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PHD DISSERTATION

Field Readiness and  
Operation Scheduling

by Gareth Thomas Charles Edwards



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PhD Thesis by

**Gareth Thomas Charles Edwards**

*Aarhus University Department of Engineering, Denmark*



ISBN 978-87-93237-95-7 (E-book)

*Published, sold and distributed by:*

River Publishers  
Niels Jernes Vej 10  
9220 Aalborg Ø  
Denmark

Tel.: +45369953197  
[www.riverpublishers.com](http://www.riverpublishers.com)

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# Abstract

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Modern farmers face the problem of increasing their overall productivity to meet the demands of a growing global population, while also being limited by the amount of available resources, e.g. land area, fuel, chemicals, etc. Data technology will play a pivotal role in helping farmers reach this goal; by correlating and analysing vast amounts of data, operations can be planned and executed based on knowledge that is incomprehensible within current farming practices.

Field readiness is a measure of a field's fitness for purpose for an operation to be executed, and is a conjunction of a field's trafficability and its workability. It is important to consider the readiness of a field when planning operations to ensure operations produce positive results while they also do not cause excessive damage. In the past readiness evaluations have relied upon an experienced farmer's visual assessment, often coupled with a "gut feeling" of how the conditions will change. In order to optimise the planning of operations more scientific methods of evaluation are needed.

The main aim of the thesis was to develop a method of creating optimised machine work plans in accordance with a field's readiness, to assist farm managers execute field operations in an efficient and non-damaging manner. This was constrained by the condition that the field readiness would need to be determined remotely avoiding the need to physically visit potentially dispersed locations.

Farm managers were included in the early stages of development to capture their knowledge and practical experience of problems associated with operations management with respect to field readiness. This was used as the basis of a developed tool to estimate field readiness and produce optimised machine work plans. Methods of determining soil trafficability and the workability of different operations were used to estimate the field readiness of remote locations, negating the necessity for the locations to be physically visited.

The field readiness was utilised as a parameter within a novel scheduling algorithm to create individual work plans for multiple machines executing consecutive operations at multiple locations. Novel optimisation algorithms were also developed and used alongside the scheduling algorithm to find the near optimal allocations of resources. It is also possible to parameterise the optimisation algorithms to offer varying degrees of near-optimality at the expense of the computational time required. This is essential for utilisation of the algorithm at different planning stages involved in operations management.

# Sammenfatning (abstract in Danish)

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Den moderne landmand står overfor en konstant udfordring om at øge sin produktivitet for at imødekomme kravene fra en voksende global befolkning, samtidig med at være begrænset af mængden af tilgængelige ressourcer, fx areal, brændstof, kemikalier osv. Informationssystemer vil spille en vigtig rolle for at nå dette produktivitetsmål, idet disse systemer gør det muligt at korrelere og analysere store mængder data som grundlag for planlægning af driften baseret på viden, der ellers ikke ville være tilgængelig ved brug af gængse metoder.

*Field readiness* er en parameter, der indikerer en marks tjenlighed overfor et givet stykke arbejde og er en kombination af jordens *trafficability* og *workability*. Det er vigtigt at overveje jordens tjenlighed, når man planlægger maskinoperationer, for at sikre positive resultater uden at skade omgivelserne. Evalueringen vedrørende tjenlighed har indtil nu oftest været baseret på en landmands erfaring og visuelle vurdering, ofte kombineret med en "mavefornemmelse" om, hvad kan forventes. For at optimere planlægningen af drift er der behov for en mere videnskabelig metode.

Hovedformålet med denne afhandling har været at udvikle metoder til at optimere arbejdsplaner for landbrugsmaskiner i overensstemmelse med jordens tjenlighed, så driften kan udføres på en effektiv og ikke-skadelig måde. Dette er udfordret af betingelsen om, at markens tjenlighed skal fastlægges uden fysisk at besøge potentielt spredte lokaliteter.

Flere landmænd indgik i de tidlige stadier af udviklingen for at gøre brug af deres viden og praktiske erfaring i forbindelse med maskinoperationer. Dette udgjorde fundamentet for udviklingen af et værktøj til at estimere *field readiness* og producere optimerede arbejdsplaner. Metoder til bestemmelse af jordens *trafficability* og *workability* i forbindelse med forskellige operationer blev anvendt til at estimere jordens tjenlighed på fjerntliggende steder.

*Field readiness* blev yderligere anvendt som en parameter i en ny planlægningsalgoritme designet til at udvikle individuelle arbejdsplaner for flere maskiner med forskellige arbejdsopgaver på flere lokationer. Nye optimeringsalgoritmer blev også udviklet og anvendt sideløbende med planlægningsalgoritmen for at finde den bedst mulige ressourceallokering. Det er også muligt at parameterisere optimeringsalgoritmer og derved beregne forskellige grader af nær-optimalitet på bekostning af en længere beregningstid. Dette var afgørende for udnyttelsen af algoritmen på forskellige stadier af driftsplanlægningen.

# Acknowledgements

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I would like to thank my main supervisor Claus Sørensen and my co-supervisor Lars Munkholm for their support throughout my PhD, for their guidance and assistance with writing tasks and for their encouragement of my development as a scientist. I would also like to thank Niels Dybro, from John Deere, with whom I have regularly met and who has given support and practical insights into the applicability of my work, as well as helping to introduce me to other experts within his organisation.

I am grateful to all of my colleagues within the Department of Engineering who have helped along the way, not just with my Ph.D. but also with the various other projects I have been apart during my time.

On a personal note, I would like to thank my dad for making me do only the truly boring tractor jobs on the farm, thereby giving me plenty of time to think of ways in which they could be done more efficiently. I would also like to thank my friends and family who have endured me through the whole PhD process and specifically in the final few months. And finally my wife Louise, who has been my smartest critic and my loudest supporter.

# Chapter 1 Introduction

---

## 1. General Introduction

Modern farmers face the problem of increasing their overall productivity to meet the demands of a growing global population, while also being limited by the amount of available resources, e.g. land area, fuel, chemicals, ect., (Tilman et al. 2002). Specifically over the last 50 years, gains in operations productivity have been achieved by increasing machine sizes thereby increasing operations capacity. However, the limits of infrastructure, such as field sizes and road widths, dictate that the maximum size of machines may have been reached (Bochtis et al., 2014). In order to further increase productivity farm managers must look towards technical and managerial solutions to utilise their resources in a more efficient manner which could include; optimising machine schedules and allocations of resources, limiting operations to only be executed at opportune times, avoiding causing damage to fields rather than elevating it with addition operations or increased chemical inputs, or affectively adapting to a changing environment both in the short term (e.g. machine breakdowns, sudden weather changes) and in the long term (e.g. climate change, political or regulatory body change).

### 1.1. Farm Management Information System

It is established that the pursuit of sustainable agriculture practices will require substantial increases in knowledge-intensive technologies and scientific analysis (Byerlee, 1994). A Farm Management Information Systems (FMIS) collects and organises information relating to farm activities to present processed knowledge to a user and to produce required reports to outside bodies, e.g. customers, regulatory bodies. Early research in to the area of FMIS (Lewis, 1998) saw FMIS as a progression of Farm Record Systems (FRS) into a computer based management system, utilising the Information Superhighway and the World Wide Web to converse with outside entities. Lewis (1998) also stated that it was the younger users who were more likely to adopt FMIS as a way to compensate for a deficit of farming experience.

Sørensen et al. (2010a) described the need for European farmers to adopt FMIS as a response to a paradigm shift, with managerial tasks requiring a more detailed focus on the environmental impact of their practices as well as an increase in produced documentation. A FMIS is seen as a tool for both collecting and reporting data to reduce the amount of time a farm manager must spend in the office. A conceptual model, Figure 1.1, of the extensive system is described and the system boundaries are identified, defining the entities within the farm manager's control and the entities which are outside of the system but that exert influence upon it.

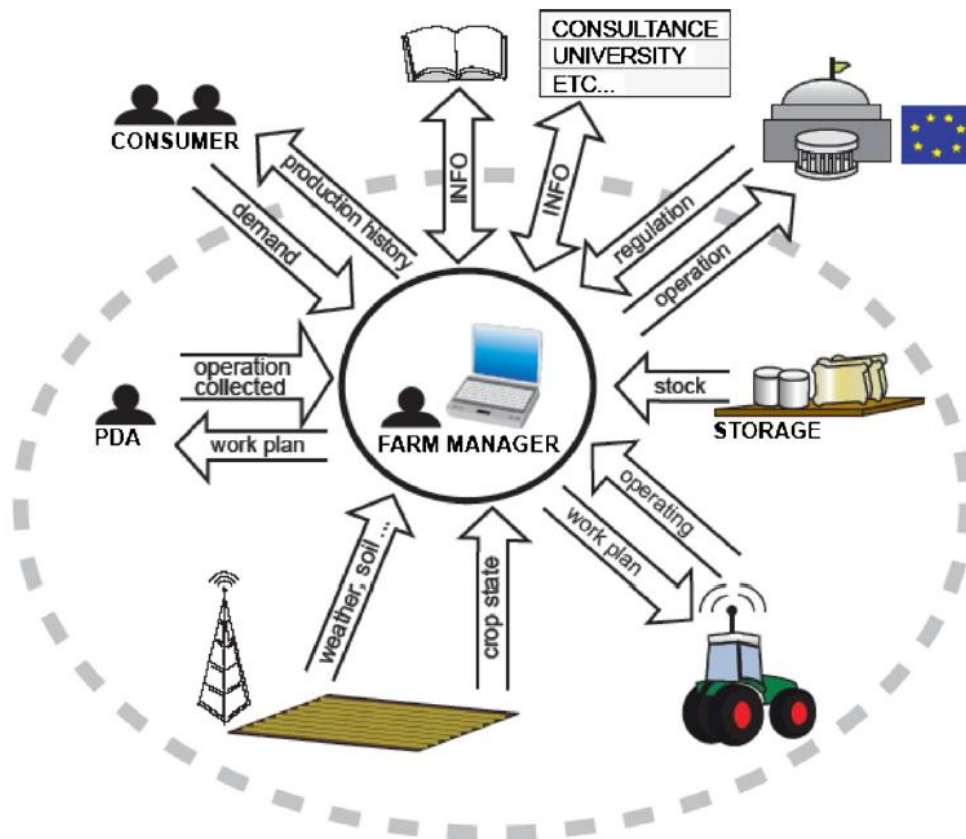


Figure 1.1: Conceptual Model from Sørensen et al., 2010a

Nikkilä et al. (2010) refined the architecture of a FMIS by considering the special case of creating work plans for agricultural operations while incorporating precision agriculture data. It is suggested that as well as collecting data from various sources, e.g. soil sensors, smart implements, the internet, etc., biological models are also needed as part of the FMIS. Biological models can be used to infer information when data is not available to be collected directly from the source. Nikkilä et al. (2010) also stated that the construction of a large FMIS would be an arduous task which is outside the scope of academic research and should not be undertaken without the backing of a large software company. Instead research should concentrate on the development of subsystems to perform specific tasks within the remit of a FMIS.

It is envisioned that further development of FMISs should include tacit knowledge of a farmer to effectively expand upon currently offered features. Also FMISs should provide farm managers access to the latest scientific research and technological developments to aid the processing of information. To fulfil this goal FMISs should be built in a modular fashion, within a defined structure which makes requirements of information, and the format in which it is supplied, for individual modules. Old modules can then be

replaced as newer modules are developed, which could incorporate new sensors or methodologies to produce improved results.

Pigs2win, (Meensel et al., 2012) is an example of a decision support system (DSS) designed to support the production of pigs in Flanders, the Netherlands. While it was designed as a separate system, it could be integrated as part of a FMIS. Implementing a participatory approach involving scientists, farmers and industry representatives, key performance indicators (KPIs) were identified. These KPIs were required to be entered by a user to classify each farm, farms could then be evaluated against one another using benchmarking. As well as classification and evaluation, a simulation module was introduced which allowed users to investigate the impact of improving KPIs. The interaction between the members of the participatory group was highly influential on the end system produced.

Carli and Canavani (2013) introduced a costing and reporting subsystem for an overall FMIS. A conceptual model was presented that supported direct costing and activity based costing as methods of farm managers to control complex cost decisions. Both costing methods were utilised as part of a business' economic analysis to assign fixed and variable costs of resources and activities to relevant products. This makes the financial implications of decisions clearer so that the farm manager can make informed choices. It is also hypothesised that the integration of optimisation algorithms could allow for some decisions to be made automatically.

Kaivosoja et al. (2014) focused on an aspect of FMIS by creating a system to interpret external data and construct an up-to-date work plan for a machine executing a spraying operation. Information was gathered pertaining to temporal and spatial conditions that place restrictions on the execution of the operation, such as current wind and rain, weather forecasts, pesticide alarms, information from aerial systems, in-field sensors, and advisory recommendations. Due to the volatile nature of the data, and that some data may only become available during execution, a task controller was developed to rapidly update the operational plan and implement the plan via the ISOBUS interface (ISO, 2007). This demonstrated how plans can first be formulated in a FMIS and then executed in an intelligent way.

In Pesonen et al. (2014) an example of a crop management system, CropInfra, was described both conceptually and as implemented on a research farm. A spraying operation was considered as the case study. This can also be thought of as a subsystem of an overall FMIS. The system brought together data from local weather stations as well as from the tractor itself, to offer decision support throughout the operation concerning changing environmental factors which affect the outcome, such as wind speed,

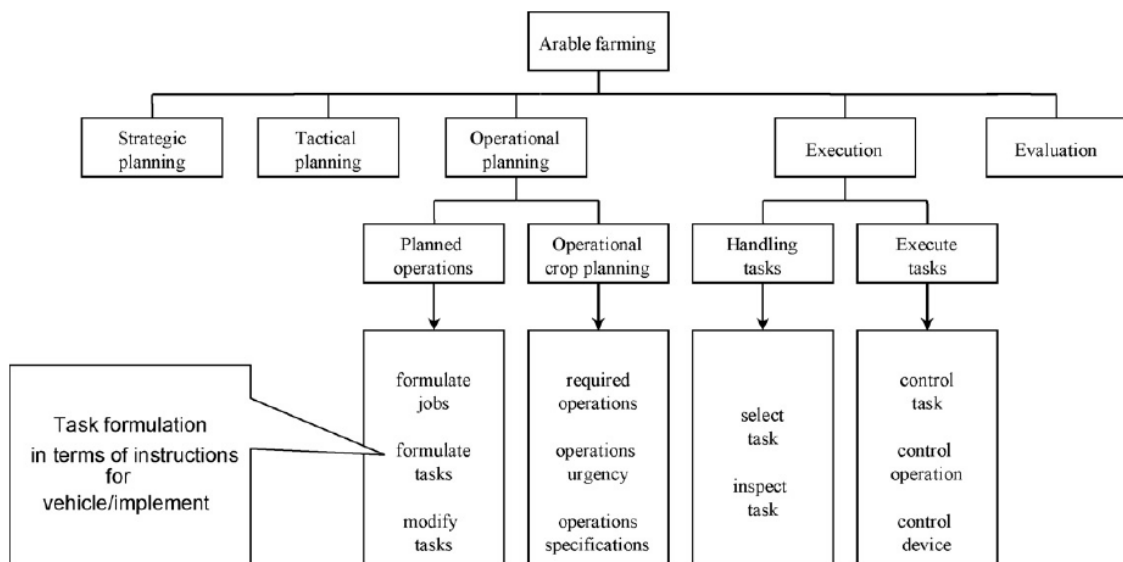


humidity, chance of rain. Data storage and data accessibility were identified as important functionalities of the system, so that data could be gathered from, and accessed by, third parties through interfaces.

After the initial work to conceptualise the overall FMIS (Sørensen et al., 2010a), research has continued by concentrating on specific sub-systems or functionalities of a FMIS. While the reintegration of such sub-systems into a governing FMIS must remain a consideration, this departmentalisation of the FMIS problem has allowed for advances and innovations to be made.

## 1.2. Operations Management

Operation management of arable farming operations is an important subsystem of an overlying FMIS. It is responsible for the tasks of when, where, and how infield operations should be executed. These tasks are carried out by farm managers or agricultural contractors, who plan work schedules for machines and labourers under their control. The processes used to plan these work schedules differ greatly between individuals and rely upon intrinsic knowledge concerning the local area and environment, and the specific operations. Also the level of detail which is planned, the sources used to gather helpful information, and the time scales in which planning is done, i.e. how far in advance of the operation's execution does the planning occur, are often highly subjective (Dury et al., 2013).



**Figure 1.2: Levels of operational management within arable farming Sørensen (2010b)**

Sørensen et al. (2010b) adapted a model, first described in Goense and Hofstee (1994), to show at which stages within the decision making process actors, i.e. farm managers, must interpret information to make operational decisions, Figure 1.2. The main planning stages, along with the time dimension of the information management level, are identified as follows; Strategic planning over years, Tactical planning

over year/months, Operational planning over week/days/hours, and Execution planning over hours/minutes/seconds. For the example of the planning of a spraying operation, Sørensen et al. (2010b) elaborates on the information flow at each planning stage showing the interaction between the entities involved with the decision making process.

The aim of the strategic planning stage is to produce a plan over the next 1 to 5 years, or 2 or more growing seasons. The strategic planning stage produces a plan for the crops that will be grown and their machinery/labour requirements, including if new machinery will be bought or if agricultural contractors will be utilised. Restriction and regulations set forth by governments and regulatory bodies are considered to ensure that the future long term plans are compliant. The plans are quite unsophisticated as there are many intangibles such as market prices and weather which cannot be known over such time scales. However regional climate data can be used to estimate windows of opportunity for operations that are required by the crop, so that fleet sizing can be considered.

The next level of planning is the tactical planning stage which considers the next 1 to 2 years, or 1 to 2 growing cycles. The tactical planning stage requires a strategic plan as an input, where the crops to produce and the available machinery have already been proposed. At this stage the definite operations to establish, maintain and harvest the crop are specified, including the order in which they are executed and any dependencies between sequential operations, e.g. planting must be executed within 2 days after seedbed preparation. The time scale is still too vast to consider producing accurate machine schedules however quantities of consumables inputs, such as seed, fertiliser, chemicals and fuel, can be calculated and procured. Also routine maintenance and replacements of machinery can be planned so that the execution of operations is not halted by faulty machines.

Operational planning considers the next immediate set of operations within the growing season, such as the establishment, maintenance or harvest of a crop. Again a tactical plan is needed as an input to the operational planning stage. Typically operational planning is initiated in the days and weeks prior to the execution of the operations, when weather forecasts can be thought of as more reliable and accurate knowledge of the state of the location where operations are to be executed can be obtained. Utilising this information, detailed schedules and machine work plans can be constructed, specifying when and where individual machines will execute operations. Operational parameters, such as implement setups (working depth, application rate, etc.) and machine specifications (operating speed, ballast configuration, etc.), are detailed for each machine/implement combination and provided, along with the machine schedule, to the operator. Some operational parameters may also be able to be adjusted at the execution stage, for

instance if a smart sprayer is being used it may be able to vary its application rate due to the encountered conditions.

Execution planning considers the execution of operations over the next hours/minutes/seconds. Many of the tasks within execution planning are on a machine level, i.e. decisions affecting the operational parameters of a single machine/implement. However, deviations from the work plans supplied by the operational planning stage may necessitate the operations to be rescheduled and new machine work plans to be produced. Deviations could include machines finishing operations earlier/later than planned, weather conditions changing from anticipated conditions, or machine breakdowns. The level of divergence from the existing plans that merits new machine work plans being sent to individual machine is influenced by the communication protocols of the fleet management system, FMS, (Sørensen and Botchis, 2010). Specifically if the response time of the communication protocols is lower than the deviations from the existing plan then new plans would not be received in time.

As each plan is passed down to successive planning stages, they must be considered as conditional on a set of parameters, such that the acquisition of additional information can cause the reversion to a previous planning stage if triggered. For example, if a 4 year plan is decided upon at the strategic planning stage and passed to the tactical planning stage but then government regulations change, it may trigger a re-initialisation of the strategic planning stage to reconsider the new regulations. Dexterity in the approach of the implementation of the FMIS is essential as the integration of a biologic process and human operators can be chaotic.

A FMIS tool, or collection of tools, must be capable of assisting farm managers at each of the previously described planning stages. Thereby encouraging the farm managers to make their decisions in a timely manner and create effective long term and short term plans. Also the cross functionality of the planning stages is pivotal to the usefulness of the FMIS.

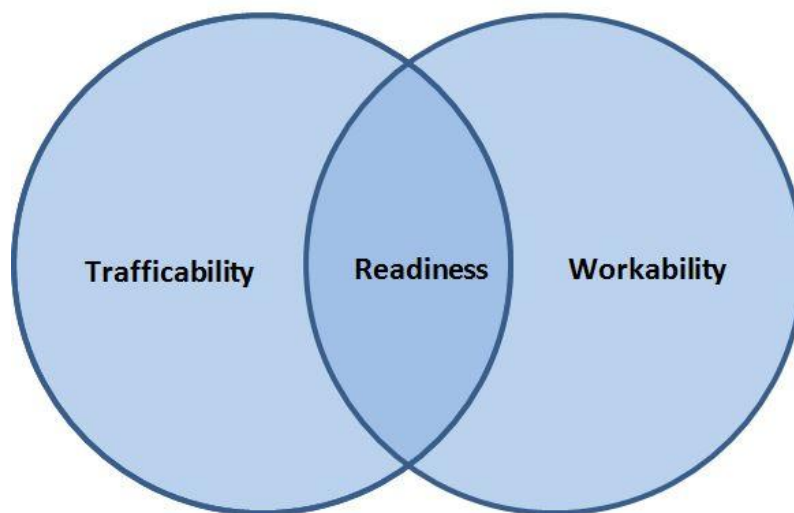
### 1.3. Field Readiness

In order to plan operations at the different planning stages a measure of the current, and future, state of the field's fitness for purpose is needed, this is known as the field's readiness. In the past the classification of a field's state has been made by a visual inspection by an expert (Hemmat and Adamchuk, 2008), however this was often laborious, required physically visiting many locations, and lacked the scientific basis to extrapolate the results into the future.

With the increased interest in precision agriculture, farm managers are able to gather more information about the status of their soils and crops. Soil mapping techniques such as electromagnetic conductivity

(Sudduth et al. 2005), soil spectrometry (Christy, 2008), and reflectance analysis of aerial photography (Jensen et al. 2007) have all been used to determine the spatial variability of soil and crop properties. In situ sensor networks have also been used, both above the soil and within the soil profile, to monitor the fluctuation of the soil and crop properties (Ruiz-Garcia et al., 2009; Jackson et al. 2008). Modelling software offers the ability to simulate responses of soil and crop properties to experienced environmental conditions, notable examples include APES (Donatelli et al. 2010), DSSAT (Jones et al., 2003) and DAISY (Abrahamsen and Hansen, 2000). Models are often initiated or parameterised using data recorded in the field to estimate future field conditions or when in field monitoring is not available.

These technologies provide information which, by itself, is of limited use to a farm manager, however the interpretation of the information into useable knowledge is an important task of a FMIS.



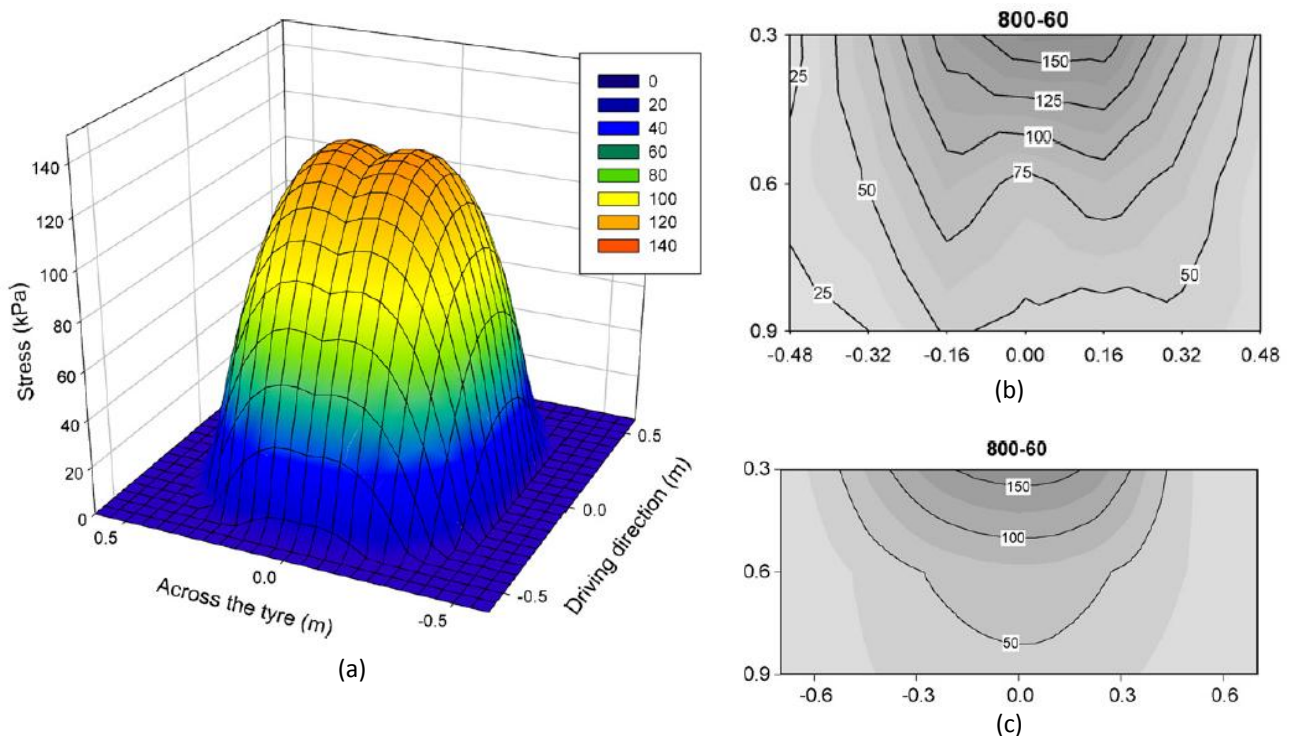
**Figure 1.3: The conjunction of trafficability and workability to produce readiness**

A field's readiness is a combination of its trafficability and its workability, Figure 1.3. By ensuring that a field is in a state of readiness, i.e. both trafficable and workable, then operations can be executed in an efficient manner causing the least amount of damage and resulting in a profitable outcome.

Trafficability is defined as the ability of the soil to support and withstand traffic, causing only minimal or reversible structural damage (Rounsevell and Jones, 1993). Structural damage within the soil and subsoil is most readily observed as soil compaction, which has been studied in depth to determine methods of detection (Motavalli et al 2003) and methods of prediction (Saffih-Hdadi et al., 2009, Canillas and Salokhe 2002, Earl 1996).

Soil compaction can have many adverse effects such as reducing the porosity of the soil, limiting the transfer of gases and minerals, and most importantly to farmers, decreasing expected yield. A study carried out in Belgium (Neuens and Reheul, 2003) showed a 13.2% loss in the growth of maize as a result of wheel induced compaction on a sandy loam soil.

Various methods for reducing soil compaction are put forward by Hamzaa and Anderson (2005), among them are; reducing the axle load and/or increasing the contact area on the soil and confining traffic to certain areas of the field. Using principles of Control Traffic Farming (CTF) has been shown to limit compaction to small areas of the field, sacrificing the yield in the trafficked tracks but leaving the rest of the field untouched (Tullberg, 2010). Additional operations, such as deep tillage or the introduction of organic matter can help to alleviate effect compaction (Kuncoro et al., 2014), however if left unchecked soil compaction can be persistent for many years (Berisso et al., 2012).



**Figure 1.4: Diagrams from Lamandé and Schjøning (2011) showing (a) the modelled stresses in the soil-tyre interface, (b) the recorded stresses in the soil profile across the direction of travel and (c) the recorded stress in the soil profile in the direction of travel**

To estimate the potential risk of an operation causing compaction of the soil a common technique is to compare the stresses caused by trafficking to the soil strength (Schjøning et al., 2012). Söhne (1953, 1958) first suggested a simple analytical model for the stress propagation within the soil profile based on the work of Boussinesq (1885) and Fröhlich (1934). An important input into the stress propagation model is the boundary conditions at the soil-tyre interface, (Keller, 2005). Schjøning et al., (2008) suggested a further

model, referred to as FRIDA, which describes the stress distribution in the tyre foot print. The model can be parameterised using the physical description of the tyres, i.e. tyre width, tyre section height, tyre rim diameter, and tyre pressure, (Schjønning et al., 2006). This model, coupled with the stress propagation model, has been tested against measurements made using in-situ sensors placed within the soil profile (Lamandé and Schjønning 2011, Lamandé and Schjønning 2008, Keller et al., 2007), Figure 1.4.

Terrainimo (Stettler et al. 2014) is a web-based tool used to estimate the trafficability of soil during field operations. The tool estimates the stress distribution in the soil-tyre interface using the wheel loads and tyre characteristics and compares how this stress is propagated through the soil profile with an estimation of the pre-compression stress. If the stress caused by the wheel loading is below the pre-compression stress then the soil is said to be trafficable. The interface is built such that these calculations are not shown to the user, rather a more simplistic representation is used indicating the risk of compacting the soil as either low, moderate or high. In this way farm managers can gauge the best conditions in which to execute operations.

Schjønning et al. (2012) offered an alternative approach to estimating the precompression stress of the soil, by proposing a limit of 50 kPa on the vertical stress within the profile. Moreover it was found that subsoil compaction at a depth lower than 50 cm became extremely hard to alleviate via natural methods, therefore the rule was stated that in order for a field to be trafficable the vertical stress within the soil profile must not exceed 50 kPa below 50 cm.

Workability is defined as the ability of an operation to be executed at a specific time to give a positive result (Droogers et al. 1996). As different field operations' objective goals vary widely, so to do the standards by which they are judged to give positive results. For example, tillage is judged by the adequacy of the seedbed as a growth medium, this can mean that the operations must be executed while the soil is within certain moisture levels (Munkholm, 2011; Mosaddeghi et al., 2009; Mueller et al., 2003), whereas the workability of a crop for harvest is more closely related to its development stage.

Dexter and Bird (2001) examined previous research within the area of the workability of soils for tillage, making a synthesis of published results to create a method for the calculation of an optimal soil moisture content. As well as an optimal water content at which soil can be broken into adequately sized aggregates, a range of values at which tillage can produce near optimal results was also suggested, Figure 1.5. This range is bounded by upper and lower soil moisture content limits. The equations for the optimal soil moisture contents and the upper and lower limits were described in terms of the parameters of the van Genuchten equation for soil water retention (van Genuchten, 1980). These parameters have been found

and publish for a great number of soils and can be retrieved from soil databases, they can also be estimated from the soil textural data using a pedotransfer function (Wösten et al., 1999).

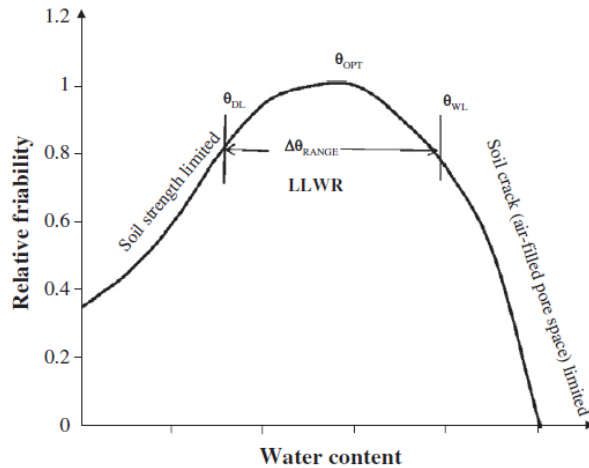


Figure 1.5: Schematic illustration of a range of near optimal water contents for tillage

The workability of a seeding operation requires the soil to be at an optimal temperature so that development can begin, furthermore if the temperature drops after seeding it can cause stress to the seed, stunting its development and affecting the eventual crop yield. Saab (2009) proposes an optimal seeding soil temperature of 85 °F , or approx. 29 °C, for maize after extensive testing with growers in Iowa. It was also shown that if the average soil temperature for a two week period after the seeding operations fell below 50 °F, approx. 10 °C, then it could have a significant effect on the number of emerging, and hence reaching maturity, plants within the field, Figure 1.6.

