual stakeholders.

2.2.1 Requirements of the stakeholders

Following are the requirements of the stakeholders relevant to the purposes of this thesis. These requirements are considered in the order of the topics in this thesis. The requirements of the stakeholders are further elaborated in Publication I and Publication IV, correspondingly for general FMIS and automated compliance control.

Farmers

As the principal and most diverse stakeholder, farmers also impose the majority of the requirements on information systems. Agricultural systems must be highly localised in both language and units, with consideration to local agricultural practices. This implies a significant localisation effort, which perhaps explains why so many agricultural information systems are local rather than localised. The information system must also be available, or appear available, at all times for important field operations. Technical issues such as poor Internet connectivity should not prevent field work. Additionally, usability is a critical factor in agricultural information systems, since it is unrealistic to extensively train the large corpus of farmers in the use of these systems. Agricultural services, on the other hand, communicate with the FMIS rather than with the farmer directly. Therefore, farmers should be considered in the FMIS user interface, rather than in the technical interfaces of services. In fact, many services can appear as FMIS features or exchange information with the FMIS without user intervention. Farmers require similar convenience from automated compliance control, i.e. automated compliance control should reduce the administrative burden of farms. The entire process should also appear transparent enough so that farmers can read the requirements of compliance and choose which production standards, possibly international ones, are relevant to their production.

Authorities

Authorities, who monitor farming activities, require access to farm data. Particularly, they require information on the use of fertilisers and pesticides, the use of which is restricted by legislation. Since this information resides in the FMIS, authorities should have a privileged access to it. Ideally, information could be made available through a service interface, i.e. the FMIS acting as a Web service that is queried by the information systems of the authorities. Authorities also require access to the results of automated compliance control, thus, much like the farm data, these results should be made available as a service.

Customers of farms

Customers of farms generally require information on the traceability and quality of the produce they are purchasing. As with authorities, this information could ideally be made available through a Web service interface in the FMIS. In automated compliance control, customers who impose their own production standards have requirements identical to the authorities pertaining to the results of automated compliance control.

Suppliers of farms

Suppliers of farms, on the other hand, require means to transfer information on their products to the FMIS. These products are the same substances which the authorities, and to an extent the customers of the farm monitor. Hence, information on their composition is essential for several stakeholders and suppliers want to provide this information to the FMIS through Web services.

Service providers

The information exchange for many services in agriculture can be modelled as Web services using some suitable technology. Web services are involved in automated compliance control, as much of the information exchange occurs between the FMIS and Web services. Providers of Web services are closely related to the providers of information systems. After all, Web services are small-scale information systems which necessitate interaction with the FMIS.

Providers of information systems

Providers of FMIS require specifications on the data formats used by various stakeholders, as it is generally up to the FMIS to perform much of the actual data integration. This also applies to service interfaces and requires significant co-operation between the providers of FMIS and other stakeholders. The service interfaces of the FMIS are particularly problematic as they can be used by several different stakeholders, who might not agree on interfaces or data formats. This issue of data formats is particularly crucial for automated compliance control, where the providers of FMIS require detailed schemata from other stakeholders whose data is used in the process.

2.2.2 Non-functional technical requirements

In addition to the specific functional requirements of the stakeholders, several non-functional technical requirements are also necessary for modern agricultural information systems. These generally desired features include openness, simplicity, the use of known and standardised formats and a general preference to existing technologies whenever possible. Together, these requirements aim to promote greater interoperability between systems and ease the implementation of new systems.

2.3 Farm management information systems

When considering agricultural information systems, services or the information flows in agriculture, the FMIS has a central role. Almost all stakeholders in agriculture are involved in significant communication between themselves and the FMIS, which contains all of the farm data and is the system involved in all farming operations. Thus, the FMIS should have interfaces for all stakeholders and each stakeholder should have an interface to the FMIS. These need not be distinct interfaces, as they may only differ in the availability or representation of information.

As information systems, FMIS have evolved significantly from the earliest implementations. The current state of FMIS could be described as early transitory between on-site software and online software based on Web technologies.

2.3.1 Historical FMIS

First FMIS were little more than electronic ledgers, designed to replace paper bookkeeping (Lewis 1998). As such, these early information systems were not unlike those seen in other domains. That is to say, they had little significant agriculture specific functionality.

2.3.2 Current FMIS

Contemporary FMIS have reached a state where they are widely recognised as an integral part of agricultural production, used globally in all areas of agriculture (Ascough II et al. 1999, Batte 2005, Alvarez & Nuthall 2006, Lawson et al. 2011). The vast majority of these FMIS are ordinary on-site software operating on the farm personal computer. Consequently, there is little use of the Internet or connectivity through Web services. Providing decision support for the farmer is a common feature of FMIS. These integrated decision support systems (DSS) can be quite complicated in their operation (Clavel et al. 2011). On the other hand, DSS are often targeted for some very focused function such as variable rate application in precision agriculture (Havlin & Heiniger 2009). While the benefit of agricultural DSS to farmers has been questioned (Matthews et al. 2008), it is common for farmers to employ decision support either from DSS or agricultural advisors.

FMIS can also support other technologies, such as RFID (radio-frequency identification) in the context of husbandry (Ruiz-Garcia & Lunadei 2011). In these cases, much of the FMIS usually operates around the particular technology (Voulodimos et al. 2010). However, even highly specialised FMIS still support the same bookkeeping and reporting functions as general FMIS. The role of these reporting features can be expected to rise as legislation evolves and farms become increasingly more multi-disciplinary in their operation. While most existing FMIS are on-site software, Web-based approaches to commercial FMIS are already available.

2.3.3 Emerging and future FMIS

Future FMIS are characterised by significantly increased information processing (Sørensen, Fountas et al. 2010), as well as utilisation and interconnectivity through the Internet (Kaloxylos et al. 2012). For precision agriculture, such information systems are a prerequisite and the extent of their functionality can only be expected to increase (McBratney et al. 2005). The process of transition for FMIS started in agricultural decision support systems, which can be seen as a function of modern FMIS (Kitchen 2008, Antonopoulou et al. 2010).

Web-based FMIS, such as the one considered in Publication I, have precedents in the recent literature. They are often focused on some specific task such as vineyards management (Blauth & Ducati 2010), or electronic poultry management (Sallabi et al. 2011). Web-based FMIS exhibit significant interconnectivity with other systems. Hence, they are generally considered in the context of Web services and service-oriented approaches (Murakami et al. 2007). Extensive and increasing interconnectivity also poses new technical challenges, particularly for data integration which has generally not been an issue in the earlier offline systems.

2.4 Service-based approaches

2.4.1 Services in agriculture

Services are already a part of agriculture, spanning from information services such as soil analyses, to more concrete services such as contracted field work. Services consisting primarily of information exchange include news on pests, composition of fertilisers, pesticides or the capabilities of farming equipment.

All this information exchange with services involves the FMIS as the central information system, storing, receiving and presenting information to the user. Prior to the Internet, many of these services, particularly soil analyses, operated by mail and the information received in the response would then be manually input to the FMIS. A more advanced form of this information exchange would be a file as an e-mail attachment, though ultimately, the arrival of information such as the results of soil analyses should be presented to the user as news rather than tasks.

2.4.2 Web services in agriculture

Due to the lack of standardisation, many of the services in agriculture that involve digital information exchange use diverse interfaces and formats that should be adapted to the FMIS. This accounts to additional work in the form of increased data integration.

For many services in agriculture, the deployment of Web services is a reasonable approach to an efficient exchange of information. A Web service by itself, is a somewhat vague term, which does not really specify any technology beyond the common Internet protocols. However, Web services generally fall into two categories, those of the SOA-family (service-oriented architecture) and REST-based approaches (Fielding 2000). While the former provide a large set of features, the latter are popular due to their inherent simplicity and have also gained significant attention in research. Semantic frameworks have been established for REST (Marinos & Krause 2009) and methodologies have been developed for the engineering of REST-based services (Selonen 2011). Semantic descriptions, identical to those available for SOA have also been extended to REST (Fensel et al. 2011).