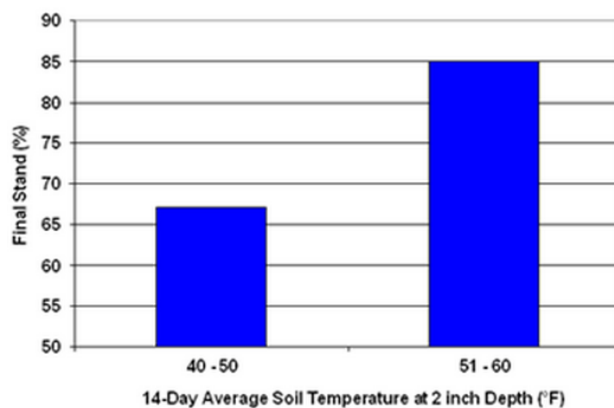


Figure 1.6: Saab (2009) the effect of temperature following the seeding operation

Balancing the requirements of trafficability and workability within a changeable weather system can be extremely difficult. Often decisions are made on a very short term basis, reacting to situations rather than planning ahead. However, if more is known about the readiness of a field then work plans can be scheduled further in advance, so that resources can be managed more efficiently. Existing methods to evaluate the trafficability and workability of fields need to be integrated into the framework of a FMIS. Also, standardising the integration and clearly defining the inputs and outputs of the methods will ensure that novel methods devised in the future can be used as replacements.

#### 1.4. Fleet Management Systems

The aim of a Fleet Management System (FMS) is to assist farm managers or agricultural contractors with resource allocation, scheduling, routing, and real-time monitoring of vehicles and material (Bochtis and Sørensen, 2009). This is a subset of the overall FMIS problem, but it is an area that can be separated and dealt with monolithically while still offering value to an end customer. FMS is also seen as an adaption of enterprise resource management from the area of industrial engineering which deals with the planning and logistics of various types of machines. The role of fleet management within farm management becomes more prominent in the later planning stages, specifically operational planning and execution planning.

A conceptual model for a FMS was detailed in Sørensen and Bochtis (2010). Considerations of the biological and meteorological conditions of the field were mentioned as a layer within offline management, however no further elaboration is given about what the conditions might be or how they were accounted for. One of the main questions raised by the conceptual model was the comparison between centralised and distributed control of individual machines, and to a lesser extent the communication requirements of a FMS to deal with these situations. A distinction was also made between offline planning and online planning. To relate this to the planning stages already mentioned in Sørensen et al. (2010b), offline planning would be considered part of the strategic, tactical and operational planning stages (although in actuality it is only appropriate at the operational planning stage when operational parameters have been established) and the online planning would be synonymous with the execution planning stage. The conceptual model outlined the need for algorithms to perform functions such as scheduling, task allocation and route planning.

Basnet et al. (2006) introduced a model for scheduling multiple consecutive operations at multiple spatially diverse locations. This was an extension of earlier work to schedule operations at a single location (Foulds and Wilson, 2005). The major novelty of the Basnet et al. (2006) model was the inclusion of minimum and maximum lags between consecutive operations' execution. These lags captured the fact that there is often an imposed period of time between field operations, e.g. for grass to dry in the field after being cut before



it is harvested for silage. However some of the assumptions within the model, such as waiting for all of the machines to arrive at a location before starting an operation, introduced unrealistic behaviour which would mean that produced schedules were not followed by machine operators.

As well as the scheduling model, Basnet et al. (2006) detailed two meta-heuristics which created optimised vehicle routing and assignment configurations that the model used to produce work plans. The first was a greedy heuristic that quickly produced a solution although this may be far from optimal. The second was a Tabu Search Algorithm (TSA) that manipulated an initial solution to find a more optimal solution. For the examples shown in the paper, the TSA was able to find more optimal solutions for the scheduling problem than the greedy solution, although the solutions were still far from the optimal solutions.



**Figure 1.7: Example of field decomposition**

Whereas Basnet et al. (2006) produced inter-field schedules for the entire fleet of machines under consideration, individual machine work plans must be constructed for in-field execution. Most in-field agricultural operations require a route plan similar to a coverage plan, where the whole field area must be covered by the machine/implement in the most efficient manner possible. Coverage planning typically is broken down into two tasks; decomposing the field into a number of parallel working tracks and headland areas, and determining a route by which all the working tracks can be visited. Many methods have been proposed for the decomposition of fields, (Oksanen and Visala, 2009; Jin and Tang ,2010; Zandonadi, 2012; Hameed et al., 2013). Figure 1.7 shows an example of a decomposed field, the green regions encompassing the field are the headland area while the yellow regions crossing the field are the working rows.

A common practice to solve the task of finding a route between all of the working rows is to cast the problem as another problem which already has a defined solution. Bochtis and Vougioukas (2008) proposed the casting of the task as a Travelling Salesman Problem (TSP), which requires all locations to be

visited exactly once. By defining two locations for each working row, one at each end, standard TSP solvers could be used to find an optimal route. Bochtis and Sørensen (2009) expanded upon this and covered a number of problems that could be cast as Vehicle Routing Problems (VRP). Utilising an optimised route can significantly reduce the time spent in the field, which may affect how and when subsequent field operations are handled by the fleet.

Fleet management plays an important role within FMIS, specifically at the operational and execution planning stages. A FMS needs to be able to both schedule when and where operations of the fleet are executed as well as how each individual machine will execute the operations in the field. Flexibility of the planning at the execution stage will enable a system to react when the consequences of actions taken result in large deviations from the predefined plans.

## 2. Research Gap

Much of the research to date has considered workability and trafficability separately, even going so far as to say that if a field is workable then it must be trafficable (Rounsevell and Jones, 1993). However, for the tasks of operations management as part of a FMIS, it is essential that both workability and trafficability are accounted for (Sørensen et al. 2010). While in the past fields have been physically sampled in an attempt to predict the readiness for an operation (Hemmat and Adamchuk, 2008), when considering large scale farming it is not practical to visit all of the locations to gain an overall view, and decisions are often made on unobserved basis. Moreover, the assessments of workability and trafficability must be analytical, and utilise readily available data or linked data depositories, in order to eliminate the necessity for expert knowledge.

The agricultural industry is seeing increased levels of automation and computerisation, with machinery being sold with on-board computers and auto-steering as standard. Also communication networks are becoming more prevalent, making overall fleet management and control a more obtainable goal. Conceptual models exist for fleet management systems (Sørensen and Bochtis, 2010) but the exact methods of producing optimised work plans for machines are lacking from the research area.

## 3. Objectives

The main aim of the thesis was to develop a method of creating optimised machine work plans in accordance with a field's readiness, to assist farm managers execute field operations in an efficient and non-damaging manner. This was constrained by the condition that the field readiness would need to be determined remotely, avoiding the need to physically visit potentially dispersed locations. Attention would

be given to the field readiness decision as an integral part of the planning stages of operations management.

It was perceived that this aim would be accomplished by designing the structure and implementation of a system to operate within the scope of an existing FMIS, integrating methods for readiness determination and operations management utilised accessible data.

The main objectives are listed below;

- Create a conceptual model based on intrinsic information from farm managers (Chapter 2)
- Determine field trafficability methods (Chapter 3)
- Determine field workability methods for specific operations (Chapter 3 and Chapter 5)
- Integrate trafficability and workability methods into a tool to assess field readiness (Chapter 3 and Chapter 5)
- Create optimised machine work plans exploiting a field's readiness (Chapter 4 and Chapter 6)
- Demonstrate the designed tool using practical examples (Chapter 3, Chapter 4, Chapter 5)

The remainder of the thesis is as follows; Chapters 2 to 6, is a collection of research papers tackling the objectives listed above and constituting much of the work within the PhD project. Chapter 7 is the general discuss of the papers, considering how they relate to one another and how they fulfil the objectives and Chapter 8 summarises the main finding and results of the thesis. Finally Appendix 1 includes a brief summary of the research tool developed as part to the PhD project to estimate field readiness and produce machine work plans.

## 4. Summary of Papers

### Chapter 2: Conceptualisation of a Field Readiness Decision Support System

Submitted to CIGR Journal

- A participatory approach is used to determine the current situation faced by farm managers and agricultural contractors whilst planning operations
- The Soft System Methodology is used to analyse the current situation and devise a conceptual model of a decision support system to assist planning operations
- Attention is given throughout to the notion of executing operations efficiently and with minimal environmental impact.

### Chapter 3: Modelling the readiness of soils for different methods of tillage

Under review with Soil and Tillage Research

- Methods for assessing soils' trafficability and workability are defined and combined in a novel tool

- The readiness of three English soils is assessed over an 11 year period
- Two methods of tillage are compared, examining the impact that the choice of tillage system has on the number of available ready days per season for tillage operations.

#### Chapter 4: Optimised schedules for sequential agricultural operations using a tabu search method

Under review with Computers and Electronics in Agriculture

- A method for scheduling multiple operations executed by multiple machines at multiple spatially diverse locations is presented.
- Two methods are also presented for optimising the schedule under defined conditions for a given scenario
- The optimisation methods are demonstrated for a real world example as well as for extensive sets of numeric examples.
- Options for configuring one of the optimisation algorithms to result in solutions under different operating criteria, (i.e. fast computational time or best near-optimal solution) are also presented and applications are discussed.

#### Chapter 5: Assessing the actions of the farm managers to execute field operations at opportune times

Submitted to Biosystems Engineering

- The execution dates' of operations on a large group of fields are considered over a two year period
- Workability is considered for spring (planting) and autumn (harvest) operations
- Assessment criteria are presented which allow for the operations' execution to be assessed in accordance with the estimated field readiness

#### Chapter 6: Coverage planning for capacitated field operations under spatial variability

Accepted and awaiting publication in International Journal of Sustainable Agricultural Management and Informatics

- A system is proposed for the real time optimisation of a harvest operation constrained by the harvester's maximum capacitance
- The system is proved by implementation on an operation management test platform which mimicked a spatial variably field that could be harvested multiple times.
- Comparisons are made as to the gains in field efficiency against more traditional methods of execution.

# Chapter 2 Conceptualisation of a Field Readiness Decision Support System

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## Abstract

Knowing the readiness of a field for an agricultural operation is an important factor when creating seasonal and daily operational plans. To insure an efficient use of resources farm managers and agricultural contractors must make difficult decisions and must often rely on a “gut feeling”. A large amount of information may be available, such as meteorologically and geographical data, however this must be filtered and converted in to actionable knowledge in order for it to be useful.

In this paper, a participatory approach is used to develop a concept of a Decision Support System (DSS) to make recommendations as to when a field is ready for an agricultural operation. Soft Systems Methodology (SSM) is used to clarify the current situation, which is inherently difficult to model due to the organic nature of the system and subjective opinions of those involved. The result of the SSM is a model that is the direct outcome of the experience of farm managers and agricultural contractors, and that can further be understood by computer scientists.

The system of the proposed DSS is described in terms of the feasible datasets required and the inter relationships between the datasets, as well as suggestions of the level of detail of data. The proposed DSS is aimed to either operate as a stand-alone system taking direct inputs, or under a larger Farm Management Information System (FMIS) framework.

## Keywords

Decision Support System, Farm Management Information Systems, Field Readiness, Soft Systems Methodology

## 1. Introduction

The decision of whether an agricultural field is ready for a given operation is a complex choice influenced by many variables and uncertainties, with many available courses of action (Recio et al., 2008). The introduction of various information and communication technologies and the concept of Precision Agricultural (PA) over the past 30 years have meant that a vast amount of data has become available to

today's farm managers. A large amount of site specific data can be collected using in field sensors or satellite imagery, (Mulla, 2013), or retrieved from online data sources using the internet, (Lehmann et al., 2012). However, this data must be meaningfully interpreted and converted from data to information and knowledge to be of value in decision making. It is the purpose of Farm Management Information Systems (FMIS) and Decision Support Systems (DSS) to organise and process the available data and support the manager's decision making by reducing the uncertainty of the outcome of an action, (Rogers, 1995; Sørensen and Bochtis 2010a).

FMIS is not a new concept (Lewis, 1998), and has been used commonly in conjunction with PA as a way of handling information. FMIS has the goal of producing an encompassing information system aimed at data acquisition and supporting the processing of manually and automatically inputted data as a way to assist the decision maker (in most cases the farmer) with communication and managerial tasks (Sørensen *et al.*, 2010). Nikkilä *et al* (2010) suggests that the development of a fully implemented FMIS is outside the scope of academic research as it would require the backing of a large software developer. A feasible approach within research would be to introduce smaller components to operate under the framework of the FMIS and communicate directly with it. These components can then be easily replaced and updated, building extra robustness into the FMIS and an ability to expand capabilities with the addition of new technologies (Nikkilä *et al.*, 2012).

One criticism that has been levied against existing FMIS is that such systems can be unintuitive to operate and be over complicated due to the amount of data that is required. Lawson *et al.* (2011) discovered through surveying a large number of farm managers from four nations, that they are preoccupied with regulatory administrative work, accounting, etc. and that there is only a limited amount of time available for operating a FMIS. It is also noted that the majority of the farmers are between 40 and 60 years old, which could limit their openness to the uptake of new technologies. Whiteley (2002) also refers to the lower adoption rate of new technologies by farmers in recent years, and suggests the lack of knowledge of the benefits as a cause.

In terms of developing new information systems, McCown (2002) suggests the use of a participatory approach involving end users (here farm managers) from the outset of the development, so that an enhanced understanding of the management practices and other user-requirements can be incorporated in the design process. Social learning principals take this idea further. Jakku and Thorburn (2010) suggests that the involvement of farm managers at the early stages of development of an agricultural support system bridges the knowledge gap between scientists and farm managers, and increases their subsequent adoption of the system. Soft Systems Methodology (SSM) (Checkland, 1981) is a method commonly used

for the capture of systems involving human activities and technological process (Liu *et al.*, 2012; Mehregan *et al.*, 2012; Nidumolu *et al.*, 2006; Macadam *et al.*, 1990). The methodology outlines the process of formulating the way in which humans interact with the world by including humanistic factors into the modelling process of, for example, information management systems, and in this way holds an advantage in comparison with hard system methodologies (Sørensen and Bochtis 2010a).

Decision Support Systems (DSS) are interactive, computer-based systems and subsystems intended to help decision makers in using communication technologies, data, documents, knowledge and/or models to complete decision process tasks (Antonopoulou *et al.*, 2010). There are many examples in literature which aim to cover an aspect of an overall FMIS or agricultural based DSS, some recent examples include Voulodimos *et al.* (2010) that evaluates reproductive management practices on dairy farms and develops a model to offer advice based on the decisions economic impact; Sørensen *et al.* (2010a) puts forward a conceptualised model of a FMIS which aims to collect and process information to help in the decision making process for arable farming; Green *et al.* (2011), and Bochtis, *et al.* (2012) propose a DSS to minimise the risk of soil compaction on sensitive soil during operations with high operating loads; and Terranimo, (Stettler, 2010), a web based tool which offers support in deciding when specific soils are trafficable by estimating the stress propagation below vehicles tyres. Terranimo operates as a stand-alone system, independent of an encompassing FMIS.

Specifically within the topic of arable farming, a lot of research into DSS has concentrated on those areas which show a direct causality with crop yield, such as irrigation management and weed management, as the commercial advantages are obvious to the developer and the end user (Parsons *et al.*, 2009). These DSS are aimed at being used by farm managers as well as advisors who advise farm managers in management strategies and often directly supply products. Weed management DSS have been developed both as standalone systems and as modules within larger FMIS. A common approach has been to use models of crop and weed development as a resultant of weather predictions, and apply threshold limits to the development stages to determine when action should be taken. Large empirical databases of the available actions (such as amount/type of pesticides) and their consequences (effects on crop yields) are used in order for strategies to be accessed and the best option suggested as a solution. Utilising models and DSS in this way aims to simplify a complex situation with multiple variables and support an end user with making an informed choice about the course of action to take.

The planning and scheduling of field operations is an important part of farm management and requires, among other things, a decision on whether an agricultural field is ready for a given operation. The idea of field readiness is a criterion, or number of criteria, that a field must satisfy in order for an operation to be

executed. Field readiness is often a combination of a field's trafficability and workability. With only a limited amount of time when a field is within a state of readiness (Rounsevell and Jones, 1993), the decision of when and where to undertake an operation is important to minimise damage/costs and maximise the yield.

Trafficability is defined as the ability of the soil to support and withstand traffic, causing only minimal structural damage (Rounsevell and Jones, 1993). Structural damage of the soil is usually seen in the form of compaction of the plough layer and subsoil, which can cause significant damage to the crop growth and reduced yield, and be costly and time consuming to attempt to remove (Alakukku et al. 2003).

Workability is defined as the ability of an operation to be carried out at a specific time to give a positive result (Droogers *et al.* 1996). As different field operations' objective goals vary widely, so do the standards by which they are judged to give positive results. For example, tillage is assessed by the adequacy of the seedbed as a growth medium, this can mean that the operations must be carried out while the soil is within certain moisture levels (Munkholm, 2011; Mosaddeghi, et al. 2009; Mueller et al., 2003; Dexter and Bird, 2001), whereas the workability of the crop is more closely related to its development stage. This leads to a window of opportunity in which the conditions for workability and trafficability are satisfied and the operation can take place.

The results of the decisions made on a field's readiness have both economic and environmental impacts. Often farm managers are compelled to take action that appears to offer benefits in the short term, such as increasing machinery capacities, which can result in negative impacts, such as higher fuel usage and soil compaction, in the long term (Gunningham, 2007). It is important to balance both the short term and long term impacts in order to achieve a sustainable system.

Following the advice of Nikkilä *et al* (2010), the aim of this paper is to develop a conceptual model of a system, or a sub-system of a greater FMIS, to focus on an aspect of the overall farm management problem. Earlier conceptual models of FMIS, Sørensen and Bochtis (2010a), and Fleet Management Systems, Sørensen and Bochtis (2010b), both highlighted the importance of considering field readiness while planning field operations. While research has been carried out to model both the workability and the trafficability, the results of these models need to be translated into actionable knowledge to be utilised by farm managers and contractors. Therefore, a conceptual model of a system has been developed that offers decision support on the question of field readiness in response to present field conditions. The hypothesis is that information gathered using a participatory approach can be used as a basis for the initial steps



towards the construction of a system that will assist in resource scheduling and the execution of field operations in a profitable manner with minimal environmental impact.

In section 2 SSM is introduced as a tool to identify and characterise management systems which involve human components and are by their nature 'messy'. In section 3 the results of the direct interviews with farmers and contractors are used as a primary source of a qualitative study for deriving user experience and user requirements for field readiness decisions, as well as identifying current problems. By analysing and modelling how both farmers and contractors make decisions on field readiness, and considering the decision making process from different viewpoints, a better understanding to the perceived problems can be gained. The conceptual model of the real world system capturing and assessing the identified problems and constraints is also proposed and described by the datasets utilised and their interconnectivity. In section 4 the conceptual model is elaborated upon and evaluated, and the methodology is assessed for its fitness for purpose.

## 2. Methods

### 2.1. Soft system methodology

Soft systems methodology (SSM) is used when there is a need to identify the important elements within a real world system which is in itself hard to define, usually due to the human aspect of the system. SSM is a process of analysis of a system which leads from the initial discovery and evaluation of the system to a dedicated action to improve it (Finegan, 1994). Figure 2.1 is an illustration of the seven stages of analysis (Checkland, 1981). It should be noted that the order in which the stages should be followed is not implied by the numbering and it is not required to follow all the stages in the process of analysis. Stages 1 and 2 are both based in the real world and encompass the knowledge gathering. At Stage 3, the problem is quantified and organised into a standard formula. Stage 4 is the emergence of a feasible solution. Stage 5 is the evaluation of the process so far, while stage 6 is the interpretation of this analysis. Stage 7 is the conclusion of the process.

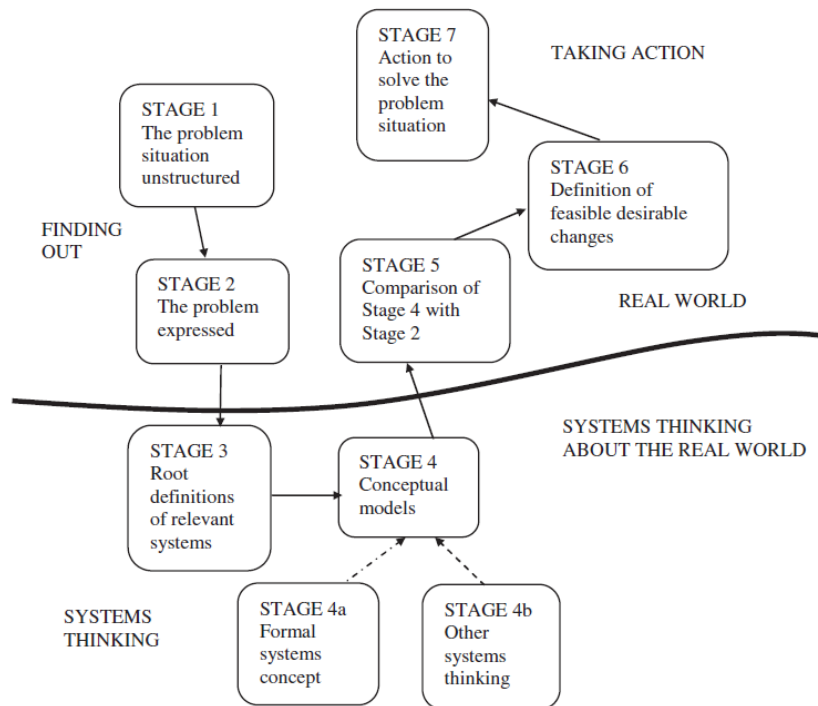


Figure 2.1: Seven stages of SSM

The seven stage analysis was later modified into four main activities (Checkland, 1999), which can be summarised as;

1. Studying/capturing the problem situation
2. Formulating models
3. Comparing the models to the problem to initiate debate/change
4. Taking action to improve the situation

Similarities between the seven stages and the four main activities can easily be seen. However, the four main activities allow for more flexibility by not strictly defining the process of each activity.

## 2.2. Empirical Data and Information Acquisition

Interviews were conducted as a way to gain insight into the current situation faced by farm managers and contractors who would be likely to use the proposed Field Readiness Decision Support System. The interviews took the forms of guided conversations, where a number of themes were put forward covering what influenced the decision process of when to execute operations. The themes discussed included, but were not limited to, economics considerations, resource management, communication protocol, data usage, and current frustrations. The interviewees were then allowed to answer and elaborate without being confined to a limited number of answers. The interviews were each carried out by the same interviewer and recorded so that they could be reviewed later. The interviews were also conducted

individually so that different parties did not affect each other's results. This is a departure from the standard SSM, in which groups are often interviewed, however it is a method used in other studies (Sørensen et al., 2010)

Four individuals, two agricultural contractors and two farm managers, were chosen to be interviewed in the first step of the process to capture the current problem situation, all of whom are based in the UK. The subjects chosen to be interviewed represented both farmers and contractors so that a balanced picture of the protocols and communication channels could be accurately drawn. The sample group size was purposely kept small at this stage of initial concept development. The first contractor concentrated on cereal production, i.e. tillage, drilling, spraying, fertilising and harvest, and the second concentrated on grass and maize silage harvest. Both of the farmers were medium size dairy farmers, the first with 180 cattle and 300 hectares of land, and the second 250 cattle and 500 hectares of land. As both of the farmers are mainly focused on dairy production, they rely on contractors to carry out most of the in-field operations. It should also be noted that both farmers are customers of the interviewed contractors. Contractors are increasingly being used by farmers, as they are able to utilise more modern machinery and systems, moreover many farmers may try to move into contracting if they invest in new equipment and want to quickly make a return on their investment (Carberry et al., 2002).

The questions asked of the interviewees were aimed at revealing their decision making process, such as what is the impetus of the decision and what information is taken into account. The interviews were influenced by the ideas of Social Learning (Pahl-Wostl and Hare, 2004), which encourages interaction to develop a shared understanding. During each interview, a rich picture was drawn as a summary of the answers given. The rich picture helped capture the interviewee's ideas in a graphical and easily interpreted way. Doing this within the interview allowed for an iterative process between the interviewer and interviewee, so that the rich picture could be created, modified and then finalised and agreed upon by both parties. Care was taken by the interviewer to ensure that the interviewee lead this process while the interviewer assisted so that the interviewer's knowledge of previous interview was not an influencing factor. Later, the rich pictures from all the interviews were consolidated to form an overall picture of the decision making process. The consolidation includes all of the elements of the individual rich pictures, including conflicting elements, to preserve all of the knowledge gained from the interviews.

Moving from the real world into the system thinking phase (stage 3 in the seven stages scheme and 2 in the four activities scheme), the decision making processes of the system to be modelled are broken down into a number of elements and formulated as a root definition. For this purpose the mnemonic CATWOE is used, each letter of which describes an element important to defining the system. C stands for customers, who

are the beneficiaries or victims of the process; A stands for actors, who are the people who carry out the process; T stands for transformation, which is the process of converting the input to the output; W stands for the worldview, which is the hypothesis of doing the process; O stands for owners, who are those who are able to stop the process; and E stands for environment, which are elements outside of the current view of the system that could potentially act upon it.

The root definition is formulated using the elements defined in the CATWOE and should be expressive enough so that a model can be created from it. The root definition should take the form of the statement 'a system to do X by Y in order to achieve Z', where X is a particular transformation process relating to T (the transformation), Y is a means in which X can be done, Z is a criteria set out, usually by O (the owners), by which X can be deemed completed and deliverable to C (the customers) (Checkland,1999).

Using these definitions, a model is proposed which attempts to fulfil the problem statement. Often more than one model is suggested so a means by which they can be evaluated is needed. Checkland (1999) offers, for evaluation, the use of the 3 Es, namely Efficacy (does it work?), Efficiency (does it use minimal amount of resources?) and Effectiveness (does it meet the longer term aim of T?). The evaluation of the concept model is stages 5 and 6, or activity 3.

Finally, from this evaluation, a suggestion can be made to improve the problem situation, as described in stage 7 and activity 4. The suggested improvements can take many forms, for example the modification of how data is collected or processed, or a complete restructuring of the current system to act in a more efficient way.

## 3. Results

### 3.1. Interviews and Rich Pictures

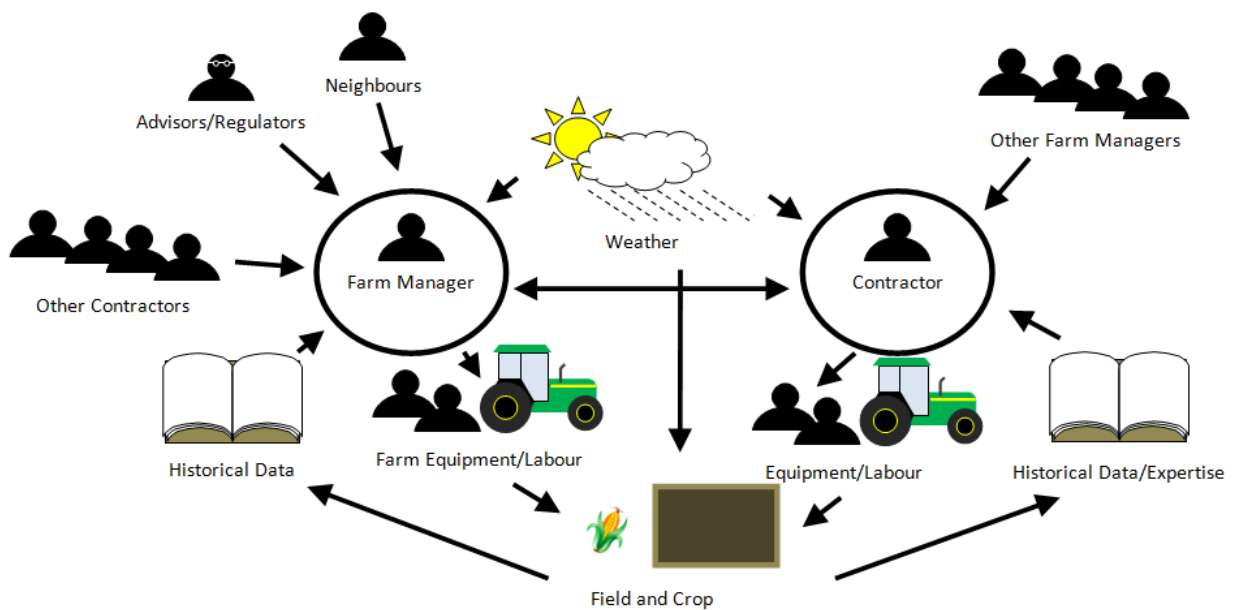
During the interviews with both the farm managers and contractors, the conversations were directed towards the current problems that are faced while deciding whether an operation should be executed at a specific location. Each respondent was asked to elaborate on data they used to inform their decision, and how information was conveyed between different involved parties. Although each respondent interviewed addressed problems they personally had to deal with, there was a general consensus. The general problems with the current situation of identifying a location's readiness are summarised in Table 1, these are then grouped into four major themes.

**Table 2.1: Summary of encountered problems**

Actions of outside entities	Scheduling is done in the short term, such as the day before, due to weather and farmers' waiting to contact contractors until their location is ready. What neighbouring farms are doing heavily influences a farm managers decision It is hard to plan around the weather, as it can be very changeable
Economic consideration	Machines need to be busy at all times, as they are expensive and their value needs to be earned back Machine idle time, due to weather or breakdowns, is paid for by contractor, and therefore needs to be minimised Contractors cannot turn down work or disappoint farm managers as they risk losing work for next year Contractors need to fit everyone into their schedule, and know in advance their working capacity Crops must yield the maximum amount of profit, as they are a large investment for the farmer
Lack of knowledge	There is not enough time to check every locations' readiness Decisions are often made on a 'gut feeling' Farm managers don't have the same task knowledge as contractors Contractors doesn't have the same knowledge of the locations as farm managers
Situation complexity	Everyone wants everything done at the same time Any plans that are made have to be flexible as the situation is likely to change Specific tasks can take a number of days and there is a need to schedule over the days and have correct weather conditions

The problems summarised in Table 2.1 highlight the complexity of the decision of a field's readiness. The main outside entity which influences the decision is the weather, which is changeable and uncontrollable. There are many sources used by the farm managers and contractors to estimate what the weather will be, however they often expect there to be a degree of uncertainty with these forecasts and must have contingency plans if the weather changes. Economic factors influence farm managers and contractor in different ways, which is to be expected as they are remunerated differently. Contractors are concerned with maintaining a high work capacitance and profitable operation of all their machines, while farm managers are concerned with the profitability of their crop. However these factors are not necessarily contradictory, and moreover if an operation is executed in a timely fashion it will be beneficial to all parties.

Both the lack of knowledge and the perceived complexity are subjective to the individual, although ignorance of these factors isn't the same as the factors having no effect. The lack of knowledge of the current state of the situation, or state of the situation either in the past or future, could be due to either a lack of equipment to gather information or lack of time/motivation to do so. This also relates to the perceived complexity of the situation, as if the gathered information does not decrease the complexity is there worth in collecting it? All of the factors will be addressed by the final solution, since it will be an aim to remove the complexity and support the decision making process for a profitable outcome.



**Figure 2.2: Rich picture of the Current situation from both the Farm Manager's and Contractor's point of views**

Continuing on from Table 1 and again with the help of the interviewees, a rich picture of the current situation was formulated, Figure 2.2. The rich picture aims to summarise the considerations that both the farm manager and the contractor must take during the decision making process concerning field readiness. For this reason both the farm manager and the contractor are focal entities within the rich picture. This is a departure from the standard SSM rich picture, which has one focal entity, however it was important to incorporate both so that their views could be represented. The main use of the figure is not the outcome itself, but rather the process of the construction of the rich picture involving the interviewer and interviewee. Although at first, the interviewees were sceptical of the merits of the method, as time progressed and the rich picture formed, the process proved to increase the interaction of the interviewer and interviewee, and the rich picture developed further with each iteration. The process helped both sides gain a greater understanding of the current situation, forcing them to delve deeper into it and consider it from different perspectives.

As can be seen from the diagram the most important elements are concentrated near the middle of the diagram and affect both the farm manager and the contractor, these being weather, equipment and labour, and the fields and crops. Both the farm manager and the contractor are also influenced by historical data although the content of these data might be very different, such as the readiness of the field in previous years for the farm manager and the outcome of similar operation in similar conditions but at different locations for the contractor. Important data can of course be shared between the two, especially easily quantifiable data such as past yield or soil maps, which can help in the decision making process.

### 3.2. CATWOE and the Root Definition

After the capture of the problem situation by the interview process and the development of the rich picture, the problem situation was formalised using the root definition and the CATWOE mnemonic. The CATWOE mnemonic of Customers, Actors, Transformation, World View, Owners and Environment were formulated as;

- C – Farmers
- A – Contractors/Farmers
- T – Empty field > Harvested crop
- W – Crops can be produced and harvested in a way that is profitable and non-damaging
- O – Farmers
- E – Weather, Soil conditions, Market prices

The transformation process is the entire process of converted an empty field to a harvested crop (T), this encompasses many operations that may be either carried out by contractors or the farmers themselves (A). While the contractors make decisions about when to execute operations and operational setups, the farm manager is the owner of the process (O) as they decide what crops will be planted/harvested and can override a contractor's decision. The system boundary defines the farmer as the end customer (C). While there may be a larger supply chain for the harvested crop in which the farmer may be an actor rather than the end customer, this is outside the scope of this research. The world view (W) is that which is being suggested in order to modify the problem situation, rather than that which may be currently held. The weather, soil conditions and market prices (E) are all outside of the control of the system but have an influence upon it.

Using the "X by Y to achieve Z" formulation, the Root Definition is defined as "A DSS to interpret data of a sufficient detail to offer advice of remote locations' readiness as the basis for and assisting with vehicle/personnel assignment and scheduling". This root definition encompasses all that the DSS needs to achieve as part of the FMIS and to satisfy the needs of the user. Since the implementation of the concept is as yet undefined, the Root Definition must be flexible to allow for interpretation. The inclusion of the phrase "data of a sufficient detail", infers that level of detail require to offer advice of remote locations' readiness is not known and will need to be established in later stages of development.

### 3.3. Conceptual Model

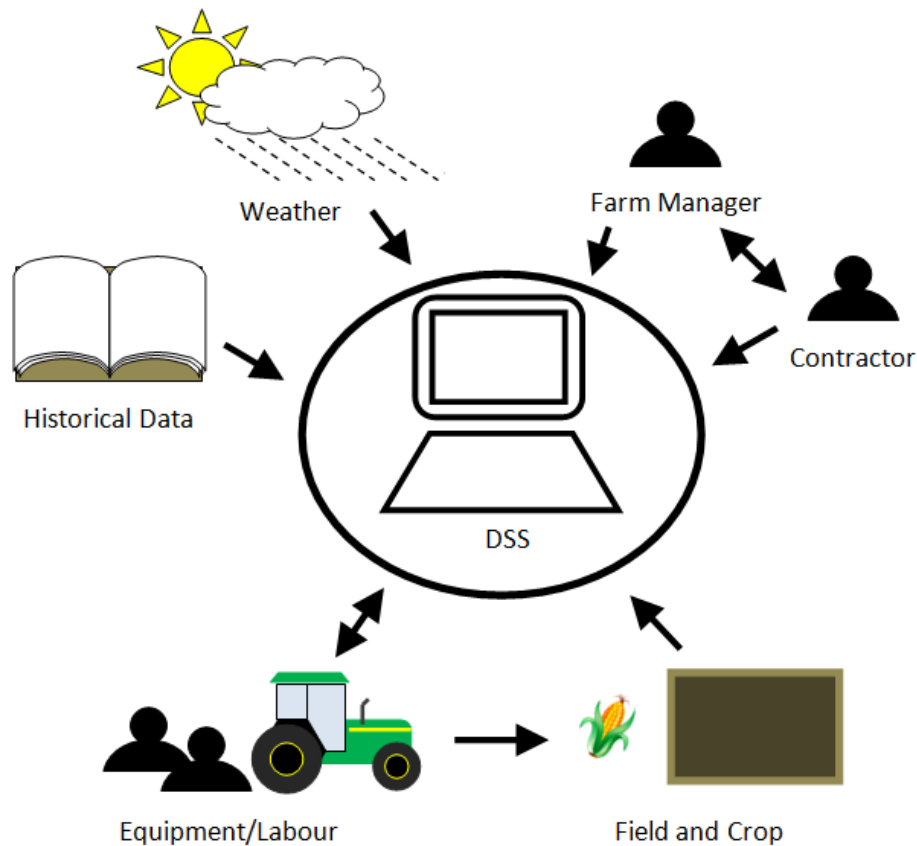


Figure 2.3: Conceptual Model

The rich picture, root definition and CATWOE mnemonic are used to construct the proposed conceptual model of the system surrounding the Field Readiness DSS, Figure 2.3. The focus of the conceptual model is changed from the farm managers and contractors to the DSS. With the DSS in the centre of the model, information is collected from weather (both historical and forecast data), farm managers, contractors, historical data of previous operations, field and crop data (such as various maps) and equipment and labour availability. The conceptual model aims to be structured independent of whomever the user may be in order to fulfil the CATWOE definition, and also independent of the actual implementation and deployment of the DSS. The output from the DSS is a schedule for the equipment and labour which is then executed, again by either the contractor or farm manager, on the field and crop to produce a harvested crop. A DSS will also provide credence to decisions made and help ease the relationship between contractor and farm manager. Operations can be scheduled on a Farm level or on a Regional level, and in both Strategic Planning and Operational Planning, as described in Sørensen et. al. (2010).



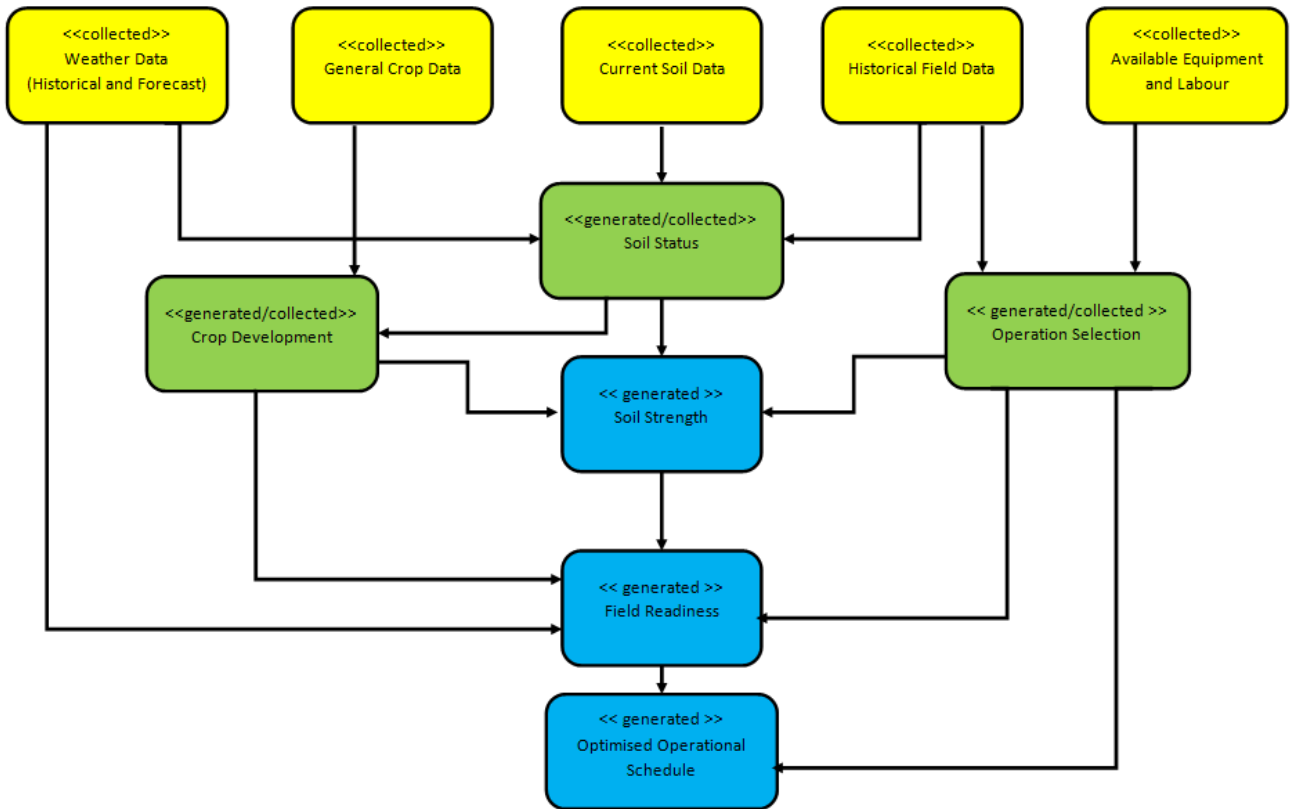


Figure 2.4: The proposed Field Readiness DSS

The conceptual model describes the framework within which the DSS will operate. Figure 2.4 shows a detailed layout of the flow of information within the Field Readiness DSS formulated using Unified Modelling Language (UML) notation. Moreover state diagrams, a subset of UML, are used, with each dataset describing a state and data flows showing the transitions between each state. Datasets are shown as rounded rectangles, with the flow of data between them represented by arrows. The status of each dataset is expressed on the first line in chevrons (<< >>), and are restricted here to either; collected, generated/collected or generated. Colour coding is also used to differentiate between the different statuses. A larger FMIS is described using the same UML notation in Nash et.al (2009).

Collected datasets are to be retrieved from sources outside of the DSS, such as online data repositories, on farm sensor systems, locally (within an overlying FMIS) stored databases, or direct user input. This retrieval will be automated in many cases to increase the ease of use of the DSS, however more detail could be gained if this user wishes to manually input specific data. Generated datasets are envisioned to be generated within the DSS, utilising information from other datasets. The methods used to calculate the generated datasets are open to modification although the functionality must remain the same. Datasets that have a Generated/collected status are available to either be collected or generated depending on the detail or accuracy needed by the user, or the available data. Typically if the dataset is available as collected

data this would be used over a generated dataset. Table 2 describes the possible data within each dataset as deemed necessary to the functionality of the DSS.

**Table 2.2: Functionality and Inputs of DSS**

Dataset	Status	Description of the possible data contained within the datasets
Weather Data	Collected	Recorded weather data and short term and long term forecasts. Data including temperature, precipitation, solar radiation, evapotranspiration, wind speed, etc.
General Crop Data	Collected	Data categorising different crop types such as; phenologic development curves, nutrient requirements, projected yield curves
Soil Data	Collected	The description of the soil at the location(s), such as; percentage clay, silt and sand at multiple depths, nutrient and mineral composition, and hydraulic properties.
Field Data	Generated	The geographical location of the field, variability of soil within the field, digital elevation map, previous use of the field
Available Equipment and Labour	Collected	List of available equipment, both owned and available for hire. Machine type, size, capacity, operating speed, non-operating speed, setup time, and operating cost.
Soil Status	Generated/collected	The current status of the soil throughout the profile, including soil moisture, nutrient content,
Crop Development	Generated/collected	The development of the crop over time as a result of the weather and operations, crop's nutrient needs, susceptibility to disease
Soil Strength	Generated	Resultant stresses caused within the soil profile from vertically applied forces and pressures. Also the malleability of the soil in response to horizontally applied forces.
Operation Selection	Generated/collected	The operations required to be executed at the field in order to cultivate the crop
Field Readiness	Generated	Readiness of the field to the desired operation. This also includes setup requirements of machinery
Optimised Operational Schedule	Generated	Detailed plans for individual machines for the execution of the operations, including start time, goal end time, locations, and machine setup parameters. The plan is optimised to minimise costs and the environmental impact of the operations.

Visualisation will be offered to the user at stages throughout the processing, to add detail to their understanding or clarify the basis for the advised action, if the user desires so. However the level of detail should be limited so as not to overwhelm the user.

## 4. Discussion

### 4.1. The Proposed DSS

The three criteria with which SSM evaluates proposed problem solutions are; efficacy, efficiency and effectiveness. Specifically for the Field Readiness DSS these can be formulated as three questions to be asked of the model;

Efficacy – Does the DSS offer a solution for completing the operations at desired locations?

Using the information which is fed into the DSS, it will be able to offer solutions. Specifically using models to interpret the weather, field, crop and historical data to propose a definition of readiness and then create schedules based on this and the available machinery.

Efficiency – Are minimum resources, ie equipment and labour, used in the completion of the operations?

The DSS will perform optimisation on the scheduling in order to get the most efficient result. The schedules may be optimised for the minimal amount of resources used in a number of ways, such as minimal time spent working, least machines used, minimal machine idle time, etc., or any combination of these.

Effectiveness – Is the field left in a state that is considered to be optimal for crop growth (i.e. was it workability) and only minimally damaged (i.e. was it trafficability)?

Trafficability is expected to be evaluated by modelling the soil strength, using the weather, field, crop and historical data, and by including operational data which will describe the loads expressed on the soil. Workability is expected to be evaluated by modelling the reaction of the soil and crop to the suggested operations (such as the seedbed produced by tillage or subsequent weed abundance for spraying) and modelling the available water and nutrients to the growing crop, the operation selection can be accessed by the positive (or negative) results that are produced. All of the required information is collected or modelling within the proposed DSS, making it available for the calculations. Both the trafficability and the workability are combined within the definition of the readiness of the field which is then included in the scheduling/optimisation process.

Figure 2.4, shows how information is initially derived from the collected data ensuring that real world data is at the basis of all of the model generated data. Moreover information from many sources and datasets are needed to further generate more datasets. This interconnectivity builds robustness into the system so that decisions aren't based on a single piece of information, which may be incorrect and incur significant uncertainty. The five "collected" datasets in Figure 2.4, Weather Data, General Crop Data, Current Soil Data, Historical Field Data and Available Equipment and Labour, are derived directly from the inputs into the DSS shown in Figure 2.3, Weather, Historical Data, Equipment/Labour and Field and Crop. The five dataset encompass the scope of data needed to describe the complexity of the current situation and are the starting points of the later generated dataset.

The Farm Manager and the Contractor entities in Figure 2.3 relate to the three generated/collected datasets, Crop Development, Soil Status and Operation Selection, as currently the observations and

experience of the farm manager/contractor are used to collect, assess and determine these data. It is important to include some user inputs into these datasets, however the degree to which the datasets are to be collected or generated allows the system to be operated under different conditions and should be determined at a later stage of development. For example some users will wish to be able to input vast amounts of data, whereas others will not have the time/inclination to do so. While collecting all possible data will inevitably lead to a result based on more accurate data, the costs of collecting this data, such as installing sophisticated sensor networks or expert evaluations, may outweigh any benefits incurred in terms of improved decision making. It could also be the case that previous datasets, or user inputs, are used to determine whether subsequent datasets are needed to be collected or generated, if this helps the DSS operate in a more efficient way.

The three “generated” datasets, Soil Strength, Field Readiness and Optimised Operational Schedule, are all outputs of the models within the DSS. The methods used in their generation will be defined in the further development of the system. These models interpret the prerequisite datasets to result in the final dataset, the Optimised Operational Schedule. If pre-existent models are incorporated within the system a non-trivial amount of work may be required in order for the information to easily flow between datasets. The output of the DSS, as shown in Figure 2.3, is the input into the Equipment/Labour to execute the operational plan on the field area.

Table 2.2 adds detail to the datasets depicted in Figure 2.4. The description of the data needed within the dataset is given, such as temperature is needed within the Weather Dataset, however the attributes of the data isn't specified, such as the frequency of observations or the precision of the values. This detail cannot be elaborated on at this conceptual stage of development, but once a functioning DSS has been developed a comparison of how increasing the levels of precision of different data and datasets increase the value of the DSS output will need to be performed. The comparison will focus on economic factors, as well as the DSS output's fitness of purpose.

## 4.2. Evaluation of methods

As mentioned in the introduction, SSM are often used to describe systems that are influenced by human factors, since most of the problems raised in Table 1 can be described as humanistic problems it can be seen that SSM was a good choice of methodology to be used.

In comparison to using hard system thinking methods to design the system, SSM allows for more flexibility. Quality Function Deployment, QFD, is an example of a hard thinking method which has often been used in the conceptualisation and development stages of a product or project (Carnevali, 2008). The process of

QFD requires the development of a quality matrix, evaluating the customer voice to a quantifiable list and defining properties and specifications, whereas SSM requires the construction of a rich picture to capture the customer's worldview. The construction of the rich picture, rather than the quality matrix, is more conducive to encourage participation from the customer, something which is deemed important for the development of FMIS by earlier studies (Meensel et al., 2012). Guided conversations and development of the rich pictures allow the subjects of the interview to be interactive with the result, so the process can better capture their thought process. Without limiting the interviewees' responses to the predefined answers of a questionnaire or ranking items in order of importance, new and unexpected areas of interest could be discussed to create a broader picture. By incorporating the ideals' of the end users from the very beginning, a relationship was cultivated which allowed for cross social learning (Pahn-Wosti and Hare, 2004). Also their involvement in further stages of the system's realisation should improve the selection or development of the components of the DSS to suit the end users' requirements.

Incorporating the views of two different entities, being farm managers and contractor created an aggregated perception of the situation. The interviewee group was purposely kept small so as not to dilute the answers of individuals amongst a much larger group. Nikkilä et al. (2010), states that regional variations in agricultural practices can affect the design of a FMIS. As a result a larger group may have contrasting views that,, may lead to an incoherent system if incorporated at the early conceptualisation stage. The converse of this is also true, i.e. that a small group may not include enough diversity and that the concept model may only deal with the needs of a specified few. However similar results were found by Clarke and Naylor (2002), which proposes a framework around a DSS for the improvement of Weed Management systems. During the development process, although a specific method is not named, interviews are conducted with potential end-users. The interviews aimed at capturing the needs of a final DSS, rather than the process of making the decision, however the responses of the interviewees fell into the same categories as listed in Table 1, being lack of knowledge, perceived complexity, economic and outside entities. The framework around the DSS is also similar to the conceptual model in Figure 2.3, while the components are labelled differently they fall within the same five categories; User information, Weather, Historical data, Equipment/Material/Labour, and Field and Crop. By obtaining similar results to those of previous studies infers the validation of the results as being representative of the demographic. Nevertheless to ensure that the conceptual model is not based on a view point solely held by the sample group, additional farm managers and contractors should be utilised during development and testing of the DSS past the conceptual stage.

Using UML notation to describe the proposed DSS, Figure 2.4, efficiently translates the needs of the farm managers and contractors into a language understandable by computer scientists and thus enables it to be easily integrated into larger FMIS, such as described in Nash et al. (2009) or Sørensen and Bochtis (2010a). The conceptual model can also be used in the further development of FMIS and their supporting infrastructure. The details of the datasets required to be collected, Table 2.2, are requirements of the data that must be made available by the FMIS.

From the conceptualised system presented here, the next step is the embodiment design. The embodiment design will develop a working prototype ready for the testing and iterative phases of the design process. The format in which the datasets are collected/received/generated/stored isn't addressed within the scope of this work as this will depend greatly on how the DSS is chosen to be implemented. There is likely to be set formats for data collected from external sources, as well as data which are outputted to external sources. Therefore a great deal of work will be concentrated on translating data to the format of the DSS. The format of the data within the DSS will depend on the platform/software on which it will operate. This may be a free choice of the developers, a suggestion from further interviews with invested actors, or limited by the pre-existing methods sourced to be part of the DSS.

## 5. Conclusion

SSM provided a framework within which structure could be given to a complex situation involving organic processes and humanistic factors, which would have been difficult to define by other means. The process was initiated by current actors within the system, who were then heavily involved in the development and progression. The rich picture developed from the interviews captured how the current actors saw the problems faced within the industry when deciding on a field's readiness, particularly the relationship between the farm manager and the contractor. Capitalising directly on their insight and experience meant that the development of the DSS was able to focus on fulfilling their requirements. This participatory approach induced a culture of social learning which helped form the "real world" problem of decision making into the "system thinking world" of system analysis.

The conceptual model, which was influenced by the problem description of the interviewees, creates a framework within which the DSS can be formulated. The description of the functionality and inputs to the DSS are independent of a specific implementation, however it fulfils the current problem situation and offers solutions based on a modified world view that "Crops can be produced and harvested in a way that is profitable and non-damaging".

The DSS is suited to act within the conceptual model as a standalone system or as part of a larger FMIS receiving information automatically rather than from a farm manager or contractor. The proposed modular layout also allows for the upgrade or replacement of modules if needs be, adding to the overall robustness of the system. Utilisation of the UML notation should allow for easy development of the conceptual model into a prototype system, and also aid in fitting the system into pre-existing FMIS.

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# Chapter 3 Modelling the readiness of soils for different methods of tillage

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## Abstract

While research has been conducted on the workability and trafficability of soils separately, it is the combination of these two factors which allows a decision to be made about a field's readiness. Knowledge about when a field is ready for an operation is essential when planning when and where operations should be executed, so that they can be executed in an efficient and cost-effective way. In this paper, methods for evaluating workability and trafficability were combined to produce a novel tool for assessing the readiness of a location for tillage operations over a period of time.

Three soils within a field were examined using the proposed tool to estimate the number of days they were in a state of readiness for conventional tillage and minimum tillage over an 11 year period. The soils were assessed for when they were trafficable, when they were workable and when they were both. The assessments were made based on the soil texture, simulated soil water content and physical parameters of machines likely to be used for the defined operations. All of the soils were ready for longer periods of time for minimum tillage than for conventional tillage. During autumn tillage, it was approximately twice as likely that the field would be ready for minimum tillage as it would be ready for conventional tillage. The tool offers the means for comparing operational management decisions either as a standalone tool or as a part of a larger farm management information system.

## Keywords

Soil workability; soil trafficability; field readiness; farm management information system; tillage operations

## 1. Introduction

The condition of the soil in which a crop is planted significantly influences the quantity and quality of the crop produced. Soil parameters such as available water or nutrient content can be readily quantified and linked to the eventual crop yield (Godwin and Miller, 2003), whereas soil condition is more difficult to quantify (Pikul et al., 2001). The structure of the soil is a key factor and it can often be damaged by excessive loading (Nevens and Reheul, 2003), or by tillage being executed at a time when it is not most

beneficial (Keller et al., 2007). To improve the quality of the soil structure during planting, a tool is needed for estimating and evaluating field conditions to ensure tillage operations are executed at opportune times so that the best outcomes are achieved.

To qualify the suitability of soils for an operation, the term readiness is introduced. The readiness of a soil for an operation is a combination of the workability and trafficability (Rounsevell and Jones 1993), both of which are influenced by the soil properties, the weather, the crop, the operation and the machinery used. The time a field is in a state of readiness for an operation is the window of opportunity. Typically in England, over a year, fields have a window of opportunity for tillage of a few weeks in autumn and spring. The readiness of a field can be utilised to create efficient schedules for machine operations (Edwards et al. 2013). The costs associated with executing operations when the field is not at an optimum level of readiness account for a large proportion of the annual variable costs a farm manager may incur (de Toro, 2005). The number of days a field might be ready for an operation is also valuable when making decisions on fleet sizing and machine capacity, to ensure that there is enough time to execute all operations at all locations within the window of opportunity (Søgaard and Sørensen, 2004).

Included in a 1984 soil survey in England and Wales was an estimation of when different types of soils would be trafficable, based on the meteorological estimate of when fields would be at field capacity and a wetness factor for each soil type related to their permeability (Ragg et al., 1984). The workability of the soils was also considered as an interaction between the climate and the soil properties. The workability and trafficability were combined to produce an estimate of the average number of Machinery Work Days in autumn, 1<sup>st</sup> Sept to 31<sup>st</sup> Dec, and spring, 1<sup>st</sup> March to 30<sup>th</sup> April, which is defined as “the number of days when the soil can be worked with acceptable risk of damage to soil structure”. The methodology used was based on the use of machines much smaller than those being used today, so it’s hypothesised that the results may no longer be applicable to modern practices. Also advances in the research fields have introduced more analytical methods for determining both workability and trafficability which could be utilised.

Trafficability is defined as the ability of soil to support a vehicle while only causing negligible, or reversible, damage (Rounsevell and Jones 1993). Damage to the soil can originate from compaction (an increase in bulk density) or deformation (changes to the structure). Both forms of damage limit the soil’s water holding capability, limit the flow of nutrients within the soil and obstruct root development, all of which adversely affect the final crop yield. Evaluation of soil trafficability is based on the comparison of stresses applied to the soil and soil strength. Soil strength and deformation depends on both intrinsic properties (soil texture, mineralogy, content and nature of organic matter) and water content. Bigger tyres, lower inflation

pressures and tracks, help to reduce the stress at the tyre/soil interface (Lamandé and Schjønning, 2008). However, as agricultural machines become larger, subsoil layers are still at risk (Lamandé and Schjønning, 2011), which can result in a reduced number of days a field may be trafficable of an operation.

Söhne (1953, 1958) first suggested a simple analytical model for the stress propagation within the soil profile based on the work of Boussinesq (1885) and Fröhlich (1934). This model proved reliably to predict the vertical stresses from the contact between the soil and tyre (Keller and Arvidsson 2004, Keller and Lamandé, 2010). Schjønning et al. (2012), proposed the '50-50 rule' which states "at water contents around field capacity, traffic on agricultural soil should not exert vertical stresses in excess of 50kPa at depths >50cm". This rule of thumb aims to minimise subsoil compaction which would then be difficult to remediate using conventional techniques. The 50-50 rule introduces a measuring standard by which an operation can be judged acceptable.

Workability is defined as the ability of an operation to be executed within predefined limits for damage and performance quality parameters. In the context of tillage, workability is defined as the ability of the soil to produce an adequate friable tilth in preparation for seeding without causing smearing or compaction (Rounsevell and Jones, 1993).

Soil penetrometers have been used to estimate a field's workability, as they can give a good indication of the current soil strength and are relatively cheap and easy to use (Earl, 1996). However, each site must be visited in order to be assessed, which is time consuming and may prove impractical in today's modern agricultural practices.

Earl, (1996) relates measurements using a soil penetrometer to measurements of soil water suction, also referred to as matric water potential, to determine the maximum allowed soil water suction pertaining to tillage operations. Only the "wet end" of the soil moisture limit was considered as under normal UK conditions soil rarely becomes too dry for tillage during spring and autumn. Results were given for six soil types. For all of the soils, the trafficability limit was always "wetter" than the workability limit.

In a later study by Earl (1997), the soil moisture deficit was used to predict the workability and trafficability of soils typical of central and eastern England and provided the average annual days when the soils are workable and trafficable. The soil moisture deficit is the amount of water needed to bring the soil profile up to field capacity. Here, the workability for tillage operations is defined as the ability of the soil to be manipulated in a desirable way. It should also be noted that for the assessment a 70 kW (~94 horse power) tractor was considered for the soil trafficability decision, whereas now a much larger tractor, approx. 150

horse power by modern standard, would be used for the operations, making the 1997 assessment redundant.

Rounsevell and Jones, (1993) suggested that if a field is workable then it must be trafficable and that the converse was not necessarily true, however this is an over simplification. Trafficability is a condition related to the vehicle being used and there may well be a case, especially when large vehicles are being used, when the soil is workable but not trafficable. In this case, smaller machines would have a larger window of opportunity to execute an operation than larger, heavier, machines, allowing the smaller machine to have a small hourly work capacity while maintaining a competitive annual work capacity.

Minimum tillage, previously referred to conservation tillage, is the practice of only performing tillage to a shallow depth. The benefits of minimum tillage have been widely documented (Morris et al., 2010) and include reduced energy consumption, reduced labour (Ozpinar 2006; Sørensen and Nielsen, 2005), and reduced soil erosion (Sharma et al., 2011). Minimum tillage is best suited to heavier stable soils, producing a better quality seedbed than conventional tillage (Wade et al., 2006). Jones et al. (2006) suggests that European farmers may be adverse to minimum tillage as they see a clean ploughed field as an indication of good land management and perceive minimally tilled fields as “untidy”. However the change from conventional tillage systems to minimum tillage systems could have an impact of both the number of days a field is workable and trafficable as less of the soil profile is required to be workable and less load it added to the tractor due to minimum tillage implements usually being trailed. Being able to evaluate different methods of tillage would be a great advantage to a farm manager when making operational management decisions such as fleet sizing and machine capacity.

In this paper, a new decision support tool is proposed to estimate the readiness of a field for tillage using available soil and weather data. By helping estimate when a field is in a state of readiness, it is hypothesised that tillage operations can be planned to give better results in terms of production of an adequate tilth and maintaining good subsoil structure. The tool is demonstrated for a real field using recorded weather data over an 11 year period. Two methods of tillage are evaluated as to the number of work days available annually when the operation can be executed.

## **2. Methods and Materials**

The objective of the decision support tool is to estimate when soils are trafficable and workable. It was required that the tool would make an assessment based on readily accessible data without the need for locations to be physically visited. Therefore some soil properties were required to be modelled, such as the hydraulic properties using establish transfer functions, and soil moisture content using a

soil/water/environment model. The collection of relevant datasets and the generation of subsequent datasets using equations and models formed the basis of the architecture of the tool.

## 2.1. The tool architecture

The basic layout and connectivity of the datasets used within the decision support tool are shown as a state diagram in UML notation, Figure 3.1. The datasets are depicted as rounded rectangles while the flow of information is shown as arrows between the datasets. The diagram is slightly modified from a conventional state diagram, in that the status of each dataset, shown on the first line of each dataset in chevrons (<< >>), has been replaced in the diagram by the source of the data. A similar scheme was used to depict a large Farm Management Information System by Nash et al. (2009).

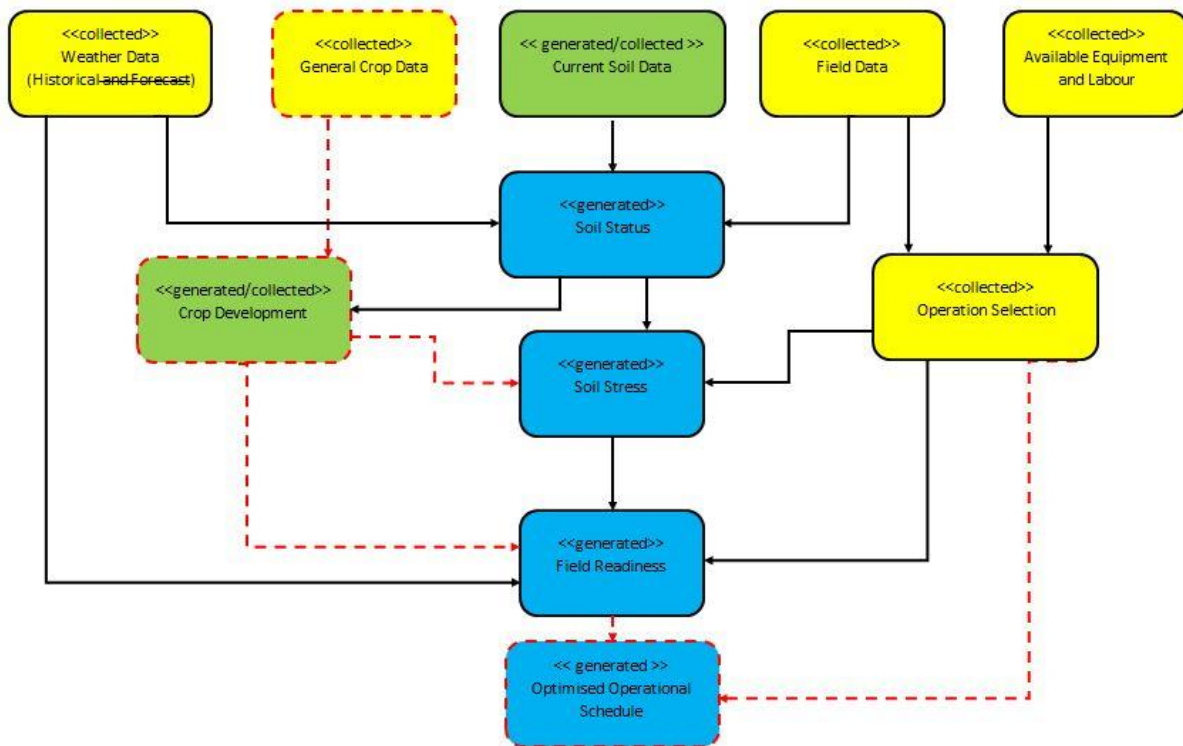


Figure 3.1: Tool Architecture

In Figure 3.1 there are three types of dataset; “<<collected>>”, “<<generated/collected>>”, and “<<generated>>”. The “<<collected>>” datasets contain data that is collected from outside sources such as online databases, data files, or direct user input. The “<<generated/collected>>” datasets contain data which has been collect from outside sources, however more data is required than is available from the source so additional data is generated. The “<<generated>>” datasets are generated within the tool, through the analysis of other datasets. The methods used to generate these datasets are detailed later. The

datasets and arrows that are shown as dashed red lines indicate entities which were included in the original concept model however they are not necessary for the current implementation of the tool.