Considering the level of interaction involved in agricultural services, such as obtaining weather information, results of soil analyses or the transfer of yield maps, the use of complicated communication protocols is rarely indicated. Rather, the exchange of information most commonly consists of stateless queries and replies, which further supports and explains the current interest for REST in the literature. Studies have already been published where REST has been successfully used for agricultural services (Martini et al. 2009), although other technologies have also been used successfully (Gocic & Trajkovic 2011). With precision agriculture, farming equipment become a notable source of data that must be incorporated to the already existing information flows in agricultural information systems (Steinberger et al. 2009).

2.5 Precision agriculture

Precision agriculture, facilitated largely by technical advances in farming equipment and information systems, is the next expected significant shift in agricultural production. Conceptually, precision agriculture corresponds to handling fields in units smaller than the field itself, or handling livestock as individuals rather than as flocks or herds. Therefore, rather than applying the same amount of fertiliser, pesticide or seeds uniformly on fields, a position-specific amount is applied. Precision agriculture, properly implemented, promises identical or improved yields with increased profits and reduced ecological impact. This improvement is achieved through reductions in the use of materials such as fertilisers or pesticides. Nevertheless, studies have been published that question the overall profitability of precision agriculture (Boyer, Wade et al. 2011), as well as the actual benefits from wide-scale adoption of precision agriculture (Wathes et al. 2008).

Implementing precision agriculture is a considerable technical challenge in agricultural engineering (Stafford 2000). Farming equipment must support variable rate operations and the equipment must be controllable based primarily on position. This control can also involve additional parameters such as online measurements, though the basis for the control lies primarily in precalculated operation plans. These operation plans are the result of optimisation and combination of several data sources, including yield maps from previous years (Naudé et al. 2012). The quantity of information in precision agriculture makes digital information transfer and processing a necessity rather than a convenience. Theoretically, in the context of information technology, the difference between traditional and precision agriculture is the use spatial data in place of scalar values. Thus, GIS (geographic information system) data is introduced to agriculture in significant quantities (Bill et al. 2012), which explains why precision agriculture is also known as information intensive agriculture. The use of GIS in agriculture is not unique to precision agriculture, as applications for GIS have been proposed outside of precision agriculture (Cook & Norman 1996).

Precision agriculture is unlikely to make a radical surge, but rather increase steadily as new equipment and technologies are adopted by farms. After all, replacing expensive pieces of working farming equipment, such as tractors, is seldom worth the possible financial benefits of precision agriculture. On the other hand, new equipment generally support precision agriculture, thus steadily increasing the potential for wide-scale adoption of precision agriculture. However, despite the considerable technical prerequisites of precision agriculture, technology alone is not the deciding factor in the adoption of precision agriculture. Research has shown that the adoption of precision agriculture depends also on the training and attitudes of farmers towards precision agriculture (Lamb et al. 2008, Kutter et al. 2011, Adrian et al. 2005, Isgin et al. 2008). These socio-economic aspects in the adoption of precision agriculture are seldom global. Hence, the adoption of precision agriculture and the factors affecting this adoption have been studied locally, where research and surveys have identified several regional and cultural variables (Daberkow & McBride 2003, Reichardt et al. 2009, Reichardt & Jürgens 2009, Robertson et al. 2012, Fountas et al. 2005, Silva et al. 2011). Thus, precision agriculture can not be adequately considered within just a technical scope.

2.6 Production standards in agriculture

Agricultural activities have a significant effect on the local ecology, especially when chemicals and other substances are introduced on the fields. For controlling this ecological impact, and assuring the safety and quality of agricultural produce, agricultural activities are governed by legislation and additional production standards. Compliance with legislation is commonly tied to the payout of farm subsidies, which in several regions are vital for the economy of farms (de Graaff et al. 2011). While large administrative regions, such as the European Union have a somewhat unified agricultural legislation, there are still regional variations to address local issues. Of the European agricultural legislation, the most significant production standard is cross-compliance, maintained by the European commission for agriculture and rural development[1]. Consequently, tools in the form of information systems, have been developed for assessing the ecological and economic impacts of cross-compliance (Bouma et al. 2010). Enforcement of production standards, such as cross-compliance, should generally be considered together with agricultural policies and national politics (Nitsch & Osterburg 2008).

Cross-compliance and other production standards have been studied both in their effect of reducing the ecological impact (Nitsch et al. 2012), as well as farms acceptance and compliance with them. Due to their restrictive nature and considerable administrative requirements, these production standards are not always welcomed by farmers (Sattler & Nagel 2010, Herzfeld & Jongeneel 2012, Davies & Hodge 2006). In addition to the production standards from legislation, i.e. where failure to demonstrate compliance carries legal consequences, there are also voluntary production standards. These voluntary standards, which by definition are more restrictive than legislation, are also more specific in their purpose. Examples might include increased traceability of produce or organic production, where the use of several otherwise legal chemical fertilisers and pesticides is further restricted. Large retailers of agricultural produce might also have their own sets of restrictions. Though voluntary, many farms adhere to these additional production standards as produce which is grown, e.g. organically, generally carries a higher revenue. When agricultural produce is sold to foreign markets, the producing farms may be required to show compliance with the production standards of both the production as well as the market country, which incurs an additional administrative burden on these farms.

[1] http://ec.europa.eu/agriculture/envir/cross-compliance/index_en.htm

2.7 Technology of automated compliance control

Determining compliance with production standards is currently a largely manual process, involving paper forms and official inspections. In addition to imposing an administrative burden on farms, significant costs are associated with the overall process (Varela-Ortega & Calatrava 2004). However, as discussed in Publication II, compliance with a significant portion of these production standards could be assessed automatically. Thus, with little to no human interaction, data collected during farming operations could be used to show compliance with production standards. The formulation of production standards as rules, the categories and relations between these rules, and restrictions on the encoding process are considered in Publication II. Some parts of production standards are generally abstract by purpose, an individual rule such as "do not pollute the environment" can not and should not be automatically assessed. On the other hand, rules that limit dates, chemicals or distances of fertiliser application from water bodies can be automatically assessed. Since individual field operations are commonly not monitored by anyone except the farmer doing the work, such rules can actually be assessed better automatically from the recorded data. While this raises certain issues, such as the reliability of the recorded data, automatic compliance control is potentially beneficial for all stakeholders in agriculture, particularly for farmers.

2.7.1 Encoding of agricultural production standards

A principal requirement for automated compliance control is having the agricultural production standards available in an encoded format that can be used as input for a computer inference system. For this, the production standards must be represented as collections of individual rules. The encoding to this representation must be done by hand from the natural language of the production standards, using human judgement to decide which parts of the production standards can or should be encoded. These rules and their interchange are closely related to logic programming, a field of computer science (Kifer 2011*b*, Boley et al. 2007). Similar rule encodings have appeared in the literature of other domains (Boyer, Mili et al. 2011), such as in the encoding of general legislation (Gordon et al. 2009). Use of rules is rare though not unprecedented in agriculture, as they have been used to provide the internal functionality of agricultural decision support systems (Shaffer & Brodahl 1998).

Interchangeability is a principal requirement for the format used to encode agricultural production standards. Several interchangeable rule formats exist and the research presented in this thesis utilises the relatively recently standardised W3C rule interchange format (RIF) (Kifer 2011*a*, Boley et al. 2007). RIF is a somewhat minimal rule format, divided into several dialects which share a common RIF Core dialect. The other dialects, the production rule dialect (RIF PRD) and the first order logic dialect (RIF BLD), provide additional rule expressions with reduced theoretical decidability of inference. The challenge with agricultural legislation is that many of the encoded rules turn out inherently spatial, i.e. they impose restrictions on areas and distances. Since spatial rule interchange formats were not otherwise available, the aforementioned RIF was extended with spatial functionality as described in Publication III to produce the necessary spatial rule interchange format.

2.7.2 Spatial computer inference

Spatial computer inference is a field of computer science encompassing logic programming and geographic information systems. Spatial inference can be used to determine the validity of a logical statement within a set of spatial data, or be used to discover and deduce new relations in the data (Abdelmoty et al. 1993, Lutz & Kolas 2007). Similar functionality can be used for knowledge representations or reasoning within a GIS (Mancarella et al. 2004). Non-spatial inference is a relatively mature field of research that has spawned several logic programming languages and environments, of which PROLOG is the most well-known. Spatial inference, on the other hand, has received much less attention in research. Systems capable of spatial inference, such as Spatial-Yap (Vaz et al. 2007), exist, though mostly as spatial extensions to PROLOG, which significantly reduces their applicability for inference with interchangeable rules. Spatial computer inference, which is the principal topic of Publication V, necessitates precise data integration over several different data sources, which is a considerable technical challenge in the agricultural domain.

2.8 Data integration in precision agriculture

Exchange of data between information systems requires either common data interchange formats or extensive data integration. Currently, no standardised or widely accepted data interchange formats or common data models exist for agriculture. Therefore, agricultural information systems, which have mostly been developed in isolation, exhibit various schemata and data formats. Though interchangeable data formats have been proposed and developed for agriculture, such as agroXML (Schmitz et al. 2009), they have been met with limited success. Standardised formats generally exist only within restricted scopes, such as the XML formats used with ISOBUS farming equipment. Therefore, the need for data integration is a fundamental requirement of agricultural information exchange between systems, and likely remains so in the foreseeable future.

Data integration in agriculture is as diverse as the available data formats, spanning from tools developed for the integration of XML documents to solutions based purely on programming. The problem of data integration has already been established in research and can be considered within a service-oriented architecture (Wolfert et al. 2010). There are also examples of integrated databases (Janssen et al. 2009), where data from diverse sources is collected to a common database and integrated with an ontology-based approach. Some studies focus on a particular aspect of agriculture, such as the integration of metadata in agricultural learning resources (Manouselis et al. 2010), where concepts are integrated using metadata application profiles. Data integration through a database has also been proposed for device data (Iftikhar & Pedersen 2011). Future applications of data integration in agriculture can benefit from the common terminology provided by the agricultural vocabulary AGROVOC, defined and maintained by the United Nations (2005). In precision agriculture, the use of open geospatial Web services can provide interoperable spatial data (Nash, Korduan & Bill 2009), thus reducing the required data integration.

With precision agriculture and spatial data, the problem becomes one of spatial data integration. Spatial data integration has been studied extensively in the context of general GIS with approaches similar to some of those seen in agriculture (Abel et al. 1998, Bareth & Doluschitz 2010, Gotway & Young 2002). Recently, semantic approaches, knowledge-based methods and particularly ontologies have gained popularity in the research (Smart et al. 2007, Janowicz et al. 2010, Maué & Schade 2009). Data integration has also been studied on the large-scale, in the context of complete spatial data infrastructures (SDI) (Mohammadi et al. 2010). Lower-level spatial data integration generally addresses the integration of individual documents. The document format used in these studies is generally GML, which is a well-established XML-based data format for both spatial and non-spatial data. Knowledge-based methods for the data integration of GML commonly use the resource description framework (RDF), which can be served together with GML to provide efficient metadata (Page et al. 2009). RDF can also be used to directly integrate spatial XML (Córcoles et al. 2003), or as a query tool to extract information from spatial XML (Córcoles & González 2004).

3. Results

This chapter summarises the results from the journal articles and groups them according to the research objectives stated in Chapter 1. The chapter advances from the most general topic, i.e. FMIS for precision agriculture, to agricultural Web services and ends in the spatial inference engine at the core of automated compliance control. This is also the order of the conceived applicability of these results on a longer time frame. Precision agriculture requires an FMIS, agricultural Web services communicate with the FMIS and automated compliance control is only feasible with an all but complete agricultural information infrastructure. Each result includes an evaluation of the proposed design and is accompanied with a description of the software prototype used for the evaluation.

3.1 FMIS for precision agriculture

3.1.1 The design

The FMIS for precision agriculture is a complicated and interconnected system, involved in almost every information flow. The requirements and design of an FMIS for precision agriculture are the topic of Publication I. This FMIS has numerous stakeholders, each with their respective requirements and concerns for the overall functionality. As the central information system, the FMIS is expected to communicate with other stakeholders, provide data integration and access to stored farm data. While traditional FMIS have largely been on-site software operating on the farm personal computer, amongst the requirements of precision agriculture are high availability and extensive communication. This justifies reconsidering the on-site approach in design. Particularly for communication with the farming equipment, on-site software would be hard put to provide a feasible connection with the tractor TC.

The stakeholders in an FMIS include most actors in the agricultural domain. Selected stakeholders and their concerns are listed in Section 2.1 of this thesis and a more complete listing of the recognised stakeholders can be found in Publication I. Common to most of these stakeholders is the need to communicate with the FMIS. This communication can occur through a user interface, for such stakeholders as farmers or farming advisors. Alternatively, the communication can take place through service interfaces for such stakeholders as service providers, farming equipment manufactures or providers of fertilisers, pesticides and other chemicals used in agriculture. While much of the comparable communication can occur over non-digital media in traditional agriculture, the spatial data in precision agriculture necessitates digital transfer.

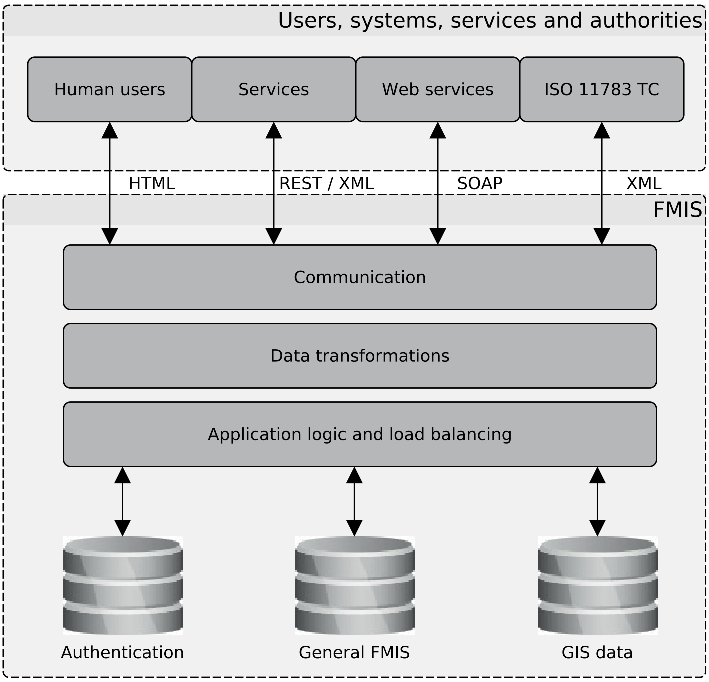

Figure 3.1. Internal architecture of the FMIS.

Figure 3.1 illustrates the overall architecture of an FMIS for precision agriculture, designed as a Web application. The architecture can be divided into three significant layers: interfaces and communication, data management, and data storage. Compared to traditional FMIS, the most significant differences are the GIS extensions and an increased need and complexity of digital communication. Spatial data, in particular, requires significant storage, processing and transfer capability uncommon in traditional agriculture.

As a centralised system, the FMIS for precision agriculture stores the data of several farms. This includes general FMIS data, a legacy of traditional agriculture still relevant in precision agriculture, as well as the spatial data inherent to precision agriculture. Thus, the FMIS for precision agriculture is essentially a GIS with storage, processing and exchange of spatial data through multiple interfaces. The spatial data should be stored in a dedicated GIS database, such as PostGIS (2005), which are generally more suitable for storing and managing spatial data than general relational database management systems (RDBMS). This separation of storage also facilitates the implementation of the FMIS for precision agriculture as an extension to existing Web-based FMIS.