The components of the decision support tool will now be described in more detail, explaining the data within each dataset defined and the methods used to generate data.

### 2.1.1. Weather Data

The daily weather data was collected at Newport Shropshire station (station 4787). The station is within 500m of the test field and the data covered the period between January 2000 and December 2011. The weather data includes wind speed, dry bulb temperature, wet bulb temperature, max air temperature, min temperature, soil temperatures at 10cm, 20cm and 100cm, relative humidity, rainfall, and solar radiation. The data was provided in MS Excel files and transferred, via an interface, into a system specific dataset specifically formatted for the decision support tool.

### 2.1.2. Field Data

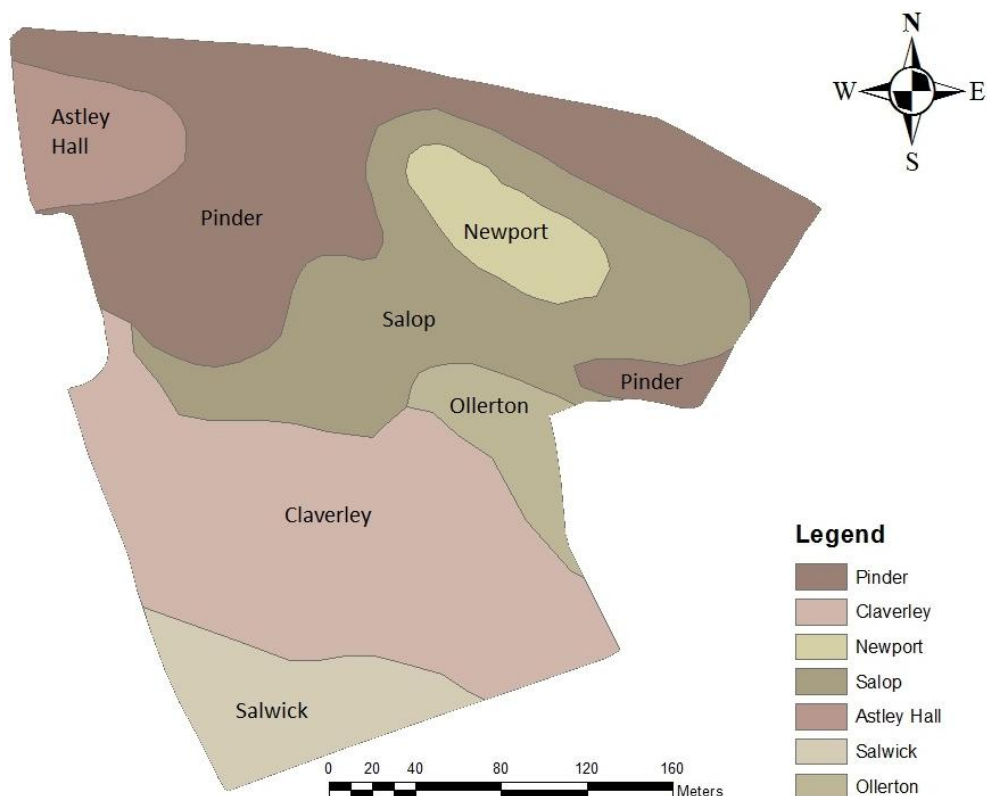


Figure 3.2: Soil type map of test field

The field to be used as the test field is located at Harper Adams University (52°46'N, 2°25'W). The area was part of a national soil survey (Ragg et al., 1984) when the soil types were well documented. Figure 3.2 shows the soil types within the field and their spatial variability.

The three main soil types were Pinder, Claverley and Salop, (Eutric Albic Luvic Stagnosols, Chromic Eutric Albic Luvic Stagnosols, and Chromic Eutric Albic Luvic Stagnosols, respectively, (WRB, 2006)) which make up approximately 80% of the total area of the test field. The field is mainly flat with only a maximum variation of 2 meters between the highest and lowest points.

### 2.1.3. Soil Data

The soil properties of the three main soil types in the test field, as determined in the 1979-1984 study (Ragg et al., 1984), are listed in Table 3.1.

**Table 3.1: Soil properties of most abundant soil types, a Colborne 1981, b Ragg 1984, c Jones 1983**

Soil	Pinder <sup>a</sup>				Claverley <sup>b</sup>				Salop <sup>c</sup>			
Depth (cm)	15	19	46	111	18	53	84	110	22	37	58	102
Sand %	39.4	42.5	44.7	27	56.9	56.7	44	41	39.1	36.7	19	11
Silt %	38.5	41.5	39.8	44	26	27.9	34	36	40	36.7	40	43
Clay %	18.3	14.9	14.9	29	13.5	14.8	22	23	18.5	25.8	41	46
Organic Content %	3.8	1.1	0.6	0	3.6	0.6	0	0	2.4	0.8	0	0
Bulk Density g/cm <sup>3</sup>	1.07	1.07	1.34	2.07	1.05	1.55	1.7	1.8	1.3	1.64	1.54	1.44

Using the collected soil properties, the soils' hydraulic properties were estimated. Continuous pedotransfer functions developed by Wösten et al. (1999) were used to estimate the parameters of the van Genuchten equation.

$$\theta = \theta_{SAT} - \theta_{RES} \times \left[ 1 + \alpha h^n \right]^{-m} + \theta_{RES} \quad 3-1$$

The van Genuchten equation (Equation 3-1) relates the soil water content to the matric water potential, where  $\theta$  is the soil water content,  $\theta_{SAT}$  is the soil water content at saturation,  $\theta_{RES}$  is the residual soil water content,  $h$  is the modulus of the matric water potential,  $\alpha$  is a scaling factor for the water potential, and  $m$  and  $n$  the parameters which govern the shape of the curve (Van Genuchten, 1980).

The optimal soil water content to execute tillage is defined as the soil water content at which tillage produces the greater proportion of small aggregates (Dexter and Bird, 2001). When tillage is performed at greater soil water contents then large clods can form and smearing can occur. Similarly when tillage is performed at lower soil water contents excessive forces must be employed. This leads to an upper (wet) and a lower (dry) soil water content limit at which tillage may be executed to produce preferable results and the soil can be defined as workable.



The optimal (Equation 3-2), upper (Equation 3-3) and lower limits (Equation 3-4) were then defined according to Dexter and Bird (2001).

$$\theta_{OPT} = \theta_{SAT} - \theta_{RES} \times \left(1 + \frac{1}{m}\right)^{-m} + \theta_{RES} \quad 3-2$$

$$\theta_{UPL} = \theta_{OPT} + \theta_{SAT} - \theta_{OPT} \times 0.4 \quad 3-3$$

$$\theta_{LPL} = \frac{2 \times \theta_{OPT} \times h_{OPT}}{h_{LPL}} \quad 3-4$$

These workability limits were stored along with the soil properties and used to define each soil.

#### 2.1.4. Available Equipment and Operational Selection

**Table 3.2: Wheel loads for tillage setups**

		Conventional Tillage	Minimum Tillage
Front	Wheel Load	19.1 kN	19.1 kN
	Tyre	520/65R28	520/65R28
	Peak pressure in the tyre footprint	102 kPa	102 kPa
Rear	Wheel Load	18.4 kN	25.8kN
	Tyre	650/65R38	650/65R38
	Peak pressure in the tyre footprint	68kPa	95 kPa
Implement	Wheel Load	~	24.5 kN
	Tyre	~	520/50-17
	Peak pressure in the tyre footprint	~	112 kPa

John Deere 6930 Premium was chosen as a representative of an average tractor that might be used, and was designated as the only vehicle eligible to be selected by the tool's Equipment and Operation Selection process. The tyres used on the tractor as recommended by the manufacturer were 520/65R28 and 650/65R38 of the front and rear, respectively (Table 3.2). All of the tyres were inflated to the manufactures recommended working pressure and the effects of different tyre inflation pressures were not considered. The tractor was weighed using individual weigh pads placed under each tyre and both with the tillage equipment attached and without, also multiple replicates were taken so that the results could be averaged.

Two operations were chosen to be compared; conventional tillage and minimum tillage. For the conventional tillage operation, a 3m plough working to a depth of 25cm was considered. Since the plough is

attached to the tractor via a 3 point linkage system, the load on the tractors axles is increased at the rear and decreased at the front. The axle load would also increase due to the dynamic weight transfer, however, in this study only the static loads are being considered. During operation one side of the tractor drives in a furrow created by the previous pass, meaning that for trafficability calculations the application of soil-tyre interface stress is beneath the soil surface. The depth of the soil-tyre interface was selected to be 12cm. The application of the soil-tyre interface is shallower than the tillage depth because it is assumed that the tractor cannot run directly on the bottom of the plough layer as the tyres on the tractor considered are wider than the furrow width of the plough. If this was not the case and the soil-tyre interface was applied at the tillage depth, 25 cm, the stresses within the soil profile would be increased and the number of trafficable days would be an over estimate.

For the minimum tillage operation, a Vadersted TD 300 was considered. Unlike the plough, the Vadersted TD 300 is trailed and attached to the tractor via the rear draw bar. This increases the static load on the rear tyres and there is also the addition of the supporting tyres of the implement which must be considered in the trafficability calculation. The minimum tillage operation was determined to require the top 7cm of the soil to be workable in order for the operation to be executed.

The wheel loads for the tractor and implements are summarised in Table 3.2. Tillage is most often carried out in either spring or autumn, however in this study only autumn tillage between 1<sup>st</sup> Sept and 31<sup>st</sup> Dec is considered.

### *2.1.5. Soil Status*

The soil status refers to the soil water content at any present time within the simulation period. The variation in the soil water content over time is calculated using DAISY (Abrahamsen and Hansen, 2000) a soil, water, and crop balance model developed at University of Copenhagen. There are a number of soil water crop balance models which could be used for the purpose of predicting the soil water content. A recent review of crop growth models, (Palosuo et al., 2011), compared 8 widely available models and concluded that DAISY had the best all round performance.

Using the weather data and soil properties, DAISY models the response of a one dimensional soil column and outputs, among other results, the soil matric potential, which is linked to the soil water content using the van Genuchten equation, Equation 3-1.

The data is stored as the matric potential within the soil at a number of different depths with a daily frequency. The frequency is in response to the frequency of the available weather data.

### 2.1.6. Soil Stress

It is important to have a good description of the stress distribution at the tyre soil interface as this forms the upper boundary of the calculation of the soil stress (Keller, 2005). The stress distribution at the contact interface between the tyre and the soil is modelled using FRIDA (Schjønning et al., 2008). The model was developed for agricultural tyres. The parameters of the FRIDA model were estimated from the loading characteristics (tyre diameter, tyre aspect ratio, tyre width, tyre inflation pressure, wheel load) using the prediction equations developed by Schjønning et al. (2006). The contact stress distribution is then used as the input into the stress propagation model.

Beneath the tyre the vertical stress is modelled throughout the soil profile using the Söhne summation procedure (Söhne, 1953), Equation 3-5.

$$\sigma_z = \sum_{i=0}^n \frac{v * P_i}{2 * \pi * r_i^2} \cos^v \varphi_i \quad 3-5$$

Where, for each discrete point on the soil interface,  $i$ ,  $\sigma_z$  is the vertical stress at a depth  $z$ ,  $P_i$  is the load at point  $i$ ,  $v$  is the concentration factor, and  $r$  and  $\varphi$  are the polar coordinates of the position. Söhne (1953) suggests values for the concentration factor of 4, 5 and 6 corresponding to hard, firm and wet soils.

In an attempt to quantify these values for the soil matric potential,  $\Psi$ , the following equation was derived:

$$v = \frac{7}{180000} \Psi^2 - \frac{31}{1200} \Psi + \frac{2590}{360}, \quad 4 \leq v \leq 6 \quad 3-6$$

The equation relates the matric potential values of 500, 100 and 50 hPa to hard, firm and wet soils, and so results in a concentration factor of 4, 5 and 6 respectively. The concentration factor is also limited to only be within the range of 4 to 6. The matric potential values for the soil profile are stored as the Soil Status. The matric potential value at a depth of 10 cm beneath the soil-tyre interaction is used to calculate the concentration factor with the same frequency as the Soil Status data is available. The depth of 10 cm was chosen as influential to how the stress propagates within the soil profile.

Using the calculated concentration factor the stress propagation under each of the loaded tyres is calculated throughout the soil profile and stored with the same frequency.

### 2.1.7. Field Readiness

As stated earlier, the field readiness is defined as a combination of when the field is workable and when it is trafficable. Schjønning (2012) states a rule of thumb for soil trafficability as when the stress within the soil profile at a depth of 50 cm does not exceed 50 kPa. Therefore to determine the trafficable days, the stress

propagation within the soil is filtered and a binary decision variable is produced, being 1 if the stress at 50 cm is below 50 kPa and 0 if it's equal or greater than 50 kPa.

The workability for the tillage operations is based on the upper and lower limits calculated earlier. The matric potential values calculated throughout the soil profile are converted to soil water content using the van Genuchten equation. The soil water content is then filtered and a binary decision variable produced for each depth, being 1 if the soil water content is within the range of the upper and lower limits and otherwise 0. Each tillage operation then has an operational depth, so the binary variables for all layers within these depths are considered and an overall binary decision variable for the workability is produced, being 1 if the decision variables for all layers within the operational depth range are 1, and otherwise 0.

## 2.2. Test Simulations and Analysis

Simulations were run for each year between 2001 and 2011, with a run-in period of twelve months before the autumn tillage period to be considered, i.e. for the 2001 autumn tillage period, the simulation was run from September 1<sup>st</sup> 2000 to Dec 31<sup>st</sup> 2001. The run-in period is used to establish initial conditions on the soil column. The autumn tillage period was set as September 1<sup>st</sup> to December 31<sup>st</sup> and was investigated to evaluate the number of days the field is ready..

The trafficability and workability were calculated for each tractor-implement setup and for each soil type within the test field. Using the data for all 11 years the average number of ready days, or available work days, is calculated. Also the probability of the field to be ready for an operation on a given day during autumn period is estimated as the ratio of number of occurrences the day being ready during the period divided by the number of years.

## 3. Results and Discussions

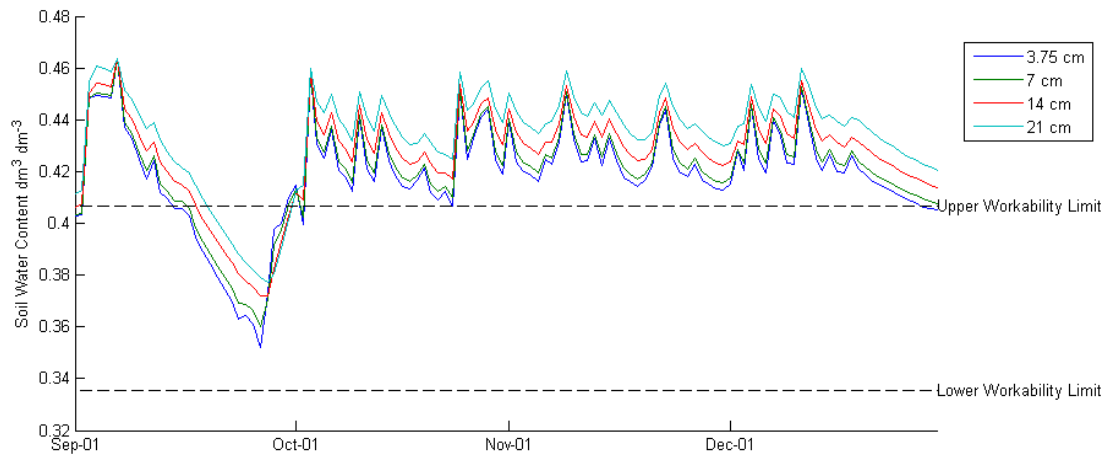
### 3.1. Workability

**Table 3.3: Estimated soils' workability limits from Equations 3-2, 3-3 and 3-4**

Soil	Upper limit ( $\text{dm}^3 \text{ dm}^{-3}$ )	Optimal limit ( $\text{dm}^3 \text{ dm}^{-3}$ )	Lower limit $\theta$ ( $\text{dm}^3 \text{ dm}^{-3}$ )
Pinder	0.47	0.43	0.39
Salop	0.41	0.37	0.34
Claverley	0.46	0.41	0.36

The soils' optimal, upper and lower workability limits were calculated using Equations 3-2, 3-3 and 3-4, respectively, and are listed in Table 3.3 The limits for all three soils are quite similar, which is to be expected as their textures are quite similar. All three soils' optimal water content for tillage are near the reference level for the soil being at field capacity. Figure 3.3 shows an example of the workability limits

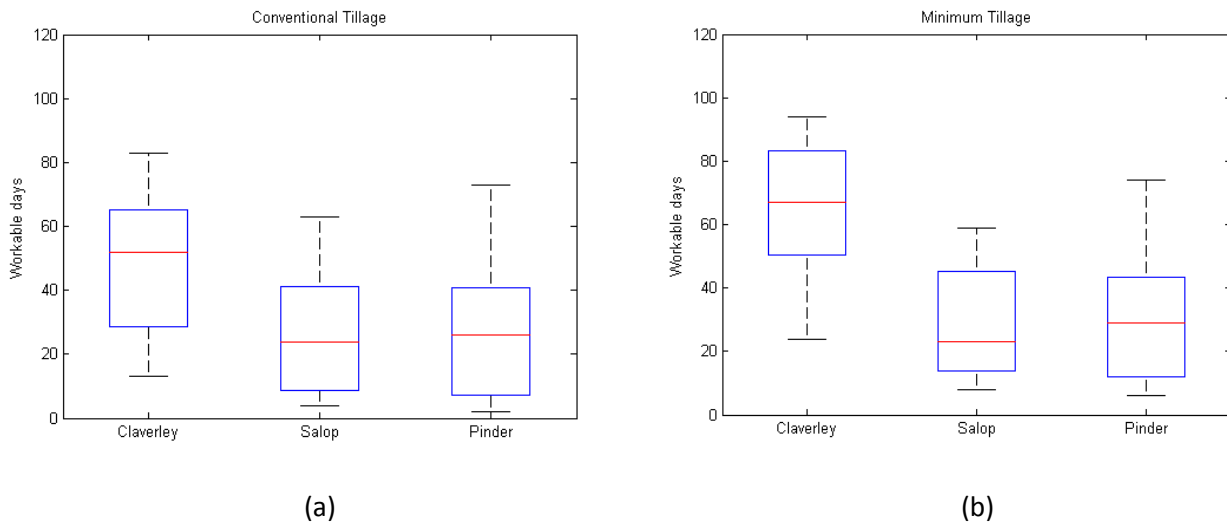
being imposed for conventional tillage on Salop soil in the autumn of 2002. These results are typical for the other soils and the other examined years. The soil water content was simulated at multiple depths within the soil profile, however only the first four of these depths (3.75 cm, 7.5 cm, 14 cm and 20cm) are within the stated working depth on the conventional tillage (25 cm). The soil water content is plotted at each of these depths. The workability limits are shown as dashed lines. The soil is deemed to be workable the simulated water contents at all of the depths are within the workability limits.



**Figure 3.3: Example of the Workability Limits imposed on Conventional Tillage on Salop soil in 2002**

It can be seen that the only time the soil is deemed workable is early in the autumn period with a total of 11 workable days, this is median value of workable days for conventional tillage for Salop. On September 1<sup>st</sup> the 3.75cm, 7.5cm and 14cm are all just below the upper soil water content limit, however the 20cm is above the upper limit, and hence too wet, therefore determining the soil to be unworkable. All of the available workable days come at the end of September, when there is a period of 11 day when all of the layers are within the range enclosed by the upper and lower limits. For the rest of the autumn period, the soil remains too wet for conventional tillage to be executed.

De Toro and Hansson (2004) also determined the workability for many operations on a Swedish farm using simulated soil moisture. During the estimation of available work days for tillage only a wet (upper) limit is placed upon the simulated soil moisture contents. This may be an acceptable simplification as the results of the present study show that the examined soil became unworkable due to breaching the wet (upper) limit. While the present study didn't find occurrences of the dry (lower) limit being breached and resulting in the soil being unworkable, it may be the case for other soils, or for other periods such as spring tillage, that it is necessary to also consider whether the soil is too dry for tillage.

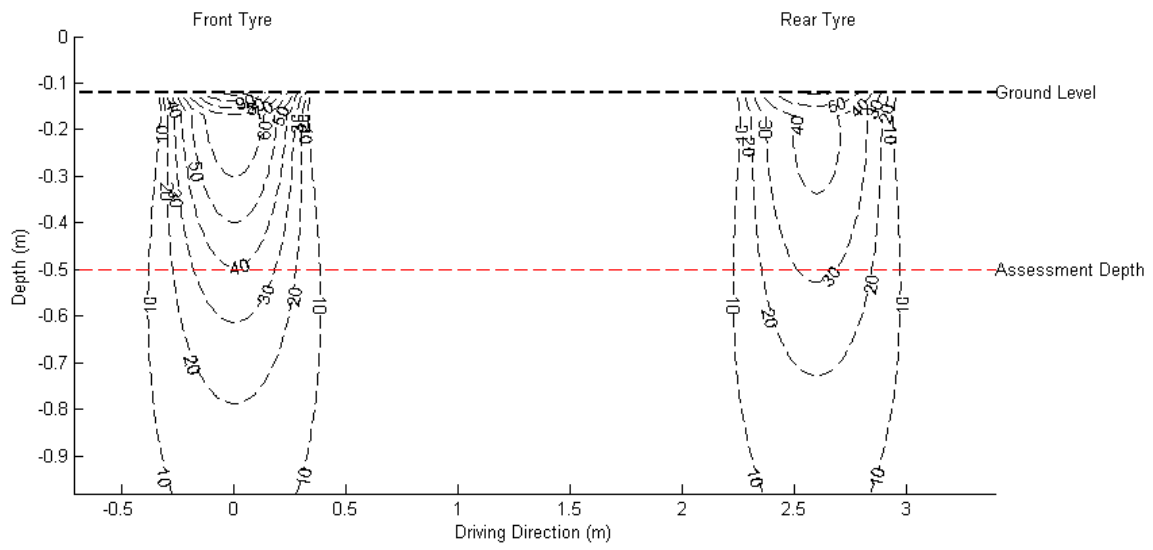


**Figure 3.4: Box plots of the yearly total workable days of the three soil types for (a) Conventional Tillage and (b) Minimum Tillage**

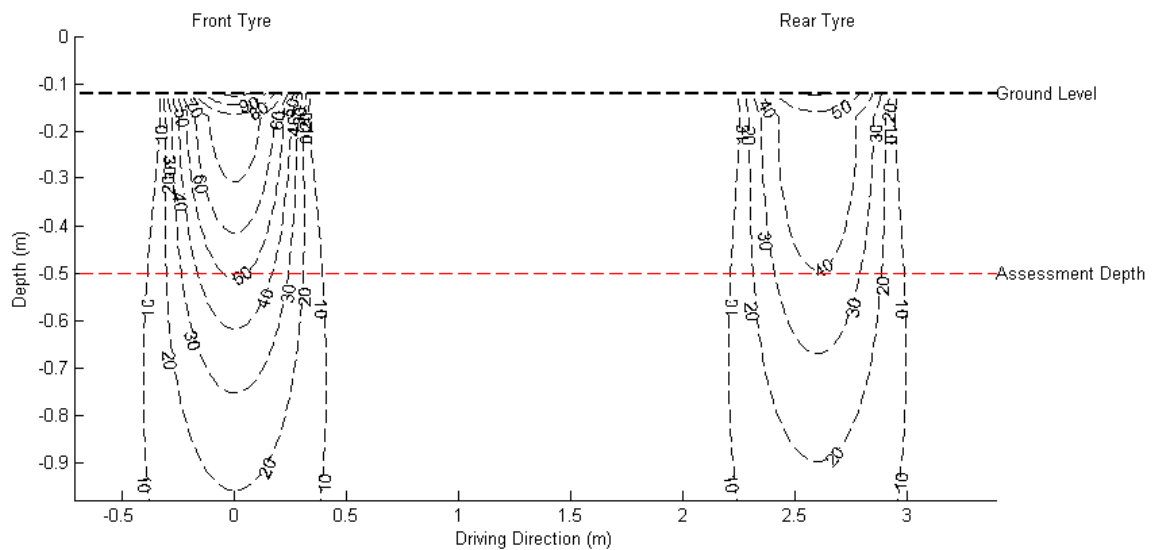
Figure 3.4 shows how the number of workable days in the autumn period varies for each soil and each tillage operation over the 11 year period. For all three soils, on average there are more days which are workable for minimum tillage rather than conventional tillage. This is to be expected as for minimum tillage the top 7 cm of soil must be workable, whereas for conventional tillage the top 25 cm must be workable. Therefore if the soil is workable for conventional tillage it must also be workable for minimum tillage.

### 3.2. Trafficability

Figure 3.5 and Figure 3.6 show how the stress propagates through the soil profile under the different machinery setups for conventional tillage and minimum tillage, respectively. The stress propagation is described by Equation 3-5, with the concentration factor being related to the soil moisture using Equation 3-6. When the soil is at its wettest it has a concentration factor,  $\nu$ , of 6, while when it is at its driest it has a concentration factor of 4. These concentration factors were used to produce Figure 3.5 and Figure 3.6. The Assessment Depth is labelled at 50 cm below the soil surface, and if the stress produced by any of the tractor's/implement's tyres is above 50kPa then the soil is deemed not trafficable. This is in accordance with the Schjønning 50/50 rule, (Schjønning, et al., 2012). The loading characteristics are described in Table 3.2.

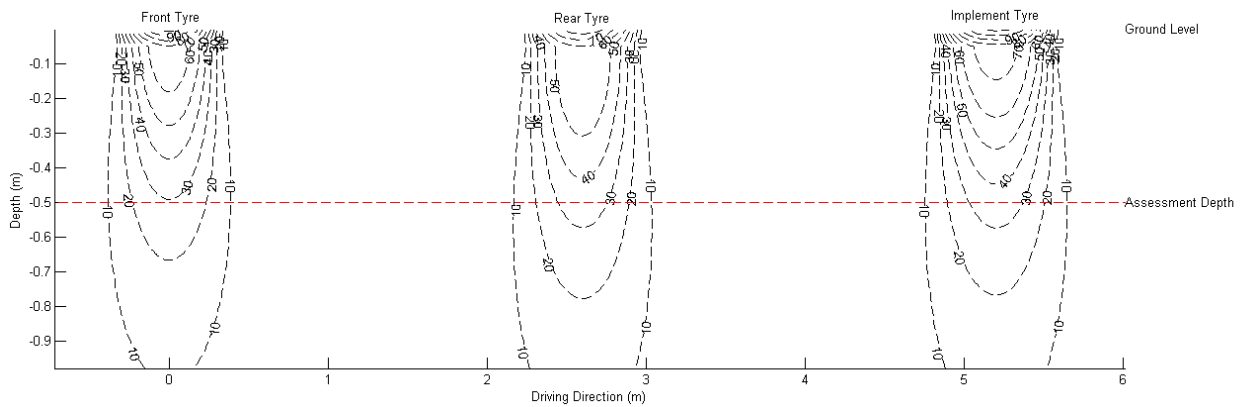


(a)

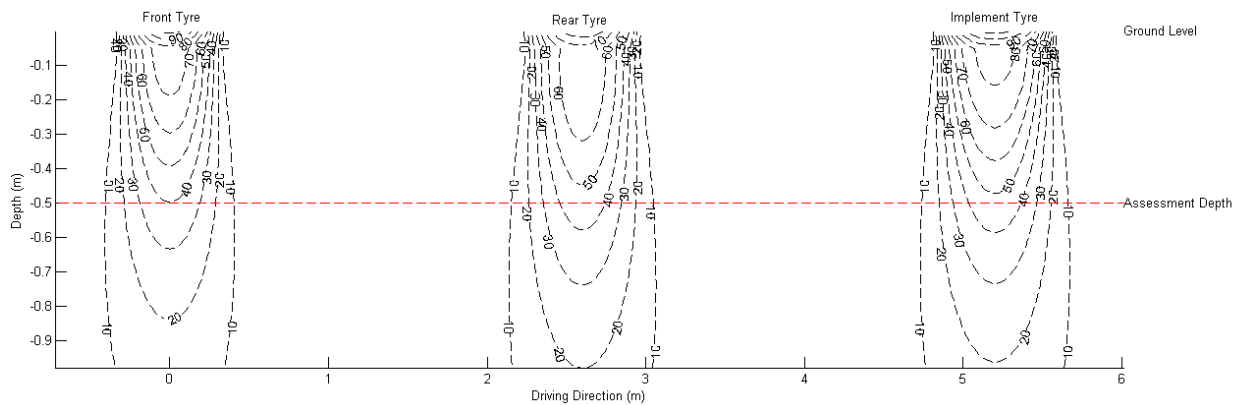


(b)

Figure 3.5: Calculated soil stress (in kPa) within the soil profile during Conventional Tillage when the soil is (a) driest, and (b) wettest



(a)



(b)

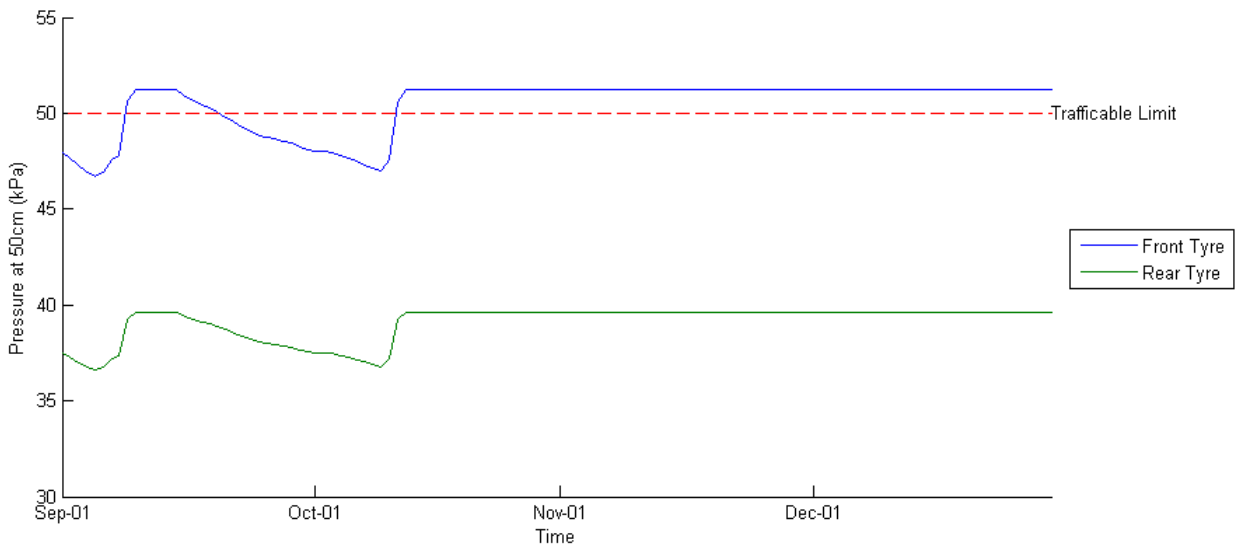
**Figure 3.6: Calculated soil stress (in kPa) within the soil profile during Minimum Tillage when the soil is (a) driest, and (b) wettest**

As can be seen, when the soil is driest, (a), the front tyre induces just under 30kPa, while the rear tyre induces just over 40kPa, both of which are acceptable and the soil is trafficable. However when the soil is wettest, (b), the front tyre induces over 50kPa, while the rear tyre just under 40kPa. Therefore, due to the front tyre, the soil is not trafficable. The load on the front tyre is less than the load on the rear tyre, however the rear tyre is much bigger and spreads the load better over a larger area. In order for the soils to always be trafficable a larger tyre could be used on the front, or the load could be decreased.