One of the most important and distinct features of a Web-based FMIS for precision agriculture is the plethora of interfaces to the system. These include communication with people in different roles, on-farm sensors, Web services based on various technologies and ISOBUS farming equipment. For human users, such as farmers, farming advisors or contractors; ordinary Web interfaces are the norm, intended to operate with the Web browsers available on modern personal computers. Additionally, separate Web interfaces to the FMIS are required for farmers using mobile devices such as smart phones or tablets when browsing fields or accessing the farm information from other locations, such as the tractor. Web services, which are also utilised in automated compliance control, form another significant group of interfaces. These interfaces are largely service specific, based on the simple object access protocol (SOAP), REST or some other Web service technology. These further include interfaces where the FMIS is acting as a Web service for other systems. This information service functionality of the FMIS is essential, for example to authorities who monitor farming activities. Web services and Web service interfaces are considered more thoroughly in Publication IV. The ISOBUS interfaces are unique to precision agriculture and utilise the ISOBUS XML-format for two-way communication between the FMIS and ISOBUS equipment.

3.1.2 The prototype

Since actual FMIS are products of large commercial software projects, any prototype implementation inherently has a narrow scope. The prototype for this result consisted of a small-scale information system that mimics the FMIS in communication with the tractor TC during precise fertilisation. Hence, the prototype can fulfil the role of an FMIS in a precise fertilisation operation. This focus restricts the prototype to functionality unique to precision agriculture, i.e. exchange of spatial data in the form of operation plans and documents.

The prototype utilised a lightweight communication protocol that permitted simple queries and file transfer between the tractor and the FMIS, intended for convenient implementation in the programming environment of the tractor TC. This protocol supported persistent connections that could be transparently resumed when the GSM-based Internet connection in the tractor was lost for any reason. However, in production use, the more common Web service based approaches would likely be more beneficial than a specialised protocol. The prototype additionally contained an ordinary browser interface that could be used to view and download the stored files without utilising the protocol intended for communication with the tractor TC.

3.1.3 Evaluation

The prototype was evaluated for correct functionality in the communication between ISOBUS farming equipment and the FMIS during the execution of a precise fertilisation operation. Precise fertilisation, as discussed in Section 1.3.1, is the use case considered most general in precision agriculture. The digital transfer of operation plans and documents is also a specific technical prerequisite of precision agriculture. For the evaluation, a client implementation to the prototype information system was provided by MTT Agrifood Research Finland, who also operated the field equipment. The workflow of the evaluation entailed parts of the execution phase of precise fertilisation (Sørensen, Pesonen et al. 2010). This consisted of the tractor obtaining the operation plan, i.e. the spatial application map for the fertiliser from the FMIS; querying weather values such as wind speed which, if excessive, could contra-indicate the spraying of the fertiliser; performing the actual field operation and finally storing the operation document on the FMIS. The operation plan and document in the evaluation were the planned and realised spatial applications maps for the fertiliser, with additional information for directing the ISOBUS fertilisation equipment. The communication took place between the prototype information system and the tractor TC, guided by the user interface on the VT. The tractor had Internet connectivity through the GSM network.

The entire design for the FMIS was additionally evaluated by comparing it with other published and related systems. These systems, discussed previously in Section 2.3.3, are the occurrences from the literature for future FMIS and other information systems in precision agriculture. Murakami et al. (2007) present a service-oriented FMIS, whereas Sørensen, Fountas et al. (2010) consider the functional requirements of an FMIS. FMIS are further considered in the context of data collection by Steinberger et al. (2009) and Peets et al. (2012), and as part of a larger information infrastructure by Wolfert et al. (2010). Web-based design is also used for agricultural DSS, an application closely related to FMIS, by Antonopoulou et al. (2010).

3.1.4 Results of the evaluation

The precise fertilisation operation and the included communication were successfully completed with the prototype information system. The operation plan was transferred to the tractor prior to the operation and the operation document was uploaded after the operation. This evaluation demonstrates the feasibility of communication between the ISOBUS tractor and a Web-based FMIS, which is a prerequisite for precision agriculture. As described in Section 1.3.1, precise fertilisation forms a general use case for precision agriculture as the application maps and documents are comparable between different field operations. Hence, the communication with ISO 11783 equipment is applicable to other field operations. The consensus in the recent literature would appear to favour Web-based approaches to FMIS; a significant likely factor to this is the increasingly more central role of the FMIS as a highly-available information system (Sørensen, Fountas et al. 2010).

Compared to other instances of FMIS, the service-oriented approach by Murakami et al. (2007) is focused on communication over their proposed AgriBUS service bus and does not consider general FMIS functionality. In studies on agricultural data collection, from either on-farm sensors or farming equipment, the availability of a Web-based FMIS is generally assumed (Steinberger et al. 2009, Peets et al. 2012). These studies thus support the Web-based FMIS design. Research on agricultural DSS also seems to move towards Web-based design (Antonopoulou et al. 2010). The Web application approach could also replace the on-site FMIS in conceived future architectures, such as that by Wolfert et al. (2010), without apparent impediments.

3.1.5 Summary of the result

A comprehensive design for a general Web application FMIS as an extension to existing and established FMIS functionality.

The requirements of the stakeholders in precision agriculture are fulfilled through several diverse Web-based interfaces; these include people in various roles and other information systems and services.

The spatial functionality in precision agriculture is realised throughout the FMIS design; in separate GIS storage, spatial data processing and the exchange of spatial data.

The communication between the Web application FMIS and ISOBUS farming equipment is feasibly provided with Web technologies.

3.2 Web services for automated compliance control

3.2.1 The design

Publication IV covers a service infrastructure for the discovery, distribution and evaluation of agricultural production standards. These standards are represented as logical rules suitable for computer inference, enveloped within an XML document described in Publication II. This publication also considers the overall feasibility of automated compliance control and concludes that compliance to a significant portion of agricultural legislation could be evaluated automatically. Automated compliance control for a rule is restricted by the content of the rule, i.e. the feasibility of formulating the rule as a logical statement. Some rules are intentionally vague and thus incompatible with any degree of automation by requiring human judgement. In addition to the rule content, the other restricting factor is the conceivable availability of suitable data for evaluating the rule. When these are both taken into account, the percentage of the total agricultural legislation that could be automatically assessed is established above 80% in Publication II. The rules encoding the agricultural legislation are expressed in GeoRIF, a true spatial superset of RIF. The GeoRIF format is specified in Publication III, which contains full listings of the spatial predicates and functions available in GeoRIF, as well as examples and conceived applications for the format beyond the encoding of agricultural legislation. Listing 3.1 is an example of one agricultural production rule, encoded from German legislation and shown in the GeoRIF presentation syntax. The distributed GeoRIF rules used for inference are verbose XML documents and not in the presentation syntax. An example of the GeoRIF XML format can be found in Publication III.

Listing 3.1. A German agricultural production rule expressed in GeoRIF.

```
Forall ?app ?wb ?sl (
  violation(duengeverordnung:2009-07-31) :- And (
    ?app#agrovoc:FertiliserApplication
    ?wb#geovoc:WaterBody
    ?sl#duvo:SteeplySlopingArea
    ?app[agrovoc:appliedFertiliser->?appF]
    ?app[agrovoc:applicationArea->?appA]
    ?app[agrovoc:sprayingEquipment->?appE]
    ?wb[geovoc:topBankLine->?tbl]
    ?sl[geovoc:boundary->?bnd]
    ?appF#duvo:FertiliserWithSignificantNutrientContent
    Or(External(geopred:dist_within(?appA ?tbl 1m))
       And(?appE#agrovoc:SprayerWithoutLimitingDevice
           External(geopred:dist_within(?appA ?tbl 3m)))
       And(External(geopred:within(External(geofunc:buffer(?tbl 20m))
                                            ?bnd))
           Or(External(geopred:dist_within(?appA ?tbl 3m))
              And(?appE#agrovoc:SprayerWithoutDirectInjection
                  External(geopred:dist_within(?appA ?tbl 10m)))))))
```

The GeoRIF rule in Listing 3.1 restricts the application of nitrogen rich fertilisers near water bodies. With special equipment, such as a sprayer with a limiting device or a direct injection mechanism, spraying is permitted closer to water bodies. Evaluation of this example rule requires information on the fertilisation operation, either planned or documented, spatial information on the fields, water bodies and steeply sloping areas, as well as information on the composition of the fertiliser and the capabilities of the spraying equipment.