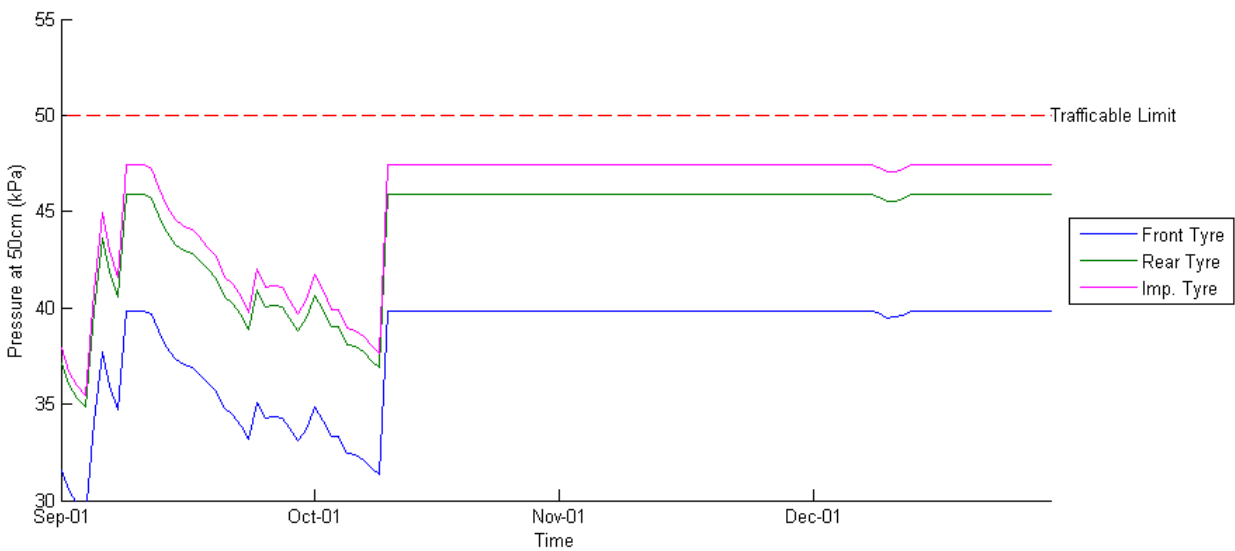
Unlike conventional tillage, in minimum tillage all of the tyre loads are applied at ground level, Figure 3.6. It is interesting to note that, although the wheel load for the rear tyre is larger than the wheel load for the front tyre, the stress at the soil tyre interface is higher for the front tyre. The stress however disperses quicker under the front tyre and for both cases, (a) and (b), the stress at 50cm is higher beneath the rear tyre than beneath the front tyre. As the implement is trailed there is the addition of an extra wheel to consider and in both cases, (a) and (b), the implement tyre induces the largest stress of the three wheels at



50cm. However in both the driest case (a) and the wettest case (b), all of the tyres of the tractor and implement produce stresses which do not exceed 50kPa. This means that the soils are always trafficable for minimum tillage.



(a)



(b)

**Figure 3.7: Estimate stress at 50cm below the soil surface of Salop in Autumn 2002 for (a) conventional tillage and (b) minimum tillage**

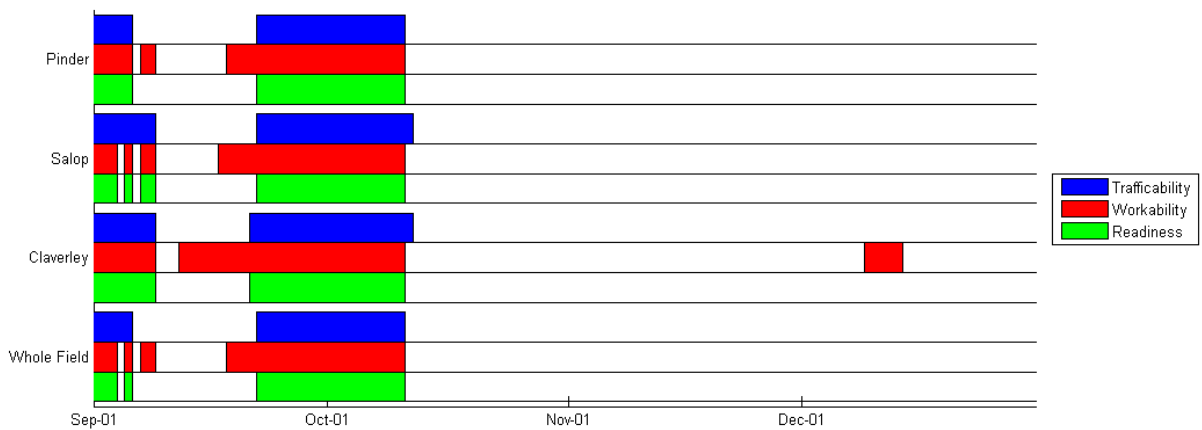
Figure 3.7 shows how the stress at a depth 50cm within the soil profile of the Salop soil varies over the autumn period of 2002 for conventional, Figure 3.7 (a), and minimum tillage, Figure 3.7 (b). For

conventional tillage there are 14 days when the soil is trafficable, with the average number of trafficable of Salop for conventional tillage being 16 days, Table 3.4. There a two periods during the period when the soil is trafficable for conventional tillage, however after mid-October the stress caused by the front tyre of the tractor exceeds the limit of 50 kPa for the rest of the period. For minimum tillage, the stress under the tyres of the tractor and the implement vary between approximately 30kPa and 47 kPa, however they never exceed the 50kPa limit ensuring that the soil is always trafficable.

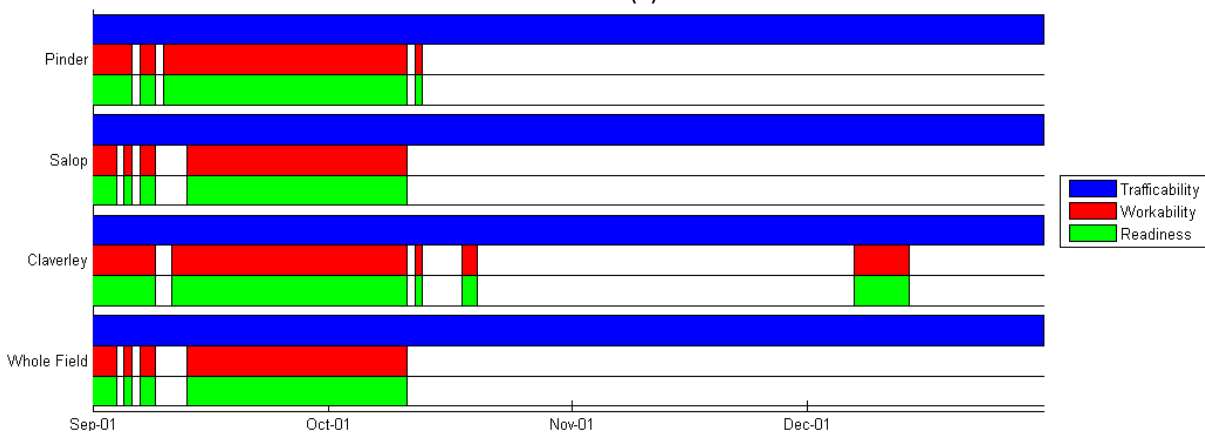
**Table 3.4: Average yearly workability, trafficability and readiness during autumn season**

		Workable (days)	Trafficable (days)	Ready (days)
Conventional tillage	Pinder	15	19	13
	Salop	15	16	10
	Claverley	40	20	15
	Whole Field	11	14	8
Minimum tillage	Pinder	32	122	32
	Salop	23	122	23
	Claverley	52	122	52
	Whole Field	21	122	21

### 3.3. Readiness



(a)



(b)

**Figure 3.8: Example of Trafficability, Workability and Readiness for the three soils and the whole field in Autumn 2002 for (a) Conventional tillage and (b) Minimum Tillage**

The estimations of the workability and trafficability are combined together to give the readiness of the soils, expressed as the time window where the operation can be executed to produce an adequate tilth without causing excessive amounts of stress in the soil profile. Figure 3.8 shows the trafficability, workability and their combination into the readiness for each operation on each soil, as well as the whole field, between 1<sup>st</sup> September 2002 and 31<sup>st</sup> December 2002. As mentioned earlier, in the case of minimum tillage the field is trafficable during the whole autumn period, indicating that the actual determination of the readiness of the soil relies on the workability. Conversely for conventional tillage the time when the soils are trafficable is limited, which in the example year shown in Figure 3.8 means that all of the soils are workable for longer periods than they are trafficable. Therefore, the determination of the readiness of the soils for conventional tillage depends on the trafficability.

The results presented here are in contradiction to Rounsevell and Jones, (1993), which hypothesised that if a field was workable then it must be trafficable. The results in Figure 3.8 clearly show that there are times for all three soils when they are not trafficable but they are workable for conventional tillage. This is likely due to improved knowledge being gained regarding both the trafficable and the workable limits, and also larger machines are now being used that would have been previously not considered. This result enforces the need to estimate both the workability and the trafficability when considering a soils readiness, rather than just the one or the other.

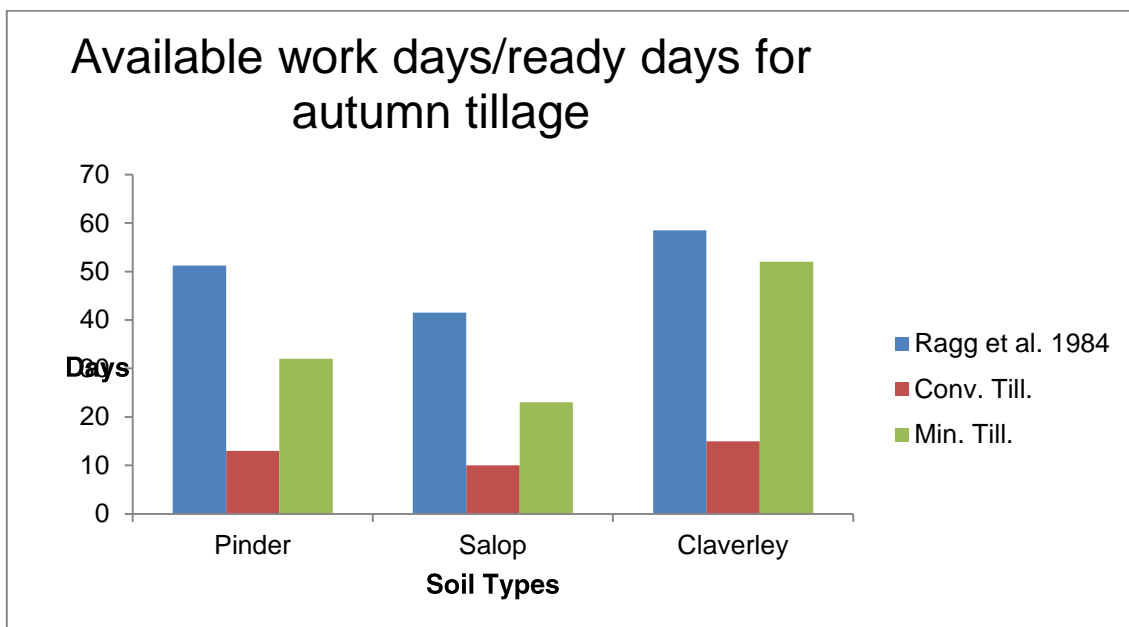


Figure 3.9: Average available work days for autumn tillage

In Figure 3.9, the results are compared to the previously published data for machinery work days by Ragg et al., (1984). The previous study estimated the number of machinery work days available for conventional

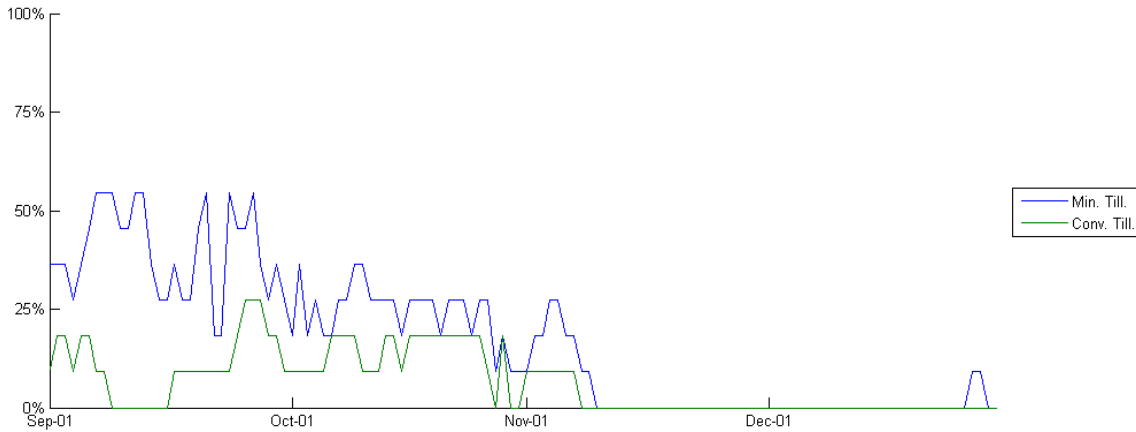
tillage and expressed results for “normal years” and “wet years”. It was also stated that a wet year occurs once every 4 years. To be able to show these results together the following simplification was made;  $\text{workdays in an average year} = (\text{workdays in a normal year} * 3 + \text{workdays in a wet year}) / 4$ . Figure 3.9 shows that for all three soils the relationship between average number of ready days for minimum tillage, conventional tillage and workdays stated in Ragg et al. (1984) is consistent. For all of the soils there are less available days for conventional tillage than there are for minimum tillage, also Ragg et al. (1984) over states the number of workable days available, in comparison.

The difference between the results of the presented tool and those of Ragg et al. (1984) could be due to many reasons. Firstly, very different methods were used, the soil and climate were generalised onto a qualitative scale in Ragg et al (1984) and used to make a generalised assessment of when a medium sized tractor (although it would be considered small by today’s standards) could execute conventional tillage. While the tool used mathematical models that can be tailored to the actual machine and implement used. Also, as mentioned, increases in the size and weight of machinery has a profound impact on the window of opportunity when work can be executed.

It could also be due to the fact that the climate has changed in the time between these studies and that the operational windows for tillage to be executed are much smaller than they used to be. Rounsevell and Brignall (1994) investigated the effect of climate change on the number of work days available for autumn tillage, however it was concluded that increase in temperature would be negated by increases in rainfall and the number of work days would be unaffected. Similar results were also reported in a study on Scottish soils (Cooper et al., 1997).

### 3.4. Comparison of tillage systems

To consider the readiness of the whole field for an operation a conjunction of the individual soil is made such that if any one of the soils is unready then the whole field is unready, as can be seen in Figure 3.8 for 2002. Table 3.4 summarises the average number of workable, trafficable and ready days for each soil type for each operations. It also includes the average number of ready days of the whole field for each operation. As can be seen there are, on average, over twice as many days per year that the whole field is ready for minimum tillage as compared to conventional tillage.



**Figure 3.10: The workday probability of the whole field for the two tillage operations over the 11 year simulation period**

Figure 3.10 shows the workday probability of the whole field for both operations over the 11 years of the simulation, which is the probability that on a specific date the whole field will be ready for an operation. For conventional tillage the most opportune time is late September to late October, with the field never being in a state of readiness after early November. For minimum tillage September is the most opportune time during the autumn period for the whole field to be ready. The probability of a ready day decreased in October, and after early November the field was rarely ready for the operation for the rest of the year. Over the autumn period the ready day probability is much higher for minimum tillage than for conventional tillage, the probability that minimum tillage can be executed is approximately twice that of conventional tillage for most of the period.

### 3.5. Evaluation of the tool

The estimations of workability and trafficability draw together two areas of research to offer an estimation of readiness in a novel way. As such direct comparisons with like for like tools cannot be made as published tools focus on either trafficability or workability. Often if trafficability and workability are both considered one is seen as a subset of the other, i.e. if a field is workable it is always trafficable.

Other studies (Earl 1997; Rounsevell 1993) use a value of the number of work days available within a period. While this is sufficient for making tactical decisions regarding such things as fleet sizes and crop choices (Sørensen, 2003), operational planning requires a more detailed description on when and where operations can be executed. The presented tool is shown to produce a prediction of readiness on a daily basis. This is also only limited by the frequency of the available weather data and could offer a prediction on an hourly basis if the frequency of the recorded weather data used as an input was increased.

Rotz and Harrigan (2005) describe a similar tool to predict the readiness of a location, accounting for both trafficability and workability within a single calculation, to be used as part of a larger farm simulation

model. According to their analysis the model is highly influenced by a parameter they introduce called the tractability coefficient which limits the soil moisture in the top part of the soil. However these coefficients must be stated by the user which may cause confusion and make the tool impossible to use. All of the parameters used within the proposed tool are either physically measured or estimated by the tool itself, removing the need for expert knowledge to utilise the tool and making it more accessible.

De Toro and Hansson (2004) used a single threshold for determining the workability, and did not calculate the trafficability. As the results of this study show this is insufficient to fully define the readiness of a given field. A comparison was also made between estimating the readiness daily and using a probability available work days. The same conclusion was achieved that the daily readiness is needed in order to schedule operations satisfactorily.

Terranimo (Stettler et al., 2014) is a web based tool for supporting decisions of trafficability. The presented tool uses the same equations as Terranimo to calculate the stress propagation within soil and the soil tyre interface. Within Denmark, a direct link can be made to a soil database and the weather database so that information can be retrieved from a latitude and longitude coordinate, also the soil moisture can be simulated over a period to give a trafficability estimation for the future. This makes it extremely easy to use, and can offer results without expert knowledge. However, as shown in the results, fields can be in a state of trafficability when they are not in a state of workability. Therefore definite conclusions cannot be drawn of whether an operation can be executed without a workability assessment.

## 4. Conclusions

The study offers a new method for predicting the readiness of soils and fields for specific operations using historical weather data. The combination of the mathematical methods used for estimating both the trafficability and the workability provide a more qualified measure of field readiness which is a major step forward in this area. The tool was demonstrated using real field data and historical weather data to estimate readiness conditions for a field for two tillage operations. The tool shows that the field was in a state of readiness for minimum tillage for longer periods each year than it was for conventional tillage. This suggests that if a farm manager would consider changing to a minimum tillage system they will gain more flexibility as regards the planning and allocation of machinery as the windows of opportunity for when the operation could be effectively executed will increase.

The examined soils experience periods when they were trafficable but not workable, and workable but not trafficable. Therefore the consideration of both of these factors is important, and must be included in field readiness predictions for operational planning.

The tool is intended to be used as a predictive tool to estimate working windows when fields are in a state of readiness in the future, as such it will have to operate utilising weather predictions and estimations of current conditions which will always have a level of uncertainty. Incorporating the tool into an existing FMIS could be beneficial to Farm Manager's decision making process at various planning stages and help to make improved informed choices. Further testing of the tool in conjunction with in-field sampling would be needed to add credence to the results.

A further application of the tool could be to evaluate the impact of a changing climate on the current operational practices of today's farmer. With consequences of climate change not yet being fully understood Farm Managers will soon have to plan operations under conditions which they may not be familiar with. The ability to test new climate data and offer advice of when and where operations can be executed could prove to be valuable in anticipating the needs of the future.

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# Chapter 4 Optimised schedules for sequential agricultural operations using a tabu search method

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## Abstract

Due to the increasing demands of a growing world population, farmers are tasked with increasing productivity without increasing resource use. This can be achieved by deploying resources in a more efficient manner and by ensuring operations will produce maximum results. However when contemplating the problem of scheduling multiple machines, executing multiple operations at multiple fields, it is a cumbersome task to find an optimal solution without the aid of a decision support tool. A field's readiness, in terms of its trafficability and workability, is an important factor to consider when scheduling operations. Executing operations on an unready field can lead to additional operational costs, such as drying grain harvested at an unready moisture level or removing subsoil compaction caused by machinery driving on unready soils. To ensure a schedule is actionable the fields' readiness must be accounted for by the scheduling process, further increasing the complexity of the problem to be solved.

In this paper, a novel scheduling algorithm is presented which creates individual machine work plans for multiple machines to execute multiple consecutive operations at multiple fields, accounting for the field's readiness for the specified operation. Two optimisation algorithms are utilised to find near optimal solutions of predefined scenarios, a standard Tabu Search and a modified Tabu Search, producing optimised work schedules. The functionality of the optimisation algorithms are tested both for a real world scenario and a large set of numerical examples. The results of the optimisation methods are assessed by their computational time and their relative error compared to the optimal solution, where available. The combination of the presented scheduling algorithm and optimisation algorithms could be used either as a stand-alone tool for farm managers and agricultural contractors as part of their logistic planning, or as a component of an overall Farm Management Information System.

## Keywords

Operation management, fleet management, scheduling, tabu search optimisation,

## 1. Introduction

Modern farmers face the problem of having to increase productivity as a result of reduced economic earnings and costly regulatory provisions imposed by society. Over the last 50 years, productivity gains have been accomplished by increasing the capacity and size of agricultural machines and in this way decrease unit costs. However, recently the use of advanced guidance systems and integrated information systems has increased farm managers possibilities to optimise current practices and operations (Lawson et al., 2011). Furthermore, an envisioned paradigm shift away from operating a small number of large machines to the concept of a large number of small intelligent machines causing minimal damage to the field (Blackmore et al. 2006; Sørensen and Bochtis, 2010), fleet management will enhance the concept of coordinating machines and increasing productivity of the available resources.

Sørensen and Bochtis, (2010) proposed a concept of a fleet management system (FMS) for agricultural machines, highlighting the requirements of generating vehicle work plans which are able to be updated due to the changing conditions of the biological agricultural processes. An automated FMS can also form part of an overall farm management information system (FMIS) which controls and monitors many operational activities of a modern farm (Sørensen et al., 2010a). In order to create the work plans for a FMS, a number of models and decision support systems need to be developed which incorporates stated requirements and provide actionable outputs.

A fleet management system is beneficial at various planning stages. Sørensen et al., (2010b), lists the planning stages of arable farming as; strategic planning over a 3-5 year horizon, tactical planning over a 1 -2 year horizon, operational planning over the current season, and scheduling of individual machine operations using work plans. A fleet management tool could be of help during the scheduling planning stage, and if the computational time was sufficiently low then the tool could be operated in an online mode. A fleet management tool could also be essential during other planning stages when long term decisions, such as investments in machinery or crop type, are made. The tool could help with cost benefit analyses of choices and add credence to management decisions.

Previous works (van Elderen 1987; van Elderen 1977) utilised dynamic programming to find scheduling solutions to the problems of harvesting grain and collecting straw bales. The modelling of the system was limited by the processing power of the computers at the time. Decisions are made at a number of stages, or “decision events” where the situation is updated and a new course of action is decided upon. However, the readiness was accounted for within the model as a probability over a weekly period, rather than a daily or

hourly period, which might limit the models ability to produce actionable results or to deal with fast changing weather behaviours.

More recently de Toro (2005), assessed scheduling solutions based on a timeliness factor, defined as the elapsed time after a specified operation execution date. The timeliness costs are expected to be the greatest influence on the annual variation of cost for a farm manager. Specified expected dates for sowing and harvest operations were forecast from examining local data from the region under consideration over a period of 15-20 years. However, this inductive method of data collection may mean the results are only justified for the considered region and cannot be applied in other regions or climates.

Basnet et. al. (2006) presented a model for scheduling farm-to-farm crop harvesting operations. This model incorporates many of the important criteria necessary to model the real life situation including minimum and maximum time lags between operations. However, it does have limitations such as; an operation is not starting in a specific field until all of the designated machines arrive at that field, and the model also does not account for a field's readiness for an operation. These limitations may make the results obtained unusable by an agricultural manager.

The problem of scheduling multiple tasks by multiple machines at multiple fields can be cast as a typical scheduling problem, depending on the formulation approach. These types of problems are often found in operations research and applied in industrial manufacturing, such as the job shop scheduling problem (JSSP) or the flow shop scheduling problem (FSSP) (Bochtis, 2010). Bochtis et al., (2013) formulated the problem of finding a permutation schedule for a number of geographically dispersed fields where a number of sequential biomass handling operations have to be carried out as a flow shop with sequence dependant set up times scheduling problem. The approach, however, was limited to the case of a single-machine per operation type. An approach dealing with multiple-machinery systems was presented in Orfanou et al., (2013) as an expansion of the previous work. However, in both cases the idea of field readiness for a task, which adds complexity to the problem, was not considered.

The decision of whether an agricultural field is ready for a given operation involves a complex decision making process influenced by many variables and uncertainties, with many available courses of action (Recio et al., 2003). The readiness of an agricultural field for an agricultural operation is a combination of the trafficability and the workability measures. Trafficability is the ability of the soil to support the motion of the machine executing the operation, while workability is the ability of the operation to produce positive results, such as a crop being harvested at the ideal moisture content. Executing operations when the fields are ready can induce significant reductions in resource use, such as reducing the need to dry a crop or

reducing the energy required to remove compaction, resulting in lower costs (de Toro, 2005). By accounting for a field's readiness while scheduling, operational costs can be reduced and hence efficiency can be increased.

The objective of this paper is to develop a tool for agricultural machinery scheduling for biomass harvesting and handling operations in a number of geographically dispersed fields that takes into account the field readiness of each field site. The tool is validated against its ability to integrate the defined operational, spatial, and temporal parameters and produce an optimised, easily readable, and actionable plan. The optimisation algorithms are assessed in terms of computational time, and the disparity, if any, between the produced result and the most optimal solution, if available. Thus, a real life example and a number of scenarios are demonstrated and tested.

## 2. Problem Description

Many agricultural operations, such as harvest and seedbed preparations, involve the scheduling of a number of separate operations which need to be executed in a specific order by one or more dedicated machines. Considering the example of grass harvest, the grass must first be cut by a mower, then raked together by a rake machine, and finally picked up chopped and transferred on-the-go to transport units. The task times for each operation at a given field are assumed proportional to the area of the field and the number of machines utilised. There is also an additional amount of time needed to setup each machine before the operation is commenced. This setup time could include lubrication, regular maintenance, or changing the machine from a transport configuration to an operational configuration.

Beyond the machinery-specific constraints, each operation has a number of agronomical conditions that must be satisfied at a field before the operation can be executed in an efficient and effective manner. The assessment of these conditions is encompassed within the term of field's readiness. A field's readiness takes many factors into account, such as susceptibility to soil compaction or crop moisture level, which are functions of both the operation and field's state. Typically when a field is unready it may still be possible to execute the operation, although it would incur additional operational cost. For the grass harvest example, the execution of operations not complying with the constraints regarding soil compaction may cause deep soil compaction requiring a subsequent sub soil tillage operation, while harvesting the grass not complying with the crop moisture thresholds may result in degraded fodder quality.

There are also often prescribed delays between operations, such as a delay between mowing and raking. Following mowing, the crop must be left in the field to wilt and dry. However, if left too long, the crop may

become too dry and transform into hay. This imposes minimum and maximum limits on the time interval between the mowing and raking operations.

If a number of fields are considered simultaneously, which also become ready at the same time, the complexity of scheduling multiple machines to carry out the operations increases. This is a problem which is encountered on a regular basis by agricultural contractors servicing multiple customers.

A scheduling model requires the following assumptions;

- The set of field fields is known
- The distance between each field is known
- Each operation can be executed by a set of machines, and a set of machines can only execute one operation
- All machines executing the same operation are of the same type and identical
- The amount of time it takes to execute an operation at a field is inversely proportional to the number of machines executing the operation
- Once a machine arrives at a field it requires a set-up time before commencing the operation
- A machine may commence an operation at a field as soon as it is ready without waiting for additional machines that may be executing the same operation
- Machines can arrive at a field and setup for an operation while another operation is taking place, but only one operation can occur at a field at a time.

### 3. Model Development

#### 3.1. Scheduling

The scheduling of the operations creates a plan for each individual machine executing each operation. The plan dictates when and where the machines have to execute the specified operation. A number of input parameters are required for the procedures involving parameter subgroups of machinery, operation, and field (see Table 4.1). The parameters in Table 4.1 are the dependant variables, depending on decisions made outside the sphere of the scheduling problem (for example, what fields need operations and what is the available machinery). The input variables, described in Table 4.2, define how the machines are assigned and the sequence in which the fields are considered. The input variables are control variables, and are adjustable by the manager during scheduling.

**Table 4.1: Schedule parameters**

Variable	Description
$n$	Total number of operation types
$H$	Total number of fields to visit. Each field is labelled 1 to $H$ , with the depot field labelled as $H+1$ .

$s_{ijh}$	Start time of machine $j$ , of operation type $i$ , at field $h$
$e_{ih}$	End time of operation $i$ at field $h$ , N.B. all machines finish operation together
$x_{ijgh}$	1 if machine $j$ of type $i$ travels from field $g$ to field $h$ , otherwise 0
$y_{ijh}$	1 if machine $j$ of type $i$ travels is used at field $h$ , otherwise 0
$m_i$	Number of available machines for operation type $i$
$pr_i$	Processing rate of operation type $i$
$ts_i$	Inter-field travelling speed on the vehicle for operation type $i$
$t_i$	Setup time of the vehicles for operation type $i$
$d_{ih}^{min}$	Minimum delay after operation type $i$ at field $h$ before operation $i+1$ can start
$d_{ih}^{max}$	Maximum delay after operation type $i$ at field $h$
$R_{ih}(T)$	Readiness of field $h$ for operation type $i$ . $R$ is a function of time $T$ .
$A_h$	Area to be processed at field $h$
$c_{gh}$	Distance between the two fields $g$ and $h$

Table 4.2: Input Parameters

$S$	The order in which the operations will be scheduled at a fields, with $S_k$ being the $k^{th}$ field to be schedule. $S_0$ and $S_{H+1}$ are the starting and ending positions, respectively.
$U_{ih}$	The number of vehicles of type $i$ , $i = 1, \dots, n$ , which will be used at field $h$ , $h = 1, \dots, H$

The scheduling problem is formulated as following:

$U_{ih} \leq m_i \quad i = 1, \dots, n \quad h = 1, \dots, H$	4-1
Machines allocated for an operation at a field cannot exceed the number available	
$U_{ih} = \sum_{j=1}^{m_i} x_{ijgh} \quad i = 1, \dots, n \quad g, h = 1, \dots, H$	4-2
The sum of $x$ for a given operation at a given field is the same as $U$	
$S_0 = S_{H+1} = H + 1$	4-3
The sequence of fields always begins and ends at the depot, field $H+1$	
$S_g \neq S_h \quad g \neq h, \quad g, h = 1, \dots, H$	4-4
Each field is only visited once	
$s_{1j1} \cdot x_{1j01} \geq c_{0h} \cdot ts_1 + t_1 \quad j = 1, \dots, m_i$	4-5
The start of operation 1 at the first field must exceed the travel time from the depot to the first field, plus the setup time.	
$s_{ijh} \geq e_{ig} + c_{gh} \cdot ts_i + t_i \cdot x_{ijgh} \quad i = 1, \dots, n, \quad j = 1, \dots, m_i \quad g, h = 1, \dots, H$	4-6
The earliest start time of machine $j$ to do operation $i$ at field $h$ is the end time at its previous field plus the time it takes to travel to the new field plus the setup time	
$s_{ijh} \geq e_{i-1,h} + d_{ih}^{min} - t_i \quad i = 2:n, \quad j = 1, \dots, m_i \quad g, h = 1, \dots, H$	4-7
Enforces the minimum delay criteria	
$s_{ijh} \leq e_{i-1,h} + d_{ih}^{max} - t_i \quad i = 2:n, \quad j = 1, \dots, m_i \quad g, h = 1, \dots, H$	4-8
Enforces the maximum delay criteria	
$R_{ih} s_{ijh} = 1 \quad i = 1:n, \quad j = 1, \dots, m_i \quad h = 1, \dots, H$	4-9
Field $h$ must be ready when machine $j$ starts operation $i$	
$R_{ih} e_{ih} = 1 \quad i = 1:n, \quad h = 1, \dots, H$	4-10
Field $h$ must be ready when operation $i$ finishes	
$\sum_{j=1}^{m_i} \int_{s_{ijh}}^{e_{ih}} R_{ih}(T) dT \cdot y_{ijh} = \frac{A_h}{pr_i}, \quad i = 1, \dots, n, \quad j = 1, \dots, m_i, \quad h = 1, \dots, H$	4-11
Total time spent working on operation $i$ at field $h$ while the field is ready, is equal to the total time needed to	

complete the operation	
$e_{ih} \geq \frac{1}{U_{ih}} \frac{A_h}{pr_i} + \sum_{j=1}^{m_i} s_{ijh} + t_i, \quad i = 1, \dots, n, \quad j = 1, \dots, m_i \quad h = 1, \dots, H$	4-12
The earliest end time of operation $i$ at field $h$ is the sum of the start times of all the machines, plus the time it would take one machine to process the field, divided by the number of machines utilised, plus the setup time	
$1 - y_{ijh} + e_{ih} \cdot y_{ijh} > s_{ijh} \cdot y_{ijh} \quad i = 1, \dots, n, \quad j = 1, \dots, m_i \quad h = 1, \dots, H$	4-13
If machine $j$ travels to field $h$ to do operation $i$ , it must start before the operation is completed	
Objective function: $\min e_{nS_{SH}} + c_{S_{SH} S_{SH+1}} \cdot t_{S_n}$	4-14
The objective function is to minimise the time at which the final machine arrives back at the depot	

The model described in Equations 4-1 to 4-14 is based on the model described in (Basnet et. al. 2006) and modified to include additional complexity in terms of scheduling the machine to start operations individually and the inclusion of the readiness variable. .

The overall schedule is built in a stepwise way starting with calculating the time taken for the first operation at the first field for the allocated machines. Since all machines executing a given operation are assumed to be identical, the allocated number of machines is chosen from those available by calculating which can arrive at the field the soonest.

Continuing with the first field, the time taken for the subsequent operations are then calculated starting from the completion time of the previous operation, plus any required minimum lag between the operations. If the lag in between operations is greater than the maximum lag, due to the machines being unable to arrive in time, then the previous operation is delayed and recalculated, this could also result in more previous operations being delayed. Once all the operations have been scheduled at the first location the process is then repeated at all the subsequent fields in turn.

**Algorithm 1: Scheduling Algorithm**

```

For Each field  $S_k; k = 1, \dots, H$ 
    For Each operation  $i; i = 1, \dots, n$ 
        Allocate the  $U_{i,S_k}$  machines which can arrive fastest.
        Schedule arrival, setup and process start and end times for each
        machine allocated using Equations 4-6 through 4-13
    Next  $i$ 
Next  $S_k$ 
    
```

Once the scheduling algorithm, Algorithm 1, has been completed and the utilisation of individual machines is known the cost of the schedule can be determined. In this case, the cost of the schedule is determined as



the overall time taken for all the machines to complete their operations, i.e. the difference between the start time of the schedule and the arrival time of the final machine at the depot, Equation 4-14. This is assumed to be a good indicator of the overall costs of the schedule. However, if desired, at more complicated calculation of the costs could be made that accounts for individual machines utilisation, fuel costs, labour costs, etc., for the same output schedule (Orfanou et al., 2013). The cost of the schedule is referred to as the solution value of the scheduling algorithm to a given scenario setup and input parameters.

## 4. Optimisation of the Scheduling

It has been shown that by using the input variables, the number of machines for each operation at each field and the order in which the fields are visited, a unique schedule can be made, with a specific cost calculated for that schedule. In the optimisation stage the input variables, the combination of which are referred to as a solution, are modified to produce new input variables which can be used to make new schedules.

As the number of operations, machines and fields increases, the problem of find an optimal solution becomes NP-Hard. A variety of different metaheuristics could be used in an attempt to estimate good solutions for NP-Hard problems such as Ant Colony Optimisation (Huang and Liao 2008), Particle Swarm Optimisation (Yin et. al. 2010) and Genetic Algorithms (Asadzadeh and Zamanifar, 2010). However, it is the Tabu Search which has often given the best results (Ponish and Coello, 2012). Moreover, the hybridation of a Tabu Search with another technique has often helped in covering the search space in more economical ways (Ponish and Coello, 2012). For these reasons both a standard Tabu Search algorithm and a modified Tabu Search algorithm were utilised as the main optimisation techniques.

### 4.1. Standard Tabu Search

The tabu search algorithm (TSA) is a memory-based meta-heuristic optimisation tool that aims to find an optimised solution by searching the search space and avoiding becoming trapped within a local area of optimality (Glover and Laguna, 2006). From an initial solution, TSA examines the local “neighbourhood” of solutions before moving to a new solution and repeating the process. As the algorithm progresses utilised moves are prohibited, or made tabu, limiting a move’s availability to be utilised for a period of time. This process results in a search technique which guides choices based on previous experience, so that the search space can be navigated efficiently and economically.

A solution’s local neighbourhood is generated using specified operators. Three operators are employed in the TSA described within this paper. These operators will hence forth be referred to as movements, as they

move a solution within the solution space, also in order to avoid confusion with the agricultural operations. The first movement switches the order of two fields that are adjacent in the sequence, to create a new sequence for the fields to be visited, Equation 4-15.

Movement 1	
$S_{0,\dots,S_k,S_{k+1},\dots,S_{H+1}} \rightarrow S_{0,\dots,S_{k+1},S_k,\dots,S_{H+1}} \quad k = 1,\dots,H-1$	4-15

The second movement increases the number of machines available for an operation at a field by one, unless in doing so would exceed the maximum machines available for that operation, Equation 4-16.

Movement 2	
$U_{ih} \rightarrow U_{ih} + 1 \quad i = 1,\dots,n; h = 1,\dots,H; U_{ih} + 1 \leq m_i$	4-16

The third movement decreases the number of machines available for an operation at a field by one unless in doing so would result in zero, Equation 4-17.

Movement 3	
$U_{ih} \rightarrow U_{ih} - 1 \quad i = 1,\dots,n; h = 1,\dots,H; U_{ih} - 1 \geq 1$	4-17

An initial solution is needed before the TSA can be instigated. A greedy heuristic is used to calculate a route from the depot to every field and back to the depot, and while this is not the shortest possible route between all the fields it is an acceptable route that can be found quickly. The assigned number of vehicles to be used at each field is set to 1 for all operations.

Using the scheduling algorithm and the initial solution, the initial solution value is generated and set as the current best global solution. A neighbourhood of solutions is generated by using each of the three movements on the initial solution in turn. Movement 1, Equation 4-15, generates  $H$  neighbouring solutions, while Movements 2 and 3, Equations 4-16 and 4-17 resp., each generate a maximum of  $nH$  solutions. This results in a maximum of  $(H-1) + 2nH$  solutions in a local neighbourhood of solutions.

The results of the movements are implemented in the scheduling algorithm, Algorithm 1, and the local solution values are calculated. The best local solution, of those which are not tabu, is then chosen as the movement to be made.

Once a movement is made it is designated as tabu for a number of iterations, in order to inhibit solutions becoming stuck around local minima or maxima and to investigate more diverse areas of the search space. The number of iterations the move remains tabu for is normally based on the number of solutions that a move can produce. If a move is made tabu for too many iterations it is possible that there are no longer any remaining moves which are not tabu. The number of iterations a move would remain tabu was determined to be different for each type of movement, as they could each provide a different number of solutions. For

Movement 1 moves were made tabu for  $H/2$  iterations, while for Movement 2 and Movement 3 moves were made tabu for  $H(1 + 2n)/3$ . Whilst a move is designated as tabu it's resultant solution is forbidden from being selected as the best local solution, unless the solution value is better than the current best global solution.

If the best local solution is better than the best global solution then it is stored as the best global solution. The procedure repeats, finding a new neighbourhood of solutions around the current solution and updating the tabu list after a movement is chosen. In Algorithm 2, the greater than symbol,  $>$ , is used to denote one solution being better than the other, however in the scheduling example described with this paper, one solution is better than another when the solution value, the overall time of the schedule, is the least.

If no improvement is made to the best global solution for a number of iterations then a diversification method is introduced, so that new areas can be found and examined. This helps to prevent local optimality. During the diversification the movements are modified by a diversification factor,  $d$ ,  $d = 1, \dots, H - 1$ , Equations 4-18, 4-19, and 4-20. It can be seen that for  $d = 1$ , Equations 4-18, 4-19, and 4-20 are identical to Equations 4-15, 4-16 and 4-17, respectively. A result of introducing the diversification factor is also that the maximum local neighbourhood size decreases to  $(H-d) + 2nH$ .

Movement 1	
$S_{0, \dots, S_{h-1}, S_h, \dots, S_{h+d-1}, S_{h+d}, \dots, S_{H+1}} \rightarrow S_{0, \dots, S_{h-1}, S_{h+d}, S_h, \dots, S_{h+d-1}, \dots, S_{H+1}}$ $h = 1, \dots, H - d$	4-18
Movement 2	
$U_{ih} \rightarrow U_{ih} + d \quad i = 1, \dots, n; h = 1, \dots, H; U_{ih} + d \leq m_i$	4-19
Movement 3	
$U_{ih} \rightarrow U_{ih} - d \quad i = 1, \dots, n; h = 1, \dots, H; U_{ih} - d \geq 1$	4-20

Once a local solution is found which is better than the best global solution the diversification factor is reset to 1, so that Equations 4-18, 4-19, and 4-20 become Equations 4-15, 4-16 and 4-17, respectively and the algorithm continues. If, however, a better best global solution isn't found again for a number of iterations the diversification factor is increased, in integer steps, until it is no longer able to produce feasible solutions. At this point the procedure is halted.

In a final step, a new solution is generated and the whole procedure is repeated again. This new solution,  $S^n$  and  $U^n$ , aims to start the procedure in a part of the available search space that is far away from the current best global solution,  $S^c$  and  $U^c$ , so that more of the available search space can be examined. Equation 4-21 and Equation 4-22 describe how the new solution is generated from the current best global solution.

$U_{ih}^n = m_i - U_{ih}^c + 1; \quad i = 1, \dots, n, \quad h = 1, \dots, H$	4-21
$S_k^n = S_{H+1-k}^n; \quad k = 0, \dots, H + 1$	4-22

**Algorithm 2: Tabu Search Algorithm**

Generate initial solution

Set initial solution as current solution and best global solution

*While* a new global solutions have been found within a number of iterations

    Generate neighbourhood of new solutions from the current solution

    (Equations 4-18, 4-19, and 4-20)

    Pick best local non-tabu solution and store as current solution

*If* (best local solution > best global solution)

*then* (Store best local solution as best global solution

            reset diversification factor)

    Update tabu table

*EndWhile*

Increase diversification factor

*If* (new solutions can still be generated with the current diversification factor)

*then* (repeat *While* loop)

*else* (     *if* ( a new solution has not been generated using Equations 4-21a and 4-21b)

*then*( generate new solution using Equations 4-21a and 4-21b ,  
                set diversification factor to initial value,  
                repeat *While* loop)

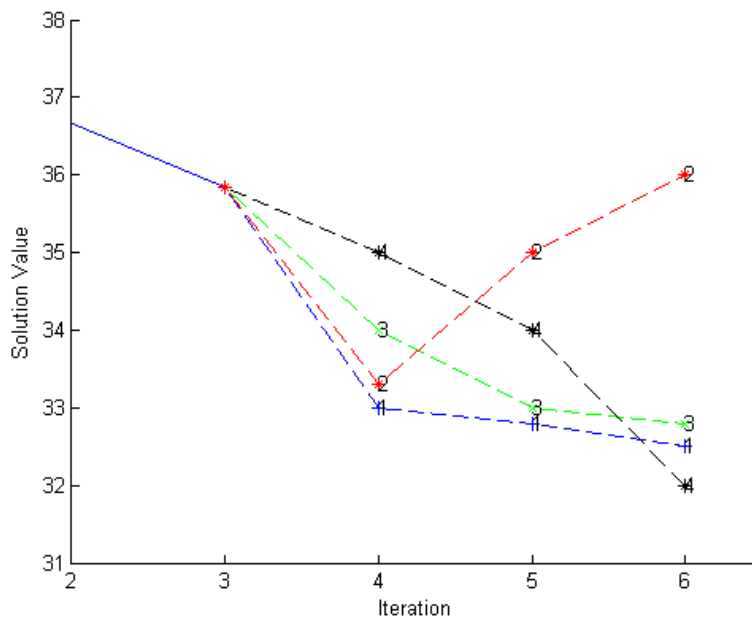
*else*( *EndALL*)     )

**4.2. Look Forward Algorithm**

In an attempt to improve upon the results of the TSA another algorithm was developed and tested, the Look Forward Algorithm (LFA), Algorithm 3. The LFA extends the TSA to include steps that helps determine the best local solutions with more confidence.

The LFA is initiated in the same manner as the TSA, i.e. a greedy heuristic is used to generate an initial solution which is also set as the best local solution. Movements, Equations 4-15, 4-16 and 4-17, are then used to generate a neighbourhood of local solutions. At this point, the LFA ranks the local solutions by their solution value and a set of best local solutions is chosen to be further examined. Solutions which are tabu are only included within this set of best local solution if their solution values are better than the best global solution. Each local solution is examined using the standard TSA for a number of iterations, with the solution value of that local solution becoming the best solution value over the iterations. After each local solution in the set has been examined they are again ranked by their new solution value and the best local solution is chosen. The movement to generate the best local solution is made tabu and if the best local solution is better than the current global solution it is then stored as the best global solution. The diversification factor is also implemented in the same way as in the TSA when no improvement of the best global solution has been seen for a number of iterations.

The number of solutions chosen to be in the set of best solutions to be further examined, and the number of iterations these solutions are progressed, are parameters of the LFA and must be defined. Due to the fact that the LFA increases the search space that is investigated it also increases the computational time compared to the TSA.



**Figure 4.1: Selection of the best local solution using LFA. The 1<sup>st</sup> to 4<sup>th</sup> best solutions at iteration 4, and their variance over two more iterations**

An example of the process of progressing the set of local solutions is shown in Figure 4.1, where the LFA is being used to find the minimal solution value. In the example four solutions are chosen to be in the set of solutions to be further examined and they are each progressed 2 more iterations. In Figure 4.1 the LFA has already advanced to iteration 4, and the neighbourhood produced from the current solution (the solution at iteration 3) is being examined to determine the best local solution. The neighbourhood of local solutions was ranked according to their solution value and the four best solutions were chosen as the set to be further examined. These four solutions are labelled 1-4 with solution 1 producing the best, minimal, solution value at iteration 4, and solution 4 producing the 4<sup>th</sup> best solution value.

The solutions are all progressed a further two iterations to iteration 6, where it can be observed that the ranking of the solutions has changed. At iteration 6 it can be observed that solution 4 will produce the best (minimal) solution value. Therefore the best solution at iteration 4 is determined as solution 4, rather than solution 1 which would have been the result of the standard TSA.

Throughout the remainder of this work the LFA is denoted as LFA(x,y) where x indicates the number of solutions chosen to be in the set of best solutions to be further examined, and y indicates the number of iterations these solutions are progressed.

**Algorithm 3: Look Forward Algorithm, LFA(x,y)**

Generate initial solution

Set initial solution as current solution and best global solution

*While* a new global solution has been found within a number of iterations

    Generate neighbourhood of new solutions from the current solution

    (Equations 4-18, 4-19, and 4-20)

    Pick a set of x best solutions

*For Each* solution in the set

        Progress solution using the standard TSA for y iterations

*If* (TSA produces a better solution value)

*then* (modify solution value of the current solution within

the set)

*EndFor*

    Re-evaluate ranking of neighbour of solutions

    Pick best local non-tabu solution and store as current solution

*If* (best local solution > best global solution)

*then* (Store best local solution as best global solution

        reset diversification factor)

    Update tabu table

*EndWhile*

Increase diversification factor

*If* (new solutions can still be generated with the current diversification factor)

*then* (repeat *While* loop)

*else* (     *if* ( a new solution has not been generated using Equations 4-21a and 4-21b)

*then*( generate new solution using 4-21a and 4-21b ,

            set diversification factor to initial value,

            repeat *While* loop)

*else*(EndALL) )

It may be the case the result of the LFA is identical to the result of the TSA, since if the first ranked solution is chosen as the best local solution then the two algorithms are the same. It is also possible for the LFA to mimic the TSA if either the number of solutions chosen to be in the set of best solutions to be further examined is 1, or if the number of iterations these solutions are progressed is 0.

## 5. Results

### 5.1. Real life example

To test the scheduling algorithm a real life example is used, scheduling the machines needed in order to harvest grass at five farms. There are three operations that must be executed at each field; the first operation is 'mowing', when the grass is cut; the second operation is 'raking', when the grass is collected together into swaths; the third operation is 'baling', when the grass is collected and pressed into bales for easier transportation and storage. Each operation is executed using a dedicated implement, the operational parameters of which are included in Table 4.3.

The five farms are located in, or near, Halfway House a village in west Shropshire near to the England-Wales border. The depot, where all of the machinery must start from and return to, is located near the centre of the village (52.70N 2.95W), Figure 2. The farms regularly use an agricultural contractor, whose base is located at the depot, for field work. The field properties and the distances between each field are summarised in Table 4.4. The readiness for each operation at each field was simulated using the chance of rain as the determining factor.

**Table 4.3: Operational parameters**

	Operation 1	Operation 2	Operation 3
	Mowing	Raking	Baling
Number of machines available (units)	2	2	1
Processing rate (ha h <sup>-1</sup> )	3.38	2.93	2.67
Road travelling speed (km h <sup>-1</sup> )	28	28	20
Setup time for operation (h)	0.1	0.25	0.2
Order of operations	First	Second	Third
Minimum delay before operation (h)	-	18	0
Maximum delay before operation (h)	-	36	8



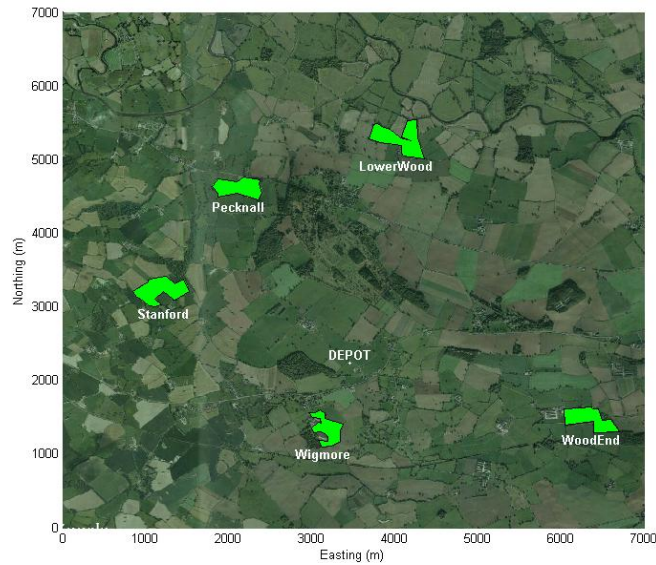
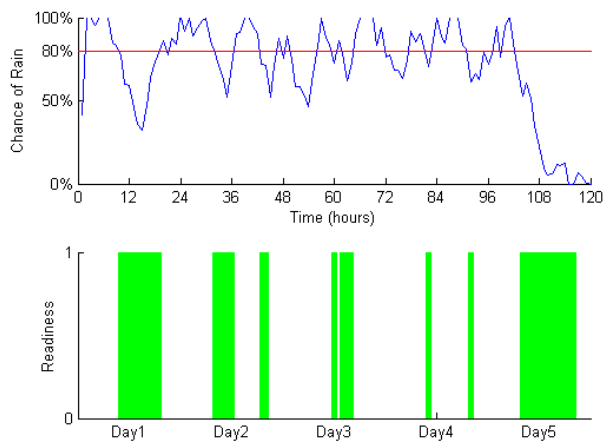


Figure 4.2: Map showing the fields' and depot's location

Table 4.4: Field properties

	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Farm Name	Stanford	Pecknall	Lower Wood	Wigmore	Wood End
Size (ha)	15.02	12.05	16.71	10.09	13.03
Distance to Depot (km)	3.36	5.12	5.12	1.12	3.52
Distance to Farm 1 (km)	-	2.4	4.96	2.72	6.56
Distance to Farm 2 (km)	2.4	-	2.4	4.48	5.44
Distance to Farm 3 (km)	4.96	2.4	-	6.08	4.48
Distance to Farm 4 (km)	2.72	4.48	6.08	-	4.32
Distance to Farm 5 (km)	6.56	5.44	4.8	4.32	-

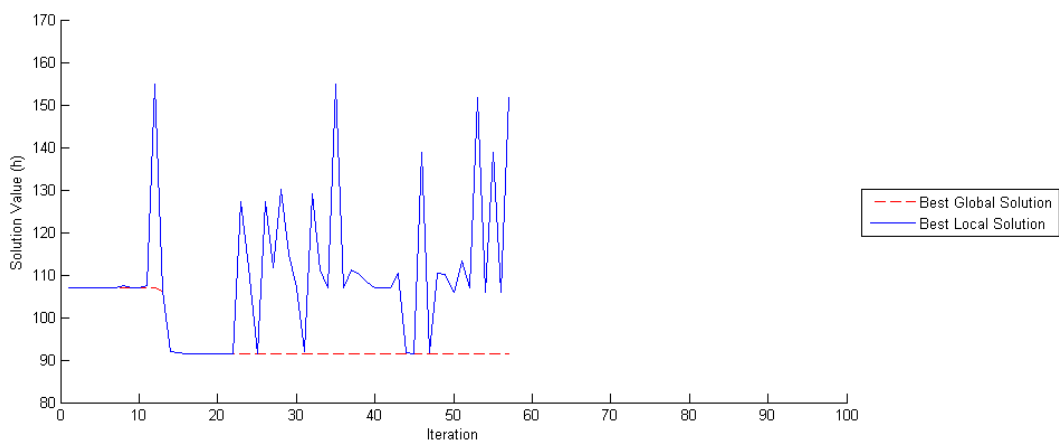
For each field, an initial chance of rain was designated between 0 and 100% using a random variable and for each subsequent hour, the chance of rain could increase or decrease between 0 and 20%. In this way, the chance of rain at each field was plotted over a two week period. The readiness for each operation was calculated by applying a decision rule stating that if the chance of rain is greater than or equal to 80% then the field is not ready, if it's less than 80% it is ready. The same rule was applied for all three operations at the same field. Also an additional rule was applied to the readiness which ensured that between the hours of 20:00 and 7:00, all of the fields were always unready constraining work to only be executed during the daylight periods.



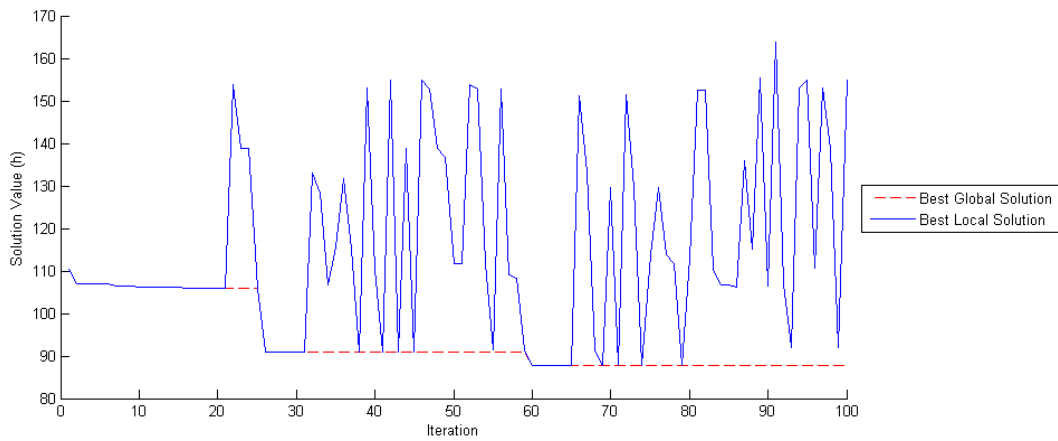
**Figure 4.3: Readiness at Farm 5 over a 5 day period**

Figure 4.3 shows the readiness calculation for Farm 5 over the first 5 days of the 14 day period simulated. The upper graph shows the simulated chance of rain over time and the red line the threshold value. The lower graph shows the binary variable of the readiness as being 1 when the chance of rain is below 80% and the time is within the daylight period.

The TSA and the LFA are used to find an optimised solution for the specific scenario. For the LFA, the parameters of the number of solutions chosen to be in the set of best solutions to be further examined was set as 5, and the number of iterations these solutions are progressed was also set as 5. Both optimisation algorithms start from the same initial solution and then vary the input variables until an optimised solution is found, so that the overall time to complete the operations at all fields and return to the depot is minimised.



**Figure 4.4: Output of the TSA**



**Figure 4.5: Output of LFA**

Figure 4.4 shows the progression of the TSA through its iterative process. The solid line shows the solution value of the current solution at each iteration step, while the dashed line shows the solution value of the best global solution. The best global solution is returned as the optimised solution once the TSA has completed. Similarly Figure 4.5 shows the progression of the LFA. The optimised solution value and computational times for both algorithms are shown in Table 4.5.

**Table 4.5: Results of the optimisation algorithms for the real scenario**

Optimisation method	Solution Value (h)	Computational Time (s)
Tabu Search Algorithm	91.5	0.167
Look Forward Algorithm (5 , 5)	87.8	0.445
Brute Force Method	87.8	2.448

To verify the results of the TSA and LFA a method was used which calculated the solution value of every possible solution within the search space, i.e. every possible combination of machine assignment and order in which the fields were visited, to find the global optimal solution. This method is known as the brute force method.

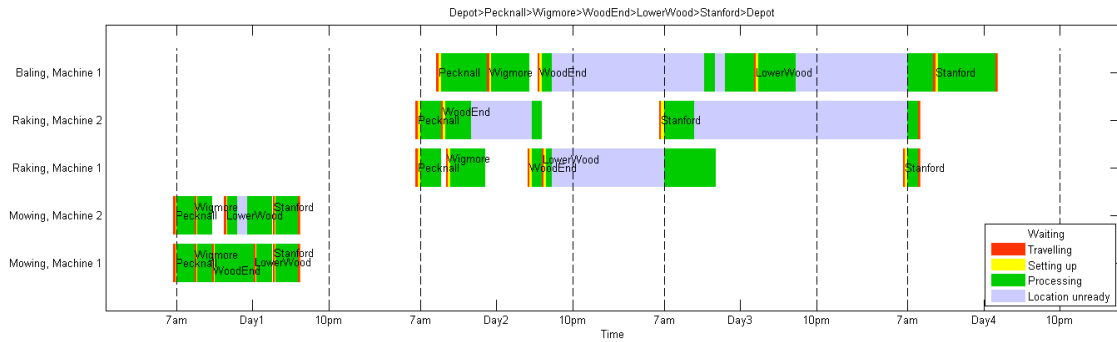


Figure 4.6: Gantt Chart of Individual Machine Scheduling

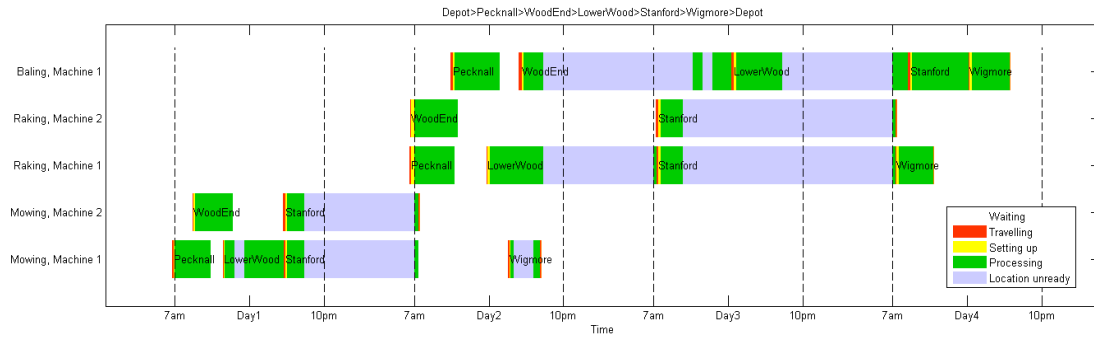
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Machine No: 1
Operation: Raking
Orders:
Date: Day 2
    06:34 Drive from Depot to Pecknall
    06:45 Setup Implement
    07:00 Begin work at Pecknall
    09:03 Finish work at Pecknall
    09:35 Drive from Pecknall to Wigmore
    09:45 Setup Implement
    10:00 Begin work at Wigmore
    13:27 Finish work at Wigmore
    17:36 Drive from Wigmore to WoodEnd
    17:45 Setup Implement
    18:00 Begin work at WoodEnd
    18:58 Finish work at WoodEnd
    18:58 Drive from WoodEnd to LowerWood
    19:09 Setup Implement
    19:24 Begin work at LowerWood
    20:00 Pause work at LowerWood overnight
Date: Day 3
    07:00 Resume work at LowerWood
    12:06 Finish work at LowerWood
Date: Day 4
    06:34 Drive from LowerWood to Stanford
    06:45 Setup Implement
    07:00 Begin work at Stanford
    08:04 Finish work at Stanford
    08:04 Drive from Stanford to Depot
    