Figure 3.2 shows the systems and services involved in automated compliance control. Farm information is expected to reside within the FMIS, which is also the central information system in automated compliance control. The service infrastructure for automated compliance control consists of three services: catalogue services, rule services and evaluation services. Catalogue services provide discovery of rule services and other catalogue services through various criteria, including spatial queries. Rule services contain the encoded production standards in the XML format described in Publication II. The evaluation services provide the spatial inference necessary for determining compliance. The service division follows the stakeholders in automated compliance control with minimal co-operation between the stakeholders with the catalogue services and the independence of the rule services. Hence, any publisher of agricultural production standards or legislation could provide their own rule service instance. The entire process of automated compliance control is driven by the FMIS, through functionality delegated to a compliance control module. The workflow of this process, given in Figure 3.3, follows the phases of precise fertilisation set forth by Sørensen, Pesonen et al. (2010).

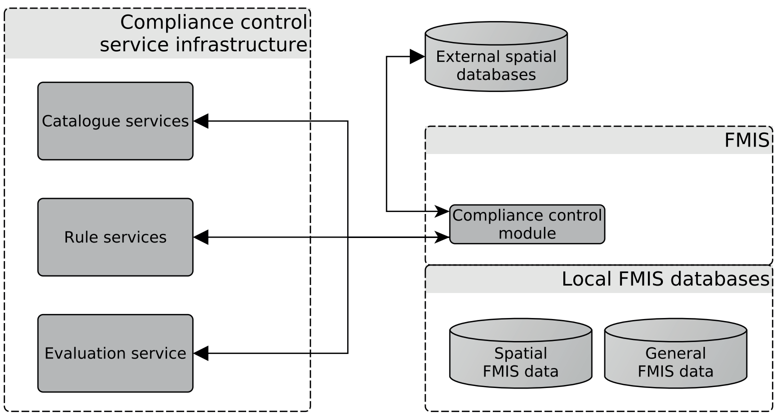

Figure 3.2. The infrastructure for automated compliance control.

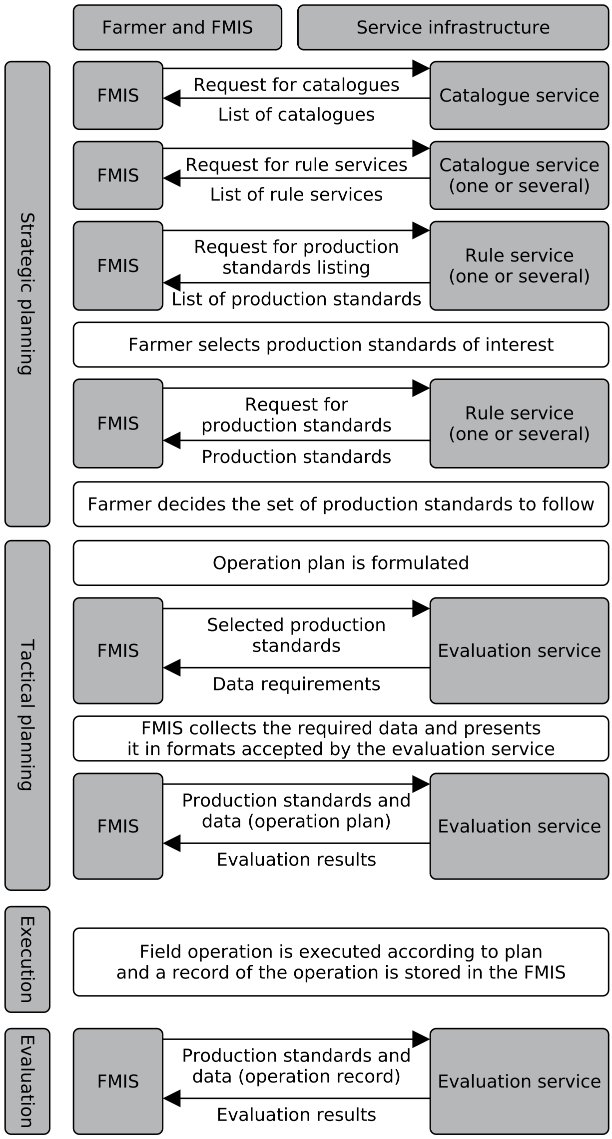

Figure 3.3. Workflow of automated compliance control.

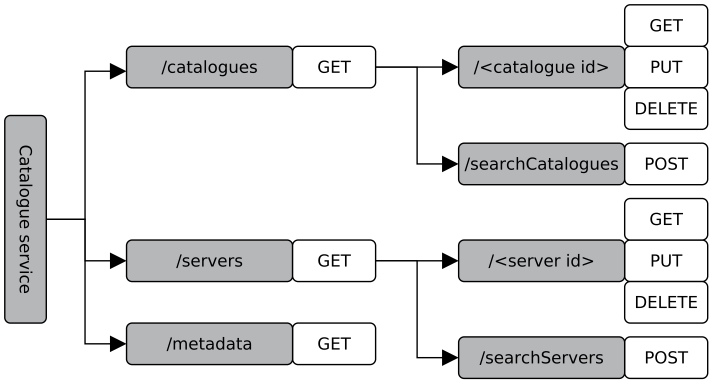

Figure 3.4. Logical REST structure of the catalogue service.

All services in the infrastructure provide REST interfaces. The structure of one such interface, for the catalogue service, is shown in Figure 3.4. The structure of the other services is presented, using the same notation, in Publication IV. The interface shows the resources and valid REST-operations for each resource. Catalogue services and rule services are accessible by identifiers and the interface supports the insertion and removal of individual entries.

3.2.2 The prototype

All three services of the presented infrastructure were implemented as prototypes in the Ruby programming language using the Ramaze Web framework. This was a labour-saving approach that rapidly resulted in the specified functionality for each service. The spatial operations in the catalogue and rule services were obtained through PostGIS, a spatial database management system. A German commercial FMIS provider supplied a client implementation for the infrastructure that was used in the evaluation of the design.

3.2.3 Evaluation

The proposed design was evaluated for correct functionality and feasibility using a service infrastructure constructed with the prototype implementations. This infrastructure consisted of several instances of the catalogue and rule services, with one instance of the evaluation service. These services were then populated with German national agricultural legislation (Düngeverordnung); selected parts of which were encoded in GeoRIF for further use with the evaluation service. The selection of these encoded parts was made on a technical basis to intentionally exhibit a diverse range of GeoRIF rule expressions, spanning from spatial to quantitative and temporal rules. The infrastructure could then be used through the client implementation, which was also presented at an agricultural engineering conference in Cologne, Germany in 2010. This client implementation featured the conceived real workflow of automated compliance control, as described in Figure 3.3, using data from the FMIS combined with data collected from services. The interface permitted the user to search for agricultural production standards and select standards of interest for further study or evaluation.

The proposed service architecture and the utilisation of Web services in agriculture was also evaluated using comparable instances from the recent literature. Since Web services are generally considered in the context of the larger agricultural information infrastructure, many of the studies addressing Web services are the same which address general FMIS. Hence, many of the same studies as in the preceding section are useful for evaluating Web service designs in agriculture. These include the service-oriented FMIS by Murakami et al. (2007), the service-oriented architecture by Wolfert et al. (2010) and agricultural data collection by Steinberger et al. (2009) and Peets et al. (2012). Additionally, there are reports where service-oriented approaches have been applied in agriculture without significant ties to a larger information infrastructure, such as the study by Gocic & Trajkovic (2011).