```

Figure 4.7: Extract from fleet management file

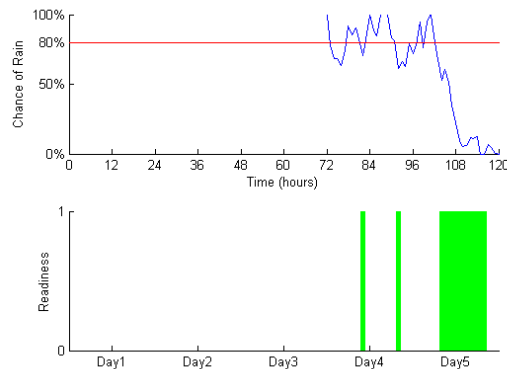
The final solution of the LFA is presented in an actionable way for an end user, e.g. a fleet manager. Figure 4.6 shows a Gantt chart of the work plans for the machines over the time period. Also, a fleet management text file is produced, listing each machine's individual orders. Figure 4.7 shows an extract from the fleet management text file listing the orders for the second machine executing the mowing operation.

## Field Readiness and Operation Scheduling



**Figure 4.8: Optimised Schedule with machine starting at fields together**

In comparison to the scheduling method detailed in Basnet et.al (2006), the schedule algorithm utilised, Algorithm 1, allows machines to start their operations as soon as they arrive at a field, if the field is ready. If the modification had not been implemented then the near optimal solution, shown in Figure 4.6, would not be possible to execute. As can be seen in Figure 4.6, for operation 1, Mowing, machine 1 begins working at “Stanford” before machine 2 arrives, which would not have been possible under the previous method of scheduling detailed in Basnet et.al (2006). Figure 4.8 shows the result of the using the brute force method in conjunction with the Basnet et.al (2006) method for the real life scenario. The result is an optimal solution with a solution value of 90.8 hours, which is greater than solution value of the new improved scheduling method, 87.8 hours.



**Figure 4.9: Modified readiness for operation 3 at farm 5**

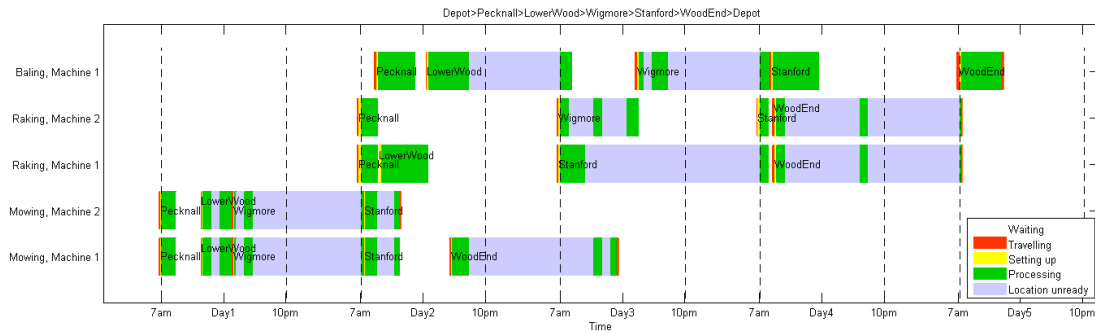


Figure 4.10: Optimised schedule with modified readiness at "WoodEnd"

To demonstrate the sensitivity of the scenario to the readiness variable, the readiness of Farm 5, “WoodEnd”, for operation 3 was changed so that the field was unready for the operation for the first three days, (Figure 4.9). Since in the current optimised solution operation 3 is executed at Farm 5 on the second and third days this affects the schedule and the current order of fields and machine assignments is likely to not be the most optimal requiring that the optimisation algorithms are implemented again. Figure 4.10 shows the new optimal solution of the brute force method, which has a new solution value of 108.3 hours.

## 5.2. Heuristics Example

In order to further test the performance of the optimisation algorithms, 18 scenarios were defined to be tested. For each scenario, a set of 100 test setups was produced where the number of farms and operations were fixed, while the other parameters were randomly selected within confined ranges as described in Table 4.6. The performance of the optimisation algorithms could be analysed for each test setup and evaluated for the computational time taken and the resultant solution value. The scheduling algorithm and optimisation algorithms were implemented in Java and executed on a laptop with an Intel Core i5-3210M CPU at 2.50 GHz, with 8GB RAM.

Table 4.6: Ranges of input parameters

Parameter	Range
$m_i$	1 to 4
$pr_i$	1 to 2
$ts_i$	0.6 to 1
$t_i$	0 to 2
$d_{ih}^{min}$	3 to 5
$d_{ih}^{max}$	5 to 10
$A_h$	1 to 15
$c_{gh}$	The position of the farms and depot were random placed on a 10 by 10 grid
$R_{ih}(T)$	0 or 1, the R parameter is stochastically generated over a large T, for each operation at each farm

$$\text{Search space} = H! \cdot \prod_{i=1}^H m_i \quad 4-23$$

For the scenarios involving a smaller number of farms and operations, the brute force method could be used which searches the entire search space to find the best possible solution, however as the number of farms and operations increases, the size of the search space increases dramatically (Equation 4-23), making an exhaustive search using the brute force method infeasible.

Analysis of the brute force method revealed that for a solution of a given setup of a scenario, the scheduling algorithm takes approximately  $1.3 \cdot 10^5$  seconds. Therefore a limit was placed on setups which had a search space of over  $2.4 \cdot 10^8$  as the processing time was likely to be over an hour. Due to this the brute force method was not executed for many of the larger setups. When at least some of the setups could not be examined using the brute force method for a given scenario, then all on the results of the brute force method for that scenario are omitted from results table, Table 4.7. As a result the brute force method was only able to be fully utilised on six scenarios where the number of fields and operations are as follows; (3,2), (4,2), (5,2), (3,3), (4,3) and (3,4)

Six optimisation methods were utilised on each test setup generated for the scenarios. The first method was the standard Tabu Search Algorithm (TSA), Algorithm 2, while the other five methods were all the Look Forward Algorithm, Algorithm 3. To examine the response of the Look Forward Algorithm (LFA) utilising different parameters for the number of solutions chosen to be in the set of best solutions to be further examined and the number of iterations these solutions are progressed, these parameter were altered across the five methods. In the first LFA the parameters were set as 2 and 2, respectively. In the remaining four methods the parameters were set as multiples of the number of fields in the scenario, since the search space increased exponentially as the number of fields increase it was deemed necessary for the LFA parameters to do the same. The solution value and computational time achieved by each optimisation method for each setup were averaged for each scenario and collected in Table 4.7.

**Table 4.7: Results of optimisation algorithms with numerical examples. LFA(2,2) denotes using the Look Forward Algorithm carrying 2 solutions forward an additional 2 iterations. H is the number of fields to be visited.**

Fields	Operations	Average Search Space	TSA		LFA(2,2)		LFA(H,H)		LFA(H,2*H)		LFA(2*H,2*H)		LFA(3*H,3*H)		Brute Force Method	
			Solution Value (h)	Computational time (s)	Solution Value (h)	Computational time (s)	Solution Value (h)	Computational time (s)	Solution Value (h)	Computational time (s)	Solution Value (h)	Computational time (s)	Solution Value (h)	Computational time (s)	Solution Value (h)	Computational time (s)
3	2	2590	31.1	0.03	30.9	0.21	30.9	0.25	30.9	0.17	30.8	0.19	30.8	0.27	30.8	0.05
4	2	240142	36.6	0.09	36.1	0.38	35.9	0.32	35.9	0.34	35.7	0.43	35.8	0.72	35.7	4.20
5	2	23238132	41.2	0.12	40.7	0.45	40.2	0.54	40.0	0.67	39.8	1.01	39.8	1.66	39.5	506
6	2	2264006117	44.7	0.17	44.0	0.39	43.3	0.71	43.2	1.01	43.0	1.55	42.9	2.55		
3	3	48636	40.0	0.08	39.7	0.29	39.7	0.15	39.6	0.20	39.5	0.25	39.5	0.38	39.4	0.75
4	3	26059708	46.4	0.16	46.0	0.37	45.5	0.42	45.3	0.53	45.2	0.78	45.0	1.34	44.2	386
5	3	6706004545	52.4	0.22	51.8	0.39	51.1	0.74	51.2	1.10	50.8	1.75	50.5	2.92		
6	3	4.50401E+12	56.7	0.29	56.3	0.39	55.1	1.31	55.0	2.07	54.8	3.46	54.7	5.89		
3	4	966887	50.8	0.13	50.5	0.33	50.3	0.21	50.1	0.29	50.0	0.38	50.0	0.70	49.8	23.3
4	4	4949447743	55.8	0.26	55.4	0.39	55.1	0.60	54.9	0.94	54.7	1.56	54.4	2.85		
5	4	3.55481E+12	58.9	0.34	58.4	0.44	57.4	1.24	57.3	2.24	57.0	3.82	56.9	6.61		
6	4	3.81E+15	68.5	0.44	67.1	0.60	66.7	2.58	66.6	4.40	66.1	7.57	65.9	12.4		
10	4	9.74E+28	88.4	0.75	87.4	1.37	85.3	24.6	85.2	39.7	85.1	62.3	84.8	102		
15	4	9.60E+44	116	1.15	116	3.24	112	124	112	205	112	318	111	495		
20	4	2.28E+62	142	1.72	140	7.48	136	428	136	682	135	1061	136	1683		
10	5	5.75E+33	101	0.88	99.7	2.14	98	42.7	98.0	62.0	97.8	106	97.4	163		
15	5	2.20E+52	131	1.52	129	6.31	125	246	125	376	125	630	124	933		
20	5	2.51E+74	155	2.39	154	12.4	148	714	149	1106	148	1873	148	2768		

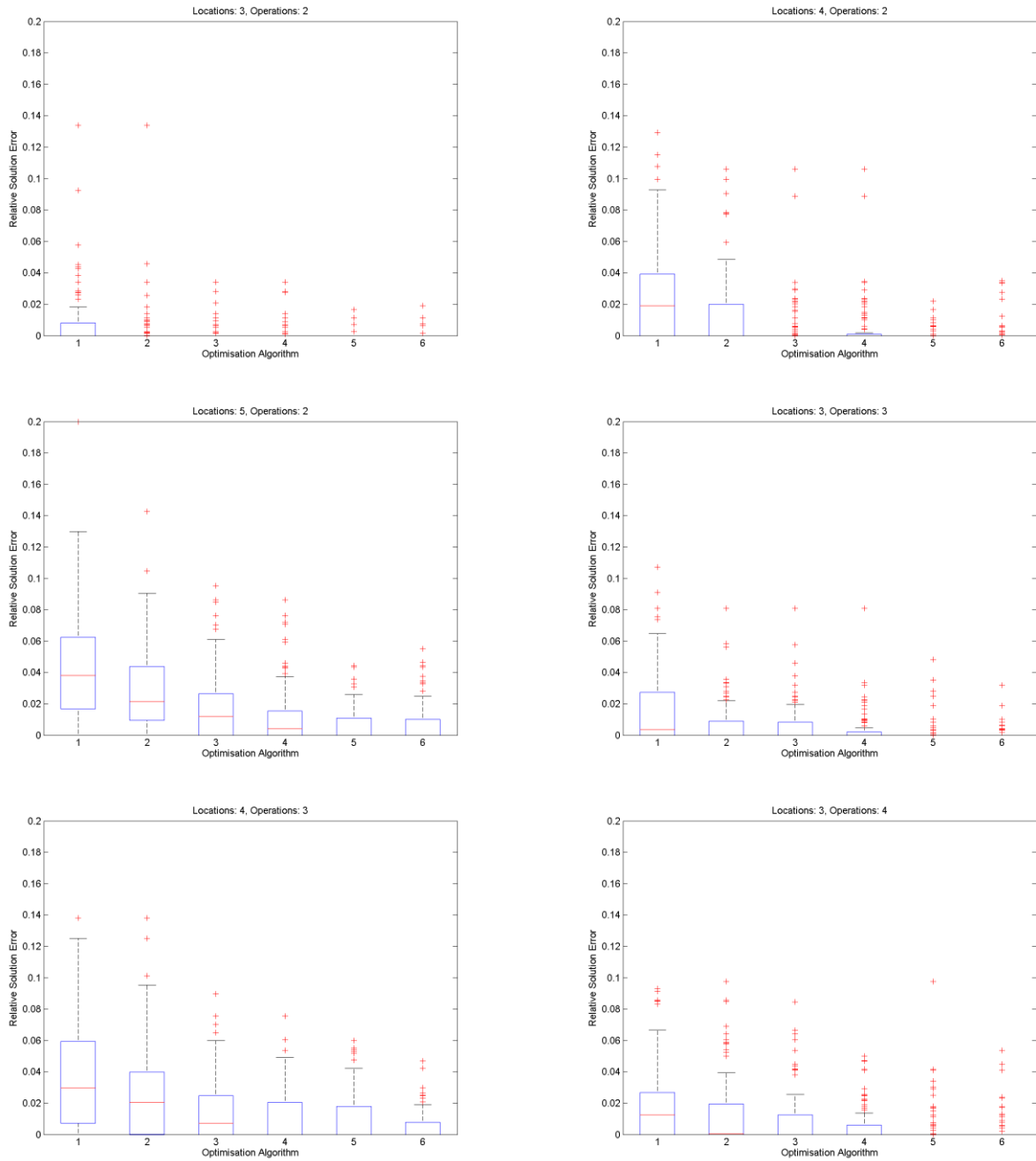
The results in Table 4.7 are summarised in Figure 4.11 and Figure 4.12. Figure 4.11 shows box plots of the variation of the relative solution error of the different algorithms for different scenarios of fields and operations. The relative error of each solution value was calculated using Equation 4-24, where  $\epsilon$  is the relative error,  $SV_a$  is the solution value calculated by the optimisation algorithm, and  $SV_{BF}$  is the globally optimised solution value calculated using the brute force method. Since the equation involves the solution value calculated using the brute force method, only the scenarios where this calculation is possible are shown in Figure 4.11.

$$\epsilon = \frac{SV_a - SV_{BF}}{SV_{BF}} \tag{4-24}$$

Figure 4.12 (a) and (b), show the average computational time of each optimisation algorithm for each scenario against the log of average search space for that scenario. The log of the average search space is



used as the size of the search spaces increase dramatically over the tested scenarios. Figure 4.12 (b) shows the results for the more extensive optimisation algorithms while Figure 4.12 (a) shows the results for the quicker algorithms.



**Figure 4.11: Box plots of the relative solution error of the small scenarios. Algorithm labelling refers to; 1 TSA, 2 LFA(2,2), 3 LFA(H,H), 4 LFA(H,2H), 5 LFA(2H,2H), 6 LFA(3H,3H)**

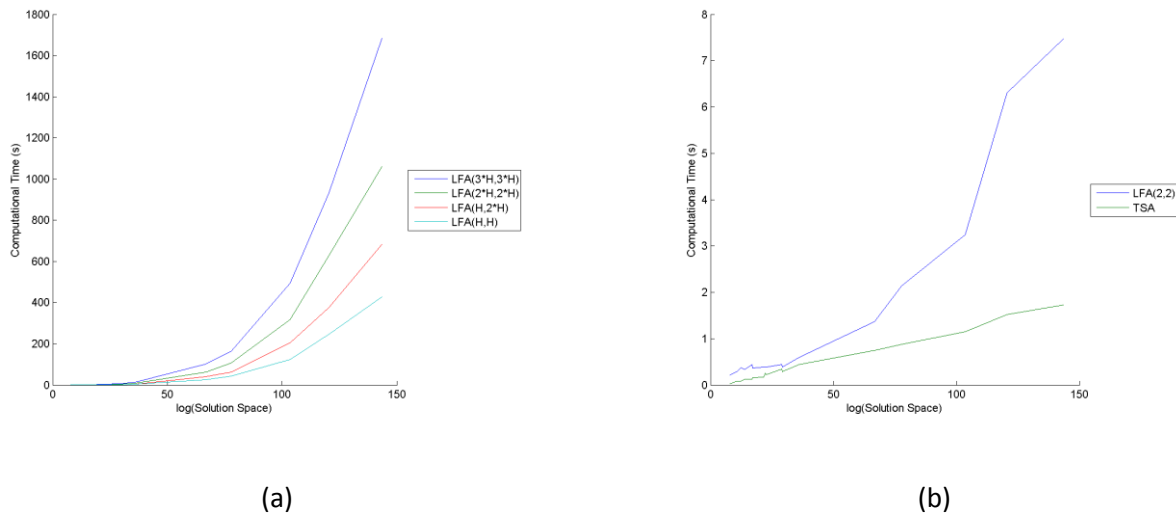


Figure 4.12: Computational Times of the utilised optimisation algorithms against the log of the Solution Space

## 6. Discussion

### 6.1. Overall performance of the model

For the real life scenario the model is able to construct an actionable schedule which can be executed by a fleet manager (Figure 4.6 and Figure 4.7).

The modification of the algorithm to allow machines to begin work as soon as they arrive at a ready field, without waiting for all the assigned machines to arrive added to the complexity of the algorithm, Algorithm 1, however it was also shown to produce a schedule that was able to complete the operations at the fields in a quicker time, Figure 4.6 and Figure 4.8. It also represents the real world more closely as it is unlikely that a fleet manager would enforce that machines sit idle at a ready location when they could be executing the operation.

The modification of the readiness variable had a profound impact on the optimal solution of the real life scenario. By changing the readiness so that operation 3 cannot be executed at Farm 5 until day 4, the original schedule became delayed and it was necessary that the order in which the fields are considered to be changed. As can be seen from Figure 4.9, there is also only two short periods on day 4 when field 5 is ready, therefore operation 3 is not able to be executed until day 5, Figure 4.10. In this example the machine allocation is unaffected by the change of readiness, although this may not be the case for another example. The solution value of the new schedule is 108.3 hours, an increase of 23% from the original schedule's solution time of 87.8 hours, Figure 4.6.

Van Elderen (1980) utilises an urgency criterion that qualified the financial impact on the decision of an operation's execution or not, such as loss of value of the crop and overtime labour hours incurred. While these specific factors are not incorporated in this work they could be realised within of the construction of the readiness variable, by limiting that no overtime can take place i.e. all fields are unready after a certain time of day, or that once a crop is below a certain value, e.g. its break-even point, the field is unready. To further address the financial implication of the scheduling a more detailed solution value equation could be utilised which calculates the operational cost rather than the overall operational time, as is shown in Orfanou et al. (2013).

In a real life utilisation of the presented tool a work schedule will likely be first calculated using forecast data to estimate the readiness. However since this forecast is likely to change over time a new schedule, which would also respond to this change, would need to be calculated. The ability of the tool to produce new schedules as the parameters change will allow for the tool to be used for real time optimisation.

## 6.2. Algorithms and procedures for optimisation

Both the TSA and the LFA offer an optimised solution for the real life scenario, however in comparison with the brute force method it can be seen that only the solution offered by the LFA is the optimal solution, Table 4.5.

Figure 4.4 shows how the TSA is quick to find a local minimum, reaching its optimised solution after 17 iterations, the algorithm then continues to search and arrives back the same optimised solution value multiple times. This could be due to the algorithm "circling" and arriving at the same solution from a different direction (as making moves tabu should limit the solution being able to be arrived at from the same direction), or the algorithm finding another new solutions but with the same solution value. The algorithm is completed after 57 iterations. Figure 4.5 shows that the LFA reaches also a local minimum in 17 iterations, the search then continues, and it finds second local minimum after 26 iterations, before finally finding the optimal solution value in 60 iterations. The algorithm continues to search the search space to ensure that a more optimal solution is not available and terminates after 100 iterations.

Although multiple solutions may be found which have the same solution value, each optimisation algorithm only returns one solution, being the first solution encountered with the best solution value. This is due to the fact that the algorithms only store a solution as the best global solution if the solution value is better than current global solution value. It may be prudent to insert another level of evaluation into the algorithms so the solutions of equal solution value may be gauged against one another. This could be achieved by introducing a more complicated evaluation criterion, considering more than just the overall

time of the whole operation, e.g. operational cost, utilisation of individual machines, or waiting time due to unreadiness. Another option could be to store all of the solutions with the same solution value and present them to a human user, who can decide which solution they would like to execute. This option would introduce a level of participation into the tool, which could increase its usability.

The LFA is approximately 2.5 times slower than the TSA, this is due to the additional complexity of the algorithm and number of iterations it takes to complete. Both of the optimisation algorithms are significantly quicker than the brute force method, with the TSA approximately 5.5 times faster and LFA approximately 1.4 times faster. In a real life scenario of this size (i.e. 5 farms, 3 operations, and a total of 5 machines) it may be acceptable to utilise the brute force method to ensure that the optimal solution is found. However as the size of the scenario increases, and hence the size of the search space, the optimisations algorithms will have to be relied upon to give optimised results. The performance of the algorithms for different sized scenarios is examined with numeric examples.

The general analysis of the results in Table 4.7 shows, that for scenarios of all sizes, as the parameters of the LFA are increased the solution values near optimality but the computational time increases. This is to be expected as increasing these parameters increases the chance that more of the search space is covered, increasing the likelihood of finding better solutions but increasing the processing time needed.

For all the scenarios tested there is a trend that the LFA with the larger input parameters have means near 0 relative error and with less variance (Figure 4.11). However it is also observed that even the mean relative error for the TSA is below 5% for all the tested scenarios, this is much lower than the relative error recorded in Basnet et al. (2006), which had relative errors of over 12% for its smallest scenarios. The computational time of the LFA algorithms for the larger scenarios can be quite large, and although only the averages are shown, for individual scenario setups the most extensive LFA algorithm, i.e. LFA(3H,3H), could be several hours to reach a solution (Figure 4.12a). However Figure 4.12b shows it is also possible to find a solution to the largest scenarios in only a matter of seconds if the LFA with the smaller valued parameters, i.e. LFA(2,2), or the TSA are used. For the smallest sized scenarios, 3 farms 2 operations, the brute force method is actually faster than all of the LFA's and the TSA. For this scenario size it would therefore be recommended to use the brute force method as it is certain to result in the optimal solution and have the lowest computational time.

While there are significant decreases in the solution values between a TSA and the first LFA, LFA(2,2), as the parameters of the LFA increase the decreases become less significant (Table 4.7). This is because the solution values are becoming nearer to the optimal solution. However since the computational time is

increasing, the worth of these smaller and smaller decrease in solution value have to be assessed. Beyond the first LFA the decrease in the solutions values is minimal, never being more than approximately 1%. Therefore it is recommended that the LFA is used with the number of solutions chosen to be in the set of best solutions to be further examined and the number of iterations these solutions are progressed, both equal to the number of fields. This LFA should offer a good solution for the scenario in a reasonable amount of time. The direct impact of the values of the parameters of the LFA should be further investigated in future work.

The usual method of assessing optimisation methods is by testing the methods against groups of benchmarking tests (Huang and Liao 2008; Yin et. al. 2010; Asadzadeh and Zamanifar, 2010; Ponish and Coello, 2012), although in this specific case of scheduling multiple machines doing consecutive operations at multiple fields there were no benchmarking tests available. The only form of comparison is Basnet et. al. (2006), however it is difficult to compare the results of the numeric examples with the examples shown in the previous work. Even though the ranges of the input values are the same in both studies, In order to further test the performance of the optimisation algorithms, 18 scenarios were defined to be tested. For each scenario, a set of 100 test setups was produced where the number of farms and operations were fixed, while the other parameters were randomly selected within confined ranges as described in Table 4.6. The performance of the optimisation algorithms could be analysed for each test setup and evaluated for the computational time taken and the resultant solution value. The scheduling algorithm and optimisation algorithms were implemented in Java and executed on a laptop with an Intel Core i5-3210M CPU at 2.50 GHz, with 8GB RAM.

Table 4.6, the inclusion of the readiness variable and allowing machines to start once they arrive affects the end solution greatly, as seen with the real world scenario. Not only do these changes affect the end solution value, they will also affect the computational time as they make the scheduling algorithm more complicated. However considering that Tabu Search Algorithm is similar to that used in the previous study, then it can be seen that the introduced Look Forward Algorithm is able to find a better final solution, although requiring a longer computational time. It is surmised that the same results would be observed if the setups utilised in Basnet et al. (2006) were available to be benchmarked against.

## 7. Conclusions and Future Work

The task of scheduling multiple machines to complete sequential operations at multiple fields has been tackled. The model of the system incorporates multiple factors affecting real life planning situations such as fields' size, spatial dispersion and readiness for an operation, as well as operational factors such as

minimum and maximum delays and machines' operational capacity. The derived model can be used as part of a fleet management system offering actionable outcomes and would be expected to yield significant benefits in terms of time savings and that operations are carried optimally at a given field.

The number of variables required to define the scenario, coupled with the sheer size of the search space of combinations of machine allocation and field order, means that it would be virtually impossible for a human to comprehend the entirety of the situation. Scheduling decisions of this type are often made by managers based on tacit knowledge and rely on past experiences. By utilising the model and algorithm as part of a decision support tool, managers are still able to be part of the decision process and have influence of the final decision made.

The TSA is able to optimise the scheduling of machines by advancement from an initial solution, to a final optimised solution. The implementation of the modified TSA, the LFA, is able to offer a solution that is often nearer to the scenario's optimal solution. Increasing the parameters of the LFA made the solution conform even closer to the optimal solution, however the consequence of which was increasing the computational time.

In the real life example the LFA is able to find the most optimal solution to the problem while the TSA finds a near optimal solution, although the LFA does require more time and iterations than TSA. Both algorithms execute much quicker than the brute force method.

Further work would be needed to quantify the affect and sensitivity of varying the parameters of the LFA has on the solution value's relative error and the computational time. When considering the inclusion of the scheduling and optimisation algorithms into a FMS, being able to vary the parameters of the LFA may be utilised. For instance at the strategic and tactical planning stages in may be more advantageous to make quick decisions therefore a less accurate solution may be acceptable and the LFA can be parameterise with low values. During operational planning (before work has started), plans may need to be more accurate as they will be the plans supplied to machines operators, however forecasts over the coming weeks might only be changing on an daily or weekly basis. Therefore a more extensive search, with the LFA having larger value parameters, would provide a more optimal solution within the required time frame. Finally as the machines are executing the operations they are likely to digress slightly from their given instructions, due to the biological nature of the operations, or machines may breakdown and be unable to complete operations. It would then be required to quickly compute new updated orders using a quick optimisation algorithm, such as using low values for the parameters in the LFA again.

Having the ability to tune the LFA to achieve a response within a certain time window, and with an estimated relative error, could greatly improve the functionality of a FMS and merits addition study into the feasibility of such a system.

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# Chapter 5 Assessing the actions of the farm managers to execute field operations at opportune times

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## Abstract

Planning agricultural operations requires an understanding of when fields are ready for operations. However determining a field's readiness is a difficult process that can involve large amounts of data and an experienced farm manager. A consequence of this is that operations are often executed when fields are unready, or partially unready, which can compromise results incurring environmental impacts, decreased yield and increased operational costs. In order to assess timeliness of operations' execution, a new scheme is introduced to quantify the aptitude of farm managers to plan operations.

Two criteria are presented by which the execution of operations can be evaluated as to their exploitation of a field's readiness window. A dataset containing the execution dates of spring and autumn operations on 93 fields in Iowa, USA, over two years, was considered as an example and used to demonstrate how operations' executions can be evaluated. The execution dates were compared with simulated data to gain a measure of how disparate the actual execution was from the ideal execution.

The presented tool is able to evaluate the spring operations better than the autumn operations as required data was lacking to correctly parameterise the crop model. The evaluation criteria could be used to identify farm managers who require decisional support when planning operations, or as a means of incentivising and promoting the use of sustainable farming practices.

## Keywords

operation management, field readiness, sustainable farming, workability, trafficability

## 1. Introduction

The decision of when and where to execute an agricultural operation is a complex choice influenced by many variables (Recio et.al., 2008). Whereas in the past farm managers have relied upon intrinsic

knowledge of their environment, as farms expand or the effects of climate change become more prominent the decision of whether a field is ready for an operation introduces more uncertainties (Cooper et al., 1997). In order to plan operations to be executed efficiently an understanding of when a field is ready for an operation is needed (Sørensen et al., 2010a). This is also essential if multiple operations are to be planned and scheduled at multiple locations (Edwards and Bochtis, 2013).

Field readiness is a measure of an agricultural field's suitability for a specific operation to be executed on it by a specific machine and produce results within a set of predefined parameters. Field readiness is considered as the conjunction of the trafficability and workability of the field, i.e. for a field to be considered ready it must be both trafficable and workable in regards to the subsequent planned field operation.

Trafficability is defined as the ability of the soil to support and withstand traffic, causing only minimal structural damage (Rounsevell and Jones, 1993). Structural damage within the soil and subsoil is most readily observed as soil compaction, which has been studied in depth to determine methods of detection (Motavalli et al 2003) and methods of prediction (Saffih-Hdadi et al 2009, Canillas and Salokhe 2002, Earl 1996). A rule of thumb was proposed by Schjønning et al. (2012), which aims to avert subsoil compaction by limiting the amount of stress within the soil profile caused by the application of the load under agricultural vehicles to a maximum of 50kPa at a depth of 50cm.

Söhne (1953, 1958) first suggested a simple analytical model describing the stress propagation within the soil profile based on the work of Boussinesq (1885) and Fröhlich (1934). This model has been shown to offer a good description of the stress propagation in agricultural soils (Keller et al. 2012, Lamandé and Schjønning, 2011, Keller and Arvidsson 2004).

Workability is defined as the ability of an operation to be carried out at a specific time to give a positive result (Droogers *et al.* 1996). The definition is purposely ambiguous as different operations have a specific set of criteria under which their results can be deemed as successful (Sørensen et al., 2010b). The workability of tillage is defined as the ability of the soil to produce adequately size aggregates without cause smearing (Rounsevell and Jones, 1993). Dexter and Bird (2001) proposed equations for determining the optimal soil moisture content for tillage in terms of the hydraulic properties of the soil. A range of soil water contents was also defined, with upper and lower limits, about the optimal soil moisture content within which tillage can be executed without causing adverse effects.

The workability of planting a crop relates to the soil temperature at the date of execution and in the following weeks. Saab (2009) states that while there is an optimal soil temperature for seeds during

planting, there is also a minimum soil temperature that cannot be breached in the weeks following planting without causing stress to the seed and ultimately affecting the crop yield. Seeders and planters also engage the soil, therefore requiring the soil to be tillable as well. A growing trend in recent years across the U.S. Corn Belt has been to move planting date earlier so as to maximise the growing season (Kucharik, 2008). While this practice aims to increase the yield of the final crop and maximise flexibility when planning the harvest, however it runs the risk of planting, and other spring operations, being executed when fields are not ready. As farm operation management practices move away from established actions, the value of a farm manager's inherent knowledge is lost and need for decision support tools increases.

Executing operations in fields which are not ready can have both short term and long term effects. Soil compaction can have many adverse effects such as reducing the volume of macropores, limiting the transfer of gases and minerals, stunting the development of the crop and decreasing expected yield (Kuncoro et al., 2014). A study carried out in Belgium (Nevens and Reheul, 2003) showed a 13.2% loss in the growth of maize as a result of wheel induced compaction on sandy loam soil. Soil compaction can also be very persistent with decreased yields (Alakukku and Elonen, 1995) the effects of soil transportation (Berisso et al. 2012) still being observable after up to 14 years after the soil was first compacted. Longer term effects have also been observed up to 29 years (Schjønning et al., 2013).

Additional operations can be executed on the field to alleviate some soil damage, however these also incur additional operational costs effecting the profitability of the crop. Damage to a standing crop may be alleviated by increased applications of chemicals although this would also increase the production costs as well as possibly effecting the environment too. De Toro (2005) estimated the cost of executing operations when fields were not defined as workable and found that these costs could comprise a significant proportion of the overall variable costs of production, with estimation of up to 150€/ha.

The untimely execution of operations does not just affect crop profitability, it can also affect the local environment. Soil compaction can limit soil water holding ability, increasing water run off (Fleige and Horn 2000) and increasing the risk of eutrophication (Smith et al. 2001) or localised flooding. If the case of a farmer's management actions affect conditions outside the local farm, regulations are likely to be placed on farmers (Nikkilä et al. 2012). Appropriate incentives are therefore essential to encourage sustainable farming practices, although measures will need to be developed to make actions auditable (Tilman et al., 2001).

Farm management information systems (FMIS) are used to collect, interpret, report and store data pertaining to farm practices. A conceptual model is represented in Sørensen et al. (2010a) in which system

boundaries are defined, dividing the entities within the farm managers control from those which are outside their control but exert an effect on the system. Farm managers are seen as active stakeholders and the key decision maker in the system, as their tacit knowledge of the environment in which the system operates should not be underestimated. As such an application of a FMIS is to act as a decision support system (DSS) offering advice and multiple solutions which can be selected by the farm manager, rather than definitive orders that must be followed. This increases participation of the farm manager as the user of the system, and therefore satisfies the need for ownership of executed decisions (McCown 2002).

An important feature of a FMIS is developing machine work plans to assist in the execution of operations (Sørensen et al., 2011). In order for the operations to be executed in a timely and efficient manner the field's readiness must be considered when constructing the work plans (Edwards and Bochtis., 2013). The work plans offered by a FMIS would then represent an ideal execution of the operations which could be used to benchmark against other work plans.