3.2.4 Results of the evaluation

The service infrastructure, constructed with the prototype services and together with the client implementation, successfully completed the workflow of automated compliance control, which suggests an overall functionality of the design. The REST interfaces, despite their simplicity compared to SOA-based solutions, were able to provide the sufficient functionality[1]. None of the involved prototype implementations were particularly complicated pieces of software, which is indicative of a general simplicity of the design. Furthermore, the service infrastructure implemented the full functionality of the design, with notable computation involved only in the spatial queries. Hence, a comparable implementation could be used to implement the actual service infrastructure for automated compliance control. The presented service infrastructure could be adapted to rule management in other domains with similar functional requirements.

[1] A representative of the German FMIS company found the specified REST interfaces "pleasant to work with."

Compared to the studies in the literature, such as that of Martini et al. (2009), the use of REST in agricultural services is not unprecedented, although SOA-based technologies have been likewise successful (Gocic & Trajkovic 2011). The role of Web services is also recognised in the conceptual model for future FMIS by Sørensen, Fountas et al. (2010). The service-oriented FMIS by Murakami et al. (2007) take the role of Web services further by defining a common AgriBUS service bus. In the future, such integrated approaches to agricultural services could alleviate the present problems with data formats and data integration. Data interoperability, which is a significant factor of information exchange in domains without established data interchange formats, such as agriculture, has also been successfully achieved with Web services (Wolfert et al. 2010), albeit with the SOA-family of technologies. Web technologies are also assumed in studies that consider the collection of agricultural data from on-farm sensors or farming equipment (Steinberger et al. 2009, Peets et al. 2012). The FMIS presented in the previous section supports Web services and supports diverse interfaces to various Web service technologies. Any Web service technology, which in practice is usually either REST or some part of the SOA-family, can be successfully used for agricultural services. However, the relative simplicity of REST could be beneficial to system interoperability in domains without established data interchange formats.

3.2.5 Summary of the result

An encoding scheme based on GeoRIF for agricultural production standards; the compliance to at least 80% of these standards could conceivably be evaluated automatically in the foreseeable future.

A complete service infrastructure for the discovery, distribution and evaluation of agricultural production standards for automated compliance control.

The communication in automated compliance control was achieved with the presented service infrastructure using REST interfaces, with the functionality of individual services divided according to the stakeholders.

The proposed solution provides the technical framework required for the conceived realistic workflow of automated compliance control.

3.3 Spatial inference for automated compliance control

3.3.1 The design

Publication V addresses the spatial inference necessary for automated compliance control. This functionality is provided with an inference engine capable of spatial inference with an interchangeable rule format. In addition to the inference engine core, the design contains three essential components: support for an interchangeable rule format, data integration and spatial computation. The interchangeable rule format used by the inference engine is GeoRIF, specified in Publication III and discussed previously in Section 3.2. The GeoRIF rule format is also used as the native language of the inference engine. This approach was made possible by the close resemblance of RIF to logic programming languages. Not having to translate rules to e.g. some instance of PROLOG with spatial extensions, also enables efficient approaches to data integration; an essential feature in inference with rule interchange. The design specifies a data integration scheme for GML, utilising common vocabularies and an intermediate RDF representation for the non-spatial content in GML. The spatial functionality in the design is achieved through an external spatial software library; based on the same OGC-SFA functionality as GeoRIF. This approach yields spatial operations in an efficiency comparable to other GIS systems.

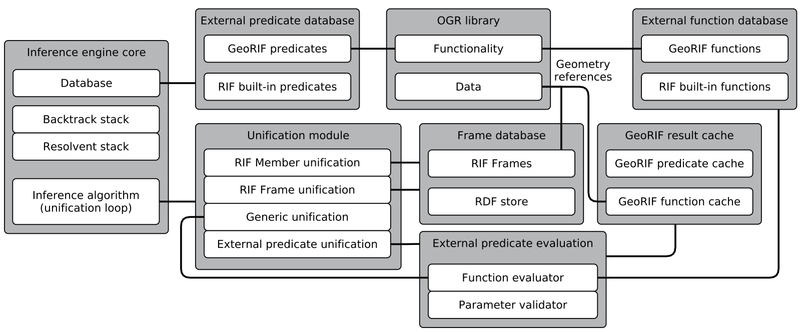

Figure 3.5. Structure of the spatial inference engine.

Figure 3.5 illustrates the internal structure of the spatial inference engine. Since GeoRIF is used as the native language of inference, the design reflects the structure and features of RIF. Overall, the design is that of a general inference engine for RIF, extended with spatial functionality. While some general inference engines are already available for RIF, their internal structure is generally incompatible with the intended spatial extensions. The spatial functionality is provided through the spatial predicates and functions, which reside within the same databases as other RIF built-in predicates and functions. Spatial data is stored in RIF Frames, an open set of binary predicates, which hold geometry references to the underlying spatial software library. This same library provides the functionality of the spatial predicates and functions. Within the core of the design, lies a backward-chaining inference engine with the closed-world assumption. The rationale for this is explained in Publication V and the approach is supported by the intended spatial functionality. The core itself is agnostic on the spatial aspects of inference, i.e. spatial data and operations are handled equally to any other content.

The figure also shows four utilised variations of the unification algorithm. In addition to the generic unification algorithm used for most terms, RIF Member, Frame and External terms require a specialised implementation of the algorithm. For RIF Frames, the unification algorithm unifies only the terms present in the resolvent. Therefore, Frames in database can contain supernumerary values compared to the resolvent but not vice versa. This is an intuitive feature absent in generic unification, i.e. all values in the input data are not required in every, or necessarily any step of the inference. The unification of Frame terms also implements the on-demand data integration from the Frame-specific RDF store. The unification of External predicates entails considerable functionality beyond the unification proper. This includes function evaluation up to an arbitrary depth of function calls for any predicate. The spatial predicates and functions in GeoRIF operate equally to other content and have their own internal geometry data type that is used with the spatial functions.

One compromise in this design is that spatial rules must be expressed in a functional rather than declarative manner, which is usually the norm in logic programming. However, this only restricts rule expression and not functionality, by requiring that all parameters in spatial predicates are instantiated prior to evaluation. This restriction, discussed more thoroughly in Publication V, is supported by the spatial functionality as well as the limitations of the available spatial software libraries.

Figure 3.5 also shows the GeoRIF result cache, which can reduce the total required computation for the evaluation. Several features and relationships of spatial predicates can be exploited with the cache for performance gain. For example, many spatial predicates are symmetric. If the result of `disjoint(A,B)` is known for any two geometries `A` and `B`, it follows that the result for `disjoint(B,A)` is also known without evaluating the predicate. The results of spatial functions can also be cached, though as functions returning geometries, they require significantly more storage than the boolean valued predicates.

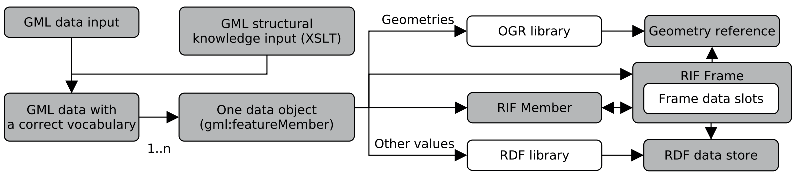

Figure 3.6. The data integration scheme in the inference engine.