An advantage of using a FMIS is the ability to offer advice on remote locations through the combination of remotely sensed data and simulation, negating the need to physical visit many spatial diverse locations.

The objective of this study is to assess the actions of farmers used to establish and harvest a crop, and to determine whether the operations were executed at opportune times. Rather than solely considering the end product of production, i.e. the yield produced by the crop, the timeliness of the execution of the operations is considered in order to incentivise farmers to use sustainable agricultural practices that produce good results while minimising the environmental impacts.

## 2. Methods

### 2.1. Experimental Data Setup

The Premier Grain Farms (PGF) group is a farm management group who grow maize in east-central Iowa, USA. As part of the regular record keeping scheme, the dates and locations of when and where operations were executed over a two year period were recorded. This operational data along with regional soil maps, field boundaries and weather station recordings were used to evaluate the readiness of the fields at different times of the year.

The main operations considered for the fields to be evaluated for readiness were the planting of the maize in the spring and the harvest in autumn. Although no information regarding tillage or fertilisation operations were included in the data sets it is known that a deep tillage operation and application of anhydrous ammonia was performed in the autumn, and a light tillage operation was performed before the

planting date in the spring. Also immediately after planting a spraying operation was performed applying a pre-emergence herbicide. At the 2 leaf stage a fertilisation, or side dressing operation was executed applying liquid urea 32% N solution centred between the rows.

To evaluate the readiness of the fields for the executed operations the field readiness decision (FRD) tool was used. This tool is a collection of data structures, simulation methods and analytical procedures. For full explanations of the objects within the FRD tool please see Appendix 1. A simplified representation of the flow of information within the main operationalPlan object is shown in Figure 5.1.

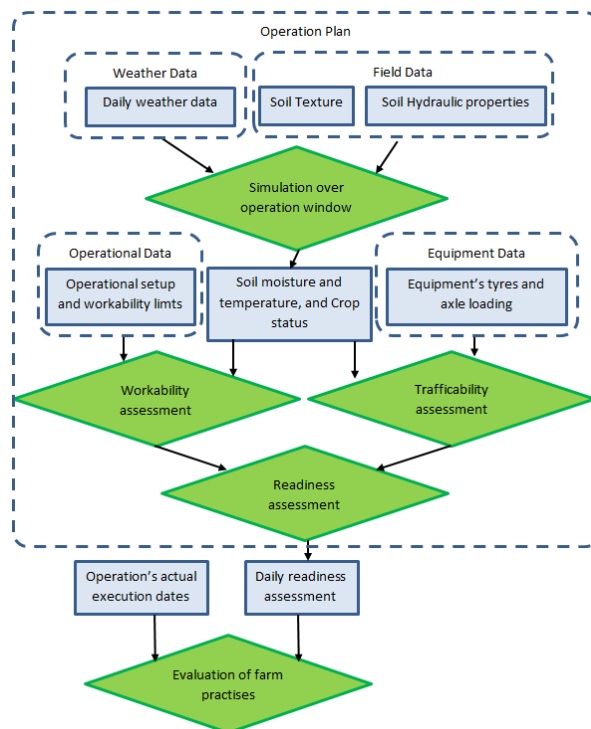


Figure 5.1: Flow of information within the operationalPlan object

The data received was in a raw form, i.e. tables and comma separated variable (CSV) files. It was then entered into the FRD tool so that the readiness evaluation could be made. The operationalPlan object is used within the FRD tool to firstly group together fields, weather, fleets of machines and groups of desired operations, and then to execute simulations and evaluations in order to create the machine specific work plans. An operationalPlan object typically covers a short period of time, such as a few months, within the overall growing season of a crop. Groups of fields which come under the operational control of a manager are often contained within the same operationalPlan object, this is helpful as if there is a limited number of machines within the fleet these constraints are taken into account. However, since the objective of this study is to evaluate farm managers' decisions rather than help plan for the future, the functionality of planning operations is not needed.

### 2.1.1. Field Data

In total the PGF group provided the field outlines of 93 fields. The regional soil map of the area in which the fields were located was also provided. The soils within the map were identified via a reference code which could be correlated with a library of soils to retrieve the clay, silt sand, organic matter, saturated hydraulic conductivity, and soil water contents at soil water potentials of 1/10 bar, 1/3 bar and 15 bar pressure.

$$\theta = \theta_{SAT} - \theta_{RES} \times 1 + ah^n - m + \theta_{RES} \quad 5-1$$

To determine the parameter of the van Genuchten equation, Equation 5-1, relating the soil water content to the soil water potential (van Genuchten, 1980) an iterative method was developed fitting the equation to the given points of the soil water retention graph defined for each soil. The parameters were then stored with each soil.



**Figure 5.2: Example of a PGF field, (a) only the field boundary, (b) overlay of the different soil types**

Interfaces were built to read the field and the soil data into the FRD tool which resulted in 93 fieldData objects. Figure 5.2(a) shows the outline of an example field within the group of 93 fields supplied by the PGF group. According to the regional soil map there are 8 different soils within the field, these are individually coloured in Figure 5.2 (b). Each soil identified with the boundary of a field was modelled as an observationPoint, where the soil and crop statuses could be simulated and evaluated. As the soil covers an area within the field, Figure 5.2 (b), the observationPoints are representative of the soil and crop conditions within that area. To establish the initial conditions of the soil at each observation point a run-in period was used so that the soil was subjected to the recorded weather of the chosen weather station (see 2.1.2) for a

period of 15 months prior to the season considered for the readiness evaluations, i.e. 1<sup>st</sup> January 2011 to 31<sup>st</sup> March 2012.

### *2.1.2. Weather Data*

The weather data for 5 weather stations for the last 20 years 1994-2014 that were located within the region was received in a CSV file. An interface was constructed converting the CSV file into the format recognised by the FRD TOOL being a set of weatherData objects each with a set of weatherAtom objects. The weatherData object collects together the data for each weather station, with the recordings of the weather station being represented as weatherAtom objects. For each weather recording, recorded with a daily frequency, a weatherAtom object was created containing the air temperature (°C), precipitation (mm), global radiation (W/m<sup>2</sup>), relative humidity (%), wind speed (m/s), minimum temperature (°C), and maximum temperature (°C). Using the coordinates of each weather station and the centres of the field boundary a simple calculation was made and for each field the nearest weather station was assigned.

### *2.1.3. Equipment Data*

Machine	John Deere 8360R	John Deere S680
Operation	Maize Planting	Harvesting
Front Tyres	380/80R38	650/85R38
Front Wheel Load (kN)	15.73	34
Rear Tyres	480/80R50	750/65R26
Rear Wheel Load (kN)	12.94	42.62

**Table 5.1: equipment tyres and loading**

There were two types of machines used for the operations, both of which are produced by John Deere. The 8360R was used for planting operations and the S680 combine was used for harvest. The 8360R had dual tyres on both the front and the rear axles, whereas the S680 only had dual tyres on the front/drive axle. The axle load and the tyres are detailed in Table 5.1, this data could be used to define the stress distribution at the soil-tyre interface. All of the machines are represented with equipment objects, with all the tyres being represented with tyre objects. Each machine had the corresponding operation object associated with it, as described above.

### *2.1.4. Operation Data*

The operations for which the fields would be considered workable for were maize planting in the spring and harvest in the autumn. The maize planting operation consisted of an implement being used which engages the soil with 2 straight disks arranged in a tight forward and downward oriented “V” to form a trench in which singulated seeds are deposited, followed by dual trench closing wheels arranged in an open downward oriented “V”. The harvest operation consisted of a harvester being used to remove the seeds of

the mature crop from the field. During the operations only the primary vehicle, e.g. the harvester during harvest, is considered for the evaluation of the trafficability of the soil.

As mentioned before no data was given regarding when tillage or fertilisation operations were conducted, however it is known that approximately 200 kg/ha of nitrogen was applied at each site with 2/3 of it applied as anhydrous ammonia in the autumn and 1/3 as liquid urea 32% N at or shortly after the 2 leaf plant growth stage. Since the dates are not known it is assumed that a tillage operation was executed within 2 days ahead of the known planting date, that the spraying operation was executed immediately after the known planting date, and that a fertilization, or side dressing, operation was executed at or shortly after the 2 leaf stage of plant growth. Each operation, including the harvest operations, was converted into an operation object, and each piece of equipment was only able to execute one operation.

Since there is no readiness assessment made for tillage, spraying and fertilisation there is no need for equipment to be defined to execute these operations. As such dummy pieces of equipment were used within the simulation to execute the tillage, spraying and fertilisation operations. The dummy pieces of equipment were setup so that any soil would always be trafficable, and the operations were always workable.

## 2.2. Parameterising the crop

The development of the crop from planting date to when it is ready to harvest is an important part of the model. Along with dates of the planting and harvesting operations' execution at each field, the farmers also recorded the maize hybrid which was planted. While all of the farmers used Pioneer brand seed, there was no data available as to how specific hybrids of seed would differ in development. As such in the simulation each field had to be planted with a generic Pioneer brand hybrid seed. In the crop model used within the FRD TOOL for simulation, DAISY (Abrahamsen and Hansen, 2000), there was already an available definition of Pioneer brand maize hybrid, however an additional step of parameterisation was necessary to better represent the development of the crop in the region.

Of the 93 available, 8 fields were randomly chosen to parameterise the model of the crop that would be used. These 8 fields would then be excluded from the further simulations and assessments of field operations so as to keep the results unbiased. The workability of the harvest operation is based on the crop's phenology. The crop's phenology is modelled within the simulation tool and is a direct result of the weather experienced by the crop, and a parameter known as the development rate, which is specified within the crop definition. For more detail on the crop model see Abrahamsen and Hansen (2000). The simulation was run for the 8 randomly selected field over 2012 and 2013 while varying the development



rate over a range of values predefined to be realistic. The date the harvest operation was executed on the field was compared with the date at which the field was first evaluated as ready according to simulation. The development rate which produced the least difference between these dates on average across the fields was chosen as adequate to be used for the simulation for the rest of the fields.

### 2.3. Evaluation of the field readiness

To evaluate the field readiness of each of the fields for the specified operations, an operationalPlan object was constructed for each field for each considered season over the 2 year period. As mentioned it is possible to group fields together that have the same farm manager or where operations are executed by an assigned fleet of machines. However the manager of each field was not included in the data and since operations weren't being planned for the future no constraints were placed on the availability of equipment. Each field therefore had 4 operationalPlan objects, covering spring 2012 to autumn 2013. The start and end dates of the season, as well as the desired operations to be executed within the season are listed in Table 5.2. The start and end dates differ also for the two years so as to encompass all of the execution dates of the operations.

Season	Operation(s)	Operational Window	
		Start	End
Spring 2012	Light Tillage Planting Spraying Fertilisation	01 – April – 2012	01 – June – 2012
Autumn 2012	Harvest Heavy Tillage Fertilisation	01 – September – 2012	15 – December – 2012
Spring 2013	Light Tillage Planting Spraying Fertilisation	01 – May – 2013	01 – July – 2012
Autumn 2013	Harvest Heavy Tillage Fertilisation	01 – September – 2013	15 – December – 2013

**Table 5.2: Operations and start/end dates of the defined seasons**

#### 2.3.1. Simulation

The first step in the evaluation process is to simulate the effect of the weather at the observation points of the field. At each observation point a set of soilMeasurement objects are created which record the status of the soil profile, such as soil moisture and soil temperature at different depths, and the status of the crop, if any crop is present. Since the weather is available with a daily frequency, so too are the soilMeasurements created with a daily frequency. Therefore the result of the simulation is the simulated

soil and crop status at each observation point with a daily frequency over the period defined by the start and end date.

### *2.3.2. Evaluate readiness*

The second step is to evaluate each of the observation points in terms the trafficability, workability and the combination of these two being the readiness. The evaluations are made on inspection of the soil and crop statuses that are produced by the simulation.

The evaluation of the trafficability of the observation points is the same for all operations. The stress propagation through the soil under the tyre of the piece of equipment is inspected. If the stress produced at a depth of 50cm beneath the soil surface is greater than 50 kPa then the soil is said to be not trafficable, otherwise the soil is trafficable. This is in accordance with the 50/50 rule put forward in Schjønnning et al. (2012). The method is explained in more detail in (chapter 3).

The evaluation of the workability is different for each operation. Since the dates were only given for planting and harvesting, it is only for these operations that a workability evaluation is made. For the planting operation an evaluation of the soil temperature and the soil moisture content is made. If the temperature of the soil is currently above a threshold, and if for the next two weeks the soil temperature remains above a second threshold, then the soil is said to be workable for planting, otherwise the soil is not workable. The thresholds are set with the operational parameters of the operation and for the generic Pioneer brand hybrid seed the first threshold is set at 10 °C while the second threshold is also set at 10 °C. To consider the fact that the planting implement engages the soil during the operation, the soil must also be tillable at the time of execution. Dexter and Bird (2001) defined an equation for optimal moisture content of soil during tillage as well as the upper and lower limits. Equation 5-2 is the equation of the upper limit in terms parameter of the van Genuchten equation, Equation 5-1.

$$\theta_{UPL} = 0.4 \times \theta_{SAT} + \theta_{SAT} - \theta_{RES} \times \left( 1 + \frac{1}{m} \right)^{-m} + \theta_{RES} \times 0.6 \quad 5-2$$

This limit is placed on the soil water content of the soil, so that when the present soil water content is below this limit, then the soil is workable, otherwise it is not. For the soil to be workable for planting it must be workable for both tillage, to a depth of 7cm, and for planting. For the harvest operation, an evaluation of the crop phenology, i.e. the current development stage of the crop, was made. The crop is said to be mature once it reaches a phenological stage of 2 (which corresponds with the sixth reproductive stage, R6), therefore if the crop's phenology is below 2 it is not workable and if it is 2 it is workable.

An evaluation of the readiness is a combination of trafficability and workability, such that if an observation point is both trafficable and workable it is ready, otherwise it is not ready. Since each of the observation points within the field cover a certain area, it is possible to say what proportion of a field is ready at a given time.

### *2.3.3. Execution*

After the evaluation of the readiness for the first operationalPlan the evaluation moves to the second operationalPlan. So that the observationPoints within the fields are in the correct state for the following operationalPlan the season's operations must be executed on a field on the dates as recorded by the farm managers. Similar to the simulation method, the effects of the weather on the observationPoints is simulated over the operational window. However the operations are added to the simulation and executed on the dates that were recorded (or estimated as is the case for tillage and fertilisation operations). The result of the execution method is that the observationPoints of a field are in a simulated state of how they could be expected to be at the end of the operational window. The fields are then used as the initial state for the next operationPlan. Assessment of the farming practises

The assessment of the farming practises of the members of the PGF group is made on two criteria; the area of the field ready for the operation on the date of execution, and the number of days unexploited when the field was ready for the operation but it was not executed.

#### *Field area ready at execution*

The readiness of the whole field is the conjunction of the readiness of the individual observation points within the field, therefore for the field to be ready all of the observation points must be ready. However due to the variation in the soil properties at each of the observation points it is possible that all of the observation points are not ready at the same time. Instead of using a binary measure of the field readiness for an operation, ie either the whole field is ready or none of it is, a quantitative measure is used which estimates the percentage of the field area that is ready for the operation. This can be used in practise to tailor how operations are executed using precision agriculture and zonal management techniques.

Each of the observation points defined for a field represents a plot within the field for which the area is defined. By summing the areas represented by observation points which are ready, a field can be said to a percentage ready. Equation 5-3 illustrates this summation, where P is the percentage of the field area ready on a given day d, n is the number of observation points with the field, R is the readiness of observation point i on day d, a is the area represented by observation point i and A is the total area of the field. R is a binary variable which is 1 if the observation point is ready on the day or 0 if it is not ready.

$$P_d = \prod_{i=1}^n R_d^i \frac{a^i}{A} \quad 5-3$$

### Unexploited field ready days

The first day that a field is ready for an operation is the first day within the operational window when all of the observation points are ready. This is considered the best time to execute the operation. If operations are executed after this day then it would mean that there had been a missed opportunity to exploit the readiness of the field. This could result in the operation being executed at a time when the whole field is not ready or cause delays in the execution of proceeding operations. It is also important to consider when operations are executed before the whole field is ready. As mentioned in section Chapter 00.0.0, it is possible that the whole field is not ready when the operation is executed. This is an untimely execution which could have produced better results had the operation been delayed.

The difference between the earliest ready day of a field and the actual execution date is given by Equation 5-4, where;  $E_a$  is the actual execution date given as a day number,  $E_s$  is the earliest ready day (or simulated execution day) given as a day number,  $D$  is the number of days difference, and  $R_d$  is the readiness of the field (expressed as 1 or 0) on date  $d$ . When  $D$  is negative the operation was executed too early before the field was ready, however if  $D$  is positive it means that the operation was executed after the field was ready and  $D$  is the number of day the operation could have been executed on.

$$D = E_a - E_s, \quad E_a \leq E_s$$

$$D = \prod_{d=E_s}^{E_a} R_d, \quad E_a > E_s \quad 5-4$$

## 3. Results

### 3.1. Parameterising the crop

Table 5.3 shows the difference between the modelled ready date of the crop and the execution date of harvest by the farm manager. Negative values indicate that the crop was harvested a number of days before it was ready, while positive value indicate that it was harvested after it was ready. Where there are no figures it indicates that at no time during the operational window did the crop become ready. If there

was synergy between the real world and the model, and if the harvest was immediately executed when the crop was ready, then it would be expected that the switch from positive to negative values for all of the fields would occur at a single development rate. However as can be seen from the table this is not the case.

**Table 5.3: Difference between the execution date and the modelled ready date for different development rates**

Development Rate	field1	field 2	field 3	field 4	field 5	field 6	field 7
0.020	~	-2	~	-23	~	~	~
0.021	~	6	~	-15	~	~	~
0.022	~	14	~	-7	~	~	~
0.023	~	21	-30	0	~	~	~
0.024	-28	25	-26	6	-16	-25	-17
0.025	-26	28	-24	12	-13	-2	-15
0.026	-22	31	-19	14	-10	3	-11
0.027	-1	33	2	18	6	9	-8
0.028	1	52	4	20	15	14	13
0.029	5	54	8	36	20	18	18
0.030	7	61	23	40	23	21	21

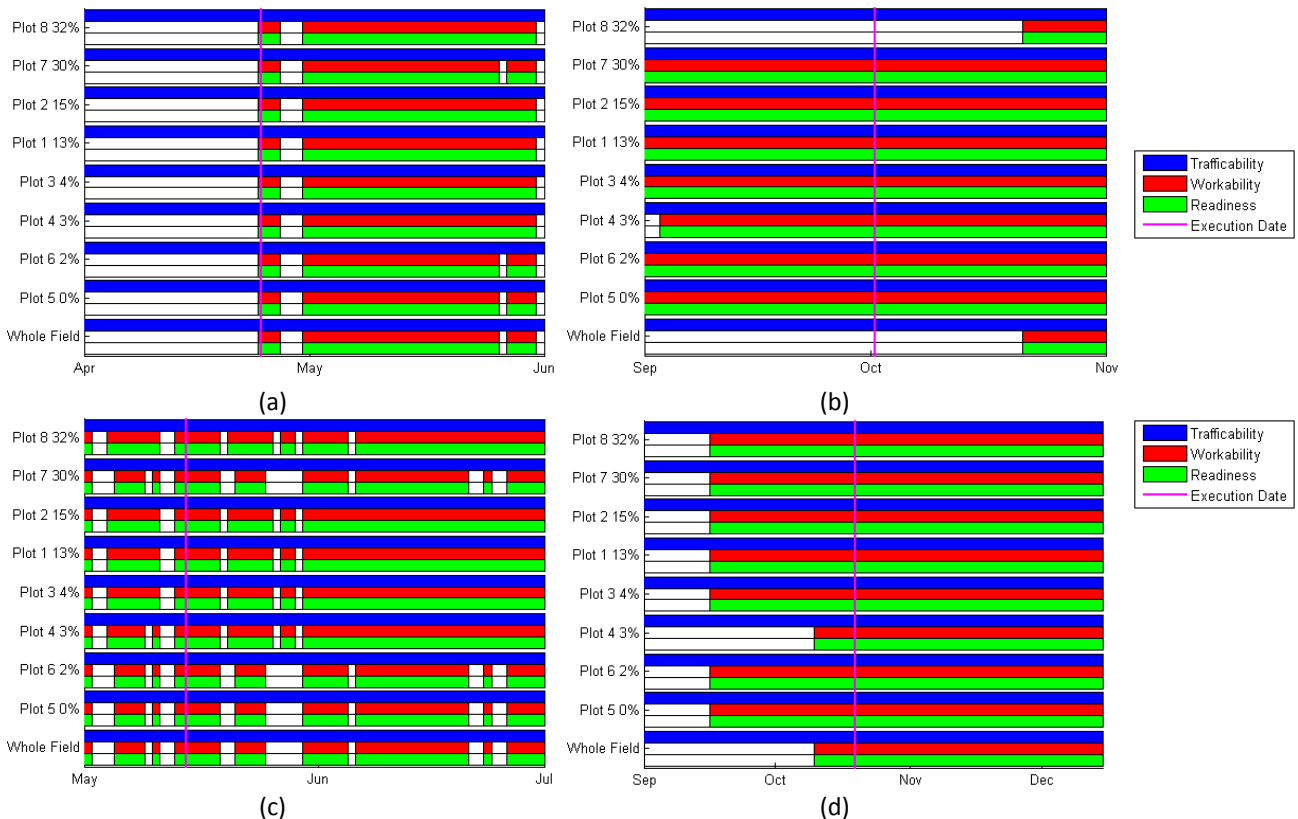
An estimation of development rate was made so that it would produce a modelled ready date close to the execution date for all fields. As such the development rate was estimated to be 0.255.

### 3.2. Readiness on date of execution operations

Figure 5.3 shows the trafficability, workability and readiness for 8 observationPoints (or plots) within an example field, each of the observationPoints representing a percentage of the overall field area as denoted on the y axis. For each plot the readiness (depicted in green) is the conjunction of the trafficability (depicted in blue) and the workability (depicted in red). The execution date when the planting and harvest operations were executed at the field during the spring and harvest periods, respectively, is depicted by the vertical magenta line.

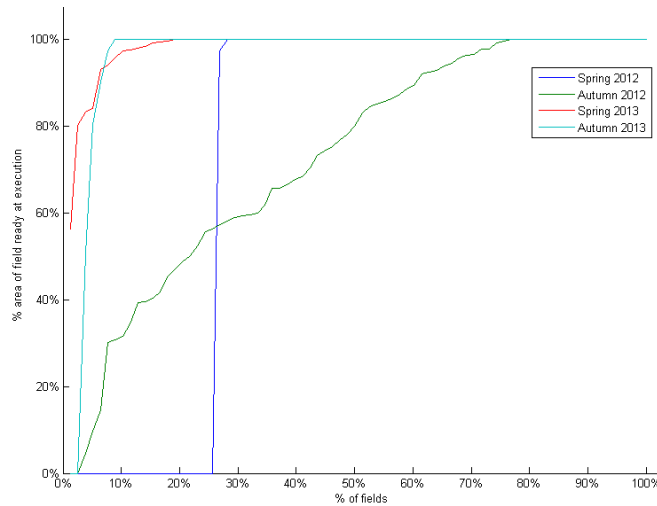
As can be seen, during spring 2012, Figure 5.3 (a), the planting operation was executed towards the end of April. At this time all of the observation points within the field had just become ready for the operation, so it can be said that the field was 100% ready when the operation was executed. This was the perfect time to execution the spring operations as any earlier and the field would not have been ready, and any later would have meant there was a missed opportunity. During harvest 2012, Figure 5.3 (b), when the operation is executed at the beginning of October only 7 of the 8 observation points are ready. Plot 8, which represents 32% of the overall field area, does not become ready until several weeks later in mid-October. Therefore

for this field in the harvest 2012 it can be said that approximately 68% of the field was ready at the time of execution



**Figure 5.3: Trafficability, workability and readiness of plots within an example field during (a) Spring 2012, (b) harvest 2012, (c) Spring 2013, and (d) Harvest 2013**

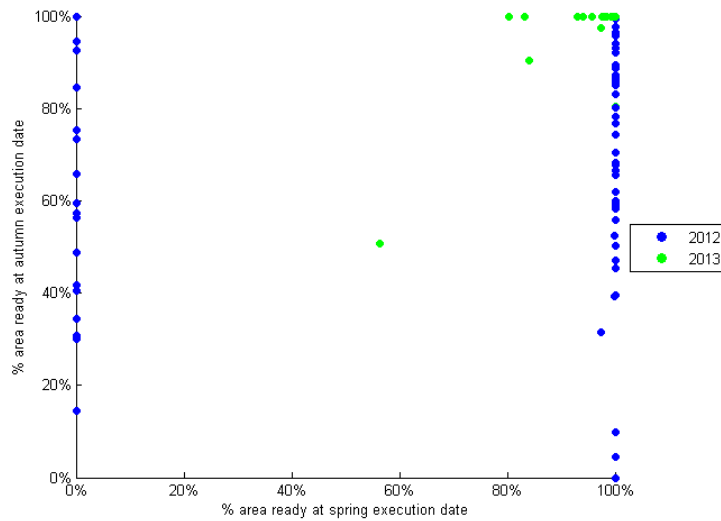
In spring 2013 the operational window is a month later than in spring 2012, as discussed in section 2.3, however there are a lot more days in spring 2013 which are ready for the operation to be executed. The whole field is ready when the spring operation is executed in mid-May therefore it was a good decision to execute on this day. However since there had already been approx. 8 days when the operation could have been successfully executed, this represents a missed opportunity. In harvest 2013 all of the observation points are again ready when the operation is executed, however there were approx. 10 days before the execution date when the harvest operation could have been executed.



**Figure 5.4: Cumulative distribution of the percentage area of a field on the Execution date**

Figure 5.4 shows the cumulative distribution of the percentage area of a field on the execution date, that is to say that for a point on a line with coordinates (x,y) that x% of fields have an y% of their area, or less, ready on the execution date. Spring 2012 has the largest number of fields where the operation is executed with 0% of the area ready, approx. 27%, whereas spring 2013 has no fields where the operation is execution when 0% of the area is ready. This would seem to indicate that the conditions during spring 2013 were more conducive to the workability of the planting operation than during spring 2012. Spring 2012 has few fields that are not either 100% ready or 0% ready when the operation is executed. This means that the observation points within the fields are either all ready for the operation or none of them are and that the different soil profiles at each observation point have little effect on the readiness. This is because part of the workability for the operation in the spring periods, the planting operation, is based on the soil temperature within the very top part of the soil and the temperature fluctuation is a result of the weather which all of the observation points experience identically.

Almost none of the fields had the harvest operation executed with 0% of the field ready, however it can be seen that there is a much larger spread of percentage areas ready during autumn 2012 than autumn 2013. Both periods had approximately the same amount of fields with 0% of area ready when the operation was executed. More fields were also harvested when 100% of the field was ready in 2013, approx. 75%, compared to 2012 when only approx. 25% of the fields were harvested when 100% of the field was ready. This again suggests that the conditions in 2012 were not as compatible as in 2013, although it could also be a knock on effect of the planting operations being executed when below 100% of the field was ready in spring 2012.



**Figure 5.5: Percentage of area ready in spring vs autumn at the date of execution**

For each field, and for each year, the percentage area ready of the field for the spring and autumn operations at the operation date are plotted against each other, Figure 5.5. It is hard to draw a link between the percentages of the area ready for the operations in 2012 as at the spring execution date the fields had either 0% or 100% of their area ready and there is also a large spread of values for the autumn operation. In 2013 there are more fields which are 100% for both operations. Also there is a noticeable trend that as the percentage area ready for the spring operations decreases so too does the percentage area ready for the autumn operation. However there is only a small amount of data that reinforces this pattern.

### 3.3. Difference between the execution date and the field’s first ready date

**Table 5.4: Summary of the ready days in each season**

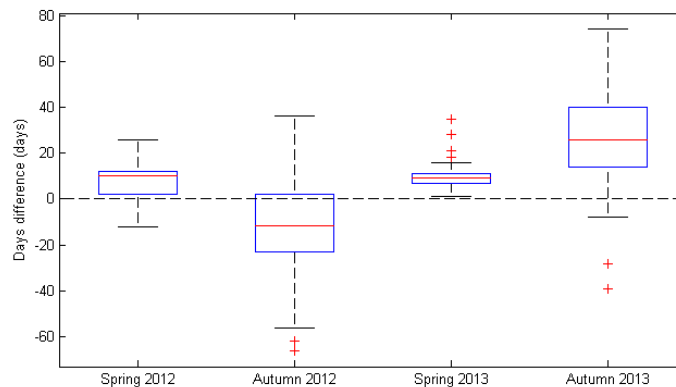
Season	No. of ready days		Days difference	
	mean	Standard deviation	mean	Standard deviation
Spring 2012	35	4.1	7	7.9
Autumn 2012	84	19.4	-9	22.0
Spring 2013	27	14.3	9	4.5
Autumn 2013	70	21.7	27	19.5

Table 5.4 is a summary of the evaluation of the readiness of the fields for the seasonal operations. The number of ready days is the number of days within the operational window when 100% of the field is in a state of readiness, i.e. all of the observationPoints within the field are ready. The Days difference is the



difference between the actual execution day and the first day the field was ready, Equation 5-4. Comparing spring 2012 and spring 2013, it can be seen that on average there are more days when the fields are ready in 2012 rather than 2013, however there is a greater standard deviation in 2013 meaning there are some fields with a lot of ready days and some with very few.

There are a great number of days available for autumn in both 2012 and 2013, and even with the large standard deviation there should be many days for the autumn operations to be scheduled. The days differences for spring show that in both 2012 and 2013 the operations were executed just after the first ready day, however in 2012 it is also likely that some operations were also executed before the whole field was ready. For autumn 2012 the mean days difference has a negative value meaning most operations were likely to have been executed before the field was ready, also there is a very large standard deviation meaning there is a wide range of values. Autumn 2013 also has a large standard deviation, however the mean days difference is also quite large, meaning the while there is also a lot of variation in how long after the first ready day the operations are executed, most of the operation are executed after the field has become ready.



**Figure 5.6: Boxplots of the days difference between the execution date of the operations and the first available ready day for each season**

Figure 5.6 shows the variance in the number of days difference between when an operation was executed compared to the first day the field was ready for the operation, for all four seasons. As already stated the ideal time to execute the operations is just after the field is ready, as executing before this would mean the field, or a part of the field, is not ready at execution whereas executing too long after the field is ready wastes opportunity. The operations executed in spring 2012 best exemplify this as the majority of the operations are executed just after first ready date. In spring 2013 all of the fields had the operation executed after the field had become ready, with some of the fields being ready for over 20 days before the

operation was executed. It should also be noted that the months covered by spring 2013 were May and June, as compared to April and May for spring 2012 Table 5.2.

In autumn 2012 most of the operations were executed before the whole field was ready, with one field having the operation executed over 60 days before the whole field was ready. Conversely the majority of operations in autumn 2013 were executed after the field had already become ready, although one field did have the operation executed approx. 40 days before the field was ready. Again looking at Figure 5.4 it can be seen the approx. 75% of fields had the operations executed in 2012 when the field was less than 100% ready, while only approx. 8% did in 2013.

## 4. Discussion

### 4.1. Evaluation of the crop parameterisation

The parameterisation of the crop was necessary to calibrate the development rate parameter of the generic Pioneer maize hybrid crop model. As stated if the crop development was perfectly modelled and the harvest operations were executed on the first day when 100% of the fields were ready without missing any ready days, then it would be expected that a specific development rate would result in zero days difference between the modelled first day ready and the harvest execution date. However as can be seen in Table 5.3 this is not the case.

Calibrating the development rate of the maize hybrid using the data from fields local to those that would be assessed intended to increase the confidence of the tool to model the maize development. However the calibration process assumed that a) the generic maize hybrid correctly modelled the particular variant used at each field, and b) the fields were harvested at the most opportune time.

An alternative method of calibrating the crop development model would necessitate in-field observations of the crop being made during its development, with measurements taken of the development stage, leaf area index, and weights of the plants' roots, stem, cob and leaf on a daily