Data integration is a significant constituent of inference with rule interchange. Figure 3.6 illustrates the data integration scheme in the design. Data integration starts with a GML file, where elements may or may not follow an expected vocabulary. In the context of agriculture, this vocabulary is that of AGROVOC, covered in Section 2.8. If necessary, the expected vocabulary can be established with an XSLT transformation of the GML file. The data in the GML content is then processed to RIF Frames. The spatial data is attached to the Frames as geometry references through the OGR spatial software library and any non-spatial data is placed in a Frame-specific RDF store, pending on-demand data integration. When a Frame is queried for a non-existent value, the RDF store for the Frame is queried and if the requested value can be produced from the RDF, it is permanently attached to the Frame as an ordinary value. This approach has the benefit of allowing GML input to contain any amount of information unnecessary to the process of inference without significant performance issues, as these values remain in the RDF stores. Moreover, the approach facilitates the detection of false negative results of inference, a common issue particularly with the closed-world assumption, since the absence of data can occur only in few select operations, such as the unification of Frames.

3.3.2 The prototype

The prototype for this result was the designed inference engine, implemented as a software library for the evaluation service described in Section 3.2. The implementation was programmed in the Ruby programming language. While interpreted high-level programming languages such as Ruby generally exhibit poor computational performance, this was not considered a significant issue as the spatial functionality was expected to dominate the overall computation. This spatial functionality was provided through SWIG (Simplified Wrapper and Interface Generator) Ruby bindings to the OGR library. The prototype nominally implemented the functionality of RIF Core, leaving predicates and functions not required by any of the test rules as stubs. Furthermore, some functionality of the other RIF dialects was also implemented, such as negation from RIF PRD. The complete functionality of GeoRIF was provided through the sets of spatial predicates and functions specified in GeoRIF, including support for GML geometry literals in GeoRIF rules.

3.3.3 Evaluation

The prototype was evaluated for correct functionality and computational efficiency, both of which are important features in computer inference. In addition to certain theoretical computational issues, e.g. evaluations that never terminate, the evaluation of a complicated rule with a large data set can entail significant computation. Moreover, spatial operations are generally computationally demanding, which further necessitates an evaluation of the computational performance.

Correct functionality of an inference engine could be established using formal methods. However, these are usually prohibitively tedious in comparison to their actual benefits. A more practical evaluation of functionality was achieved with a set of test cases, many of which are provided by W3C for all RIF dialects. The spatial functionality in GeoRIF was evaluated with agricultural rules, such as the one in Listing 3.1 of Section 3.2.1, using data known to violate or conform with a particular rule.

Listing 3.2 contains a GeoRIF rule that invokes worst-case quadratic time complexity with an arbitrary data set. Since the rule contains contradicting predicates, i.e. those of spatial overlap and disjointness, it will evaluate to false with any data set. Hence, exhaustive computation in the order of $\mathcal{O}(n^2)$ over the data set occurs. Such exhaustive computations, necessary for negative results of inference, are particularly suitable for evaluating the overall performance of an inference engine.

Listing 3.2. A rule to invoke quadratic worst-case behaviour.

```
Forall ?geom1 ?geom2 (
  jointSets(?geom1, ?geom2) :- And (
    ?geom1#example:GeometrySet
    ?geom2#example:GeometrySet
    ?geom1[area->?geomArea1]
    ?geom2[area->?geomArea2]
    External(geopred:overlaps(geofunc:convex-hull(?geomArea1),
                              ?geomArea2))
    External(geopred:disjoint(geofunc:convex-hull(?geomArea1),
                              ?geomArea2))))
```

	Size (MB)	Number of geometries
NUTS levels 0-1	11.3	151
NUTS levels 0-2	19.6	468
NUTS levels 0-3	32.7	1921

Figure 3.7. Data sets used for the performance evaluation.

Figure 3.7 shows the data set used in the performance evaluation. The data set is the GML version of the European Nomenclature of territorial units for statistics[2] (NUTS), which describes the regional division of Europe in an increasing level of detail. The evaluation was performed on a 64-bit Intel E5335 2.00GHz Linux system with sufficient memory for the data sets, where each test was carried out a total of 20 times.

[2] http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction

3.3.4 Results of the evaluation

The functionality of the inference engine was found correct in all test cases. This included the available spatial agricultural production rules, encoded for use with the service infrastructure presented in the previous result, as well as the relevant W3C RIF test cases. Indeterminate results, indicating a possible false-negative result, were obtained when appropriate parts of the data were omitted. Hence, there is no conceivable reason to assume that the implemented parts of RIF or the GeoRIF functionality in the prototype would operate incorrectly.

	With caching			Without caching		
	Overall run-time (s)	Spatial operations	Spatial computation (%)	Overall run-time (s)	Spatial operations	Spatial computation (%)
Full evaluation, NUTS 0-1	21.4 ± 0.1	24025	65.2 ± 3.5	60.5 ± 0.1	47596	85.8 ± 2.7
Full evaluation, NUTS 0-2	160.4 ± 0.4	224583	40.5 ± 2.4	334.6 ± 0.9	447761	80.2 ± 1.9
Initialisation, NUTS 0-3	2.6 ± 0.1	1922	58.0 ± 1.5			

Figure 3.8. Results of the performance evaluation.

Figure 3.8 presents the results of the performance evaluation, where the quadratic behaviour invoked by the rule in Listing 3.2 can be seen. Although spatial computation constitutes a majority of the computation in all test cases, it is as low as 40.5% when smaller geometries are involved. However, the prototype used for the performance evaluation is implemented in the Ruby programming language, which even by a modest estimate is an order of magnitude slower than a comparable C++ implementation. With C++, the spatial computation can reasonably be expected to constitute at least 95% or more of all computation. On the other hand, with the NUTS data set, this would yield a modest two-fold overall performance increase over the Ruby implementation at best. Caching the results of spatial predicates and functions also yielded considerable performance gains, although the actual benefits of caching will still depend significantly on the individual rule.

The presented design for spatial inference with an interchangeable rule format contains no functionality specific to agriculture. Therefore, the approach could well be adapted for spatial inference and rule interchange in other domains. When implementing spatial inference, the spatial operations dominate the computation to such an extent that especially with larger geometries, the non-spatial computation becomes negligible.

3.3.5 Summary of the result

A new design for a backward-chaining closed-world spatial GeoRIF inference engine with rule interchange and data integration.

GeoRIF is a true spatial superset of RIF with spatial literals, predicates and functions supplemented to RIF.

The spatial operations of inference were provided efficiently with an external software library and without a loss of functionality.

On-demand data integration is possible with GML when GeoRIF is used as the native language of inference.

The computational efficiency of spatial inference is dominated by the spatial operations and can be improved with caching.

4. Conclusions

The research objectives stated in Section 1.1 were achieved with the technical solutions presented and evaluated in Chapter 3. Therefore, with these information systems, the primary research objective of automated compliance control becomes attainable. However, practical issues remain that limit the wide-scale adoptability of automated compliance control; one such hindrance being the currently low rate of adoption for precision agriculture. The individual results that constitute automated compliance control, on the other hand, could be applied as independent technologies on a significantly shorter time frame.

For general FMIS in precision agriculture, the several benefits of a Web-based design would appear to overcome the drawbacks of the approach. Particularly, the desideratum of a highly-available FMIS with capabilities for significant exchange of spatial information is a clear contra-indication to the traditional on-site solutions. Recent literature on FMIS and related systems is also moving towards Web-based solutions (Kaloxylos et al. 2012). With a Web-based design, interfaces between the FMIS and the stakeholders in precision agriculture can be feasibly provided, including the communication with the ISOBUS farming equipment. Moreover, the increasing selection of Web services for agriculture can be conveniently interfaced with the FMIS as a Web application. Hence, a Web-based design is reasonable for modern FMIS and can be expected as the design of future FMIS in precision agriculture. The only reservations on this approach relate to the availability of an adequate Internet connection, which nowadays is less of an issue even in rural areas.

Web services, used for the primary information infrastructure in automated compliance control, are becoming increasingly popular in agriculture. The services used in this thesis were all based on REST; a simple and efficacious approach to service-oriented design. The same functionality could have been achieved with other technologies, though the simplicity of specifying and interfacing with REST services can be used as an argument in their favour. Particularly the contemporary lack of established data interchange formats in agriculture, which necessitates a degree of data integration for most communication, incommodes complicated interfaces. Thus, REST provides a favourable design to the information infrastructure for automated compliance control. Furthermore, it is an approach which can be advocated for the design of future services in agriculture. Even without the evaluation service, which necessitates extensive data availability and data integration, the service infrastructure could be utilised for delivering up-to-date agricultural production standards to FMIS and farmers.

At the core of automated compliance control, lies spatial inference with an interchangeable rule format, which is not specific to the application domain of agriculture. The spatial inference is achieved using GeoRIF, a true spatial superset of the W3C RIF. RIF provides versatile rule interchange with a structure suitable for inference. Hence, RIF can be used as the native language of inference without rule transformations; an approach found beneficial in this thesis. The necessary spatial extensions to RIF, which form GeoRIF, are feasibly provided with a well-established selection of spatial predicates and functions based on the OGC-SFA. Additionally, OGC-SFA has several mature implementations which provide the spatial computation for inference without compromises in computational efficiency. In the end, GeoRIF is a befitting format for both the rule expression and evaluation in automated compliance control. Moreover, GeoRIF and native inference with GeoRIF provides a flexible solution for spatial inference that has plausible and conceivable applications in other domains.

While it is concluded that automated compliance control to production standards in precision agriculture is attainable, the designs presented and evaluated in this thesis are only parts of a larger whole. To truly become practical and available to the average farmer, realisation of automated compliance control would necessitate action from several stakeholders in precision agriculture. In addition to the various legal and social issues, farmers should adopt precision agriculture, FMIS providers should provide the information systems, and authorities would have to provide legislation in an encoded format. However, this infrastructure can be built up gradually, with conceivable benefits from the individual systems and services.

5. Discussion

5.1 Technology of automated compliance control

Automated compliance control relies on technologies that have only recently been incorporated in agricultural engineering. These include Web technologies and new technologies that are still being developed, such as spatial rule interchange and inference. The solution for automated compliance control proposed in this thesis relies on a combination of technologies, with an overall emphasis on Web-based design in lieu of the traditional on-site software approach. While the functionality of automated compliance control could be adapted to on-site software, it is difficult to conceive the practical benefits of this approach over the proposed solution. On the other hand, Web technologies are not without certain disadvantages.

One advantage of the proposed solution is its relative simplicity, in both the service infrastructure as well as in the GeoRIF rule format. Moreover, the solution is composed of graspable components that can be developed independently. Only the general FMIS for precision agriculture covered in Section 3.1 is something that would qualify as complicated software. The other components of automated compliance control are small services, of which only the spatial inference engine within the evaluation service is technically somewhat involved. The REST interfaces used for the service infrastructure are easy to understand and interface. Furthermore, parts of their functionality, such as obtaining a production standard or an individual rule, are accessible even with an ordinary Web browser.

Some of the disadvantages in the proposed solution are inherent to Web technologies, i.e. the dependency on the availability of Internet connectivity, which in rural areas can be a justifiable issue. While this problem can be alleviated with caching, for example in the case of operation plans, little can be done for activities that require interaction. REST yields simple interfaces in service-oriented design. However, this inherent simplicity is only to the extent that information can be passed as request parameters and returned as usable files. Complicated input information, such as the spatial queries in the service architecture presented in Section 3.2, requires additional input to the request. While this information is downright trivial per se; even with a well-defined structure specified easily in XSD (XML schema definition), it does not conform with any standards. The XML operations necessary to process this additional information are not complicated, but they are schema-specific, which is generally undesirable.

With the GeoRIF rules and inference, the greatest conceivable disadvantage lies in rule expressions - additional RIF dialects are required to express the more complicated rules. Since RIF is inference oriented, rule expression in RIF is more restrictive than in more general rule formats. On the other hand, since RIF is bounded by the limitations of computer inference, inference with rule formats significantly more general than RIF is likely to face theoretical and practical problems.

The individual components of the proposed solution for automated compliance control have conceivable applications in domains other than agriculture. The general FMIS for precision agriculture is the component least likely to have any meaningful utilisation outside of agriculture. On the other hand, the service infrastructure used in automated compliance control could well be adapted for rule interchange in other domains. The GeoRIF rule format and the inference engine presented for GeoRIF in Section 3.3 have the widest conceivable applicability beyond their use in this thesis. Agnostic of the application domain, GeoRIF and the design for the corresponding inference engine, could be utilised for generic spatial rule interchange and inference.

There is also ground for improvement and further research on the proposed technologies for automated compliance control. While much of the actual development on general FMIS takes place as commercial software product development, academic studies can produce new applications that necessitate functionality in the FMIS. With data integration, it remains to be seen whether an integrated service architecture, such as one those proposed in the literature and covered in Chapter 2, will eventually be achieved in agriculture. This would greatly improve interoperability and permit the exchange of complicated data between information systems with a significantly reduced need for data integration. Until such time, however, simple interfaces, such as those provided by REST, with uncomplicated though service-specific formats are likely to flourish.

While there is little conceivable further research on GeoRIF itself, spatial inference is still in its infancy. There is significant ground for further improvements in the form of heuristics and optimisations. Additionally, the expression of spatial rules in GeoRIF is functional rather than declarative, which is usually the norm in logic programming. As discussed in Publication V, declarative spatial rules would require additional research to produce the notion of a “most general geometry”, a spatial analogue of the most general unifier (MGU).

5.2 Feasibility of automated compliance control

As stated in the previous chapter, automated compliance control is attainable but remains impractical in its present state. Currently, the adoption rates for precision agriculture remain low, general FMIS for precision agriculture are not readily available and agricultural production standards are not available in any encoded format. Since the encoding of the production standards is done manually, and will be done manually in the foreseeable future, it is difficult to conceive a current stakeholder with sufficient incentive or the resources for this work.

However, automated compliance control need not be adopted overnight as a whole. Rather, it can be built up gradually starting from the FMIS for precision agriculture. The service infrastructure for automated compliance control, without the evaluation service which calls for a considerable availability of data in an applicable format, could be used for the distribution of production standards without their GeoRIF encodings. This would conveniently provide up-to-date production standards for FMIS. While the theoretical limit of automatic evaluation is established at roughly 80% of the German production standards, this is unlikely to be reached in the early phases of automated compliance control. On the other hand, as the availability of data improves, so will the percentage of production standards that can be automatically evaluated. The above estimates were also formed based on the German agricultural legislation and may differ for the legislation of other countries and regions.

There are numerous challenges in the adoption of automated compliance control. Amongst these is the availability of automatically recorded data, which is tied to the adoption and prevalence of equipment for precision agriculture. The availability of which, much like the availability of FMIS for precision agriculture, can be expected to improve over time. In addition to the technical problems involving data integration and system interoperability, there are more fundamental challenges to automated compliance control. One such challenge is the reliability of data recorded during operations. Such issues concerning data integrity lie outside the scope of this thesis, as they affect the farming equipment and data collection rather than general information systems. However, data integrity must be addressed in design before any extensive adoption of automated compliance control is feasible.

The next step towards automated compliance control is the adoption of precision agriculture. While automated compliance control does not rely directly on precision agriculture, it does rely on the equipment of precision agriculture which produce data in the form of documentation of field operations. This creates a justifiable link between automated compliance control and the adoption of precision agriculture, which is unlikely to happen on any fast pace, at least not any faster than the introduction of ISOBUS farming equipment. Automated compliance control by itself, is an unlikely driver in the adoption of precision agriculture. However, once the technical prerequisites have been met, providing automated compliance becomes a worthwhile endeavour.

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Monitoring compliance with agricultural legislation currently expends significant manual effort on an otiose task. In the future, much of this task could be automated with information technology, spatial computer inference and data from ISO 11783 precision farming equipment. This doctoral thesis addresses the problem of automated compliance control through design science and the recognised stakeholders in modern agricultural production. Designs for systems and services completing the workflow of automated compliance control are presented. These are then demonstrated functional and feasible with prototype implementations.

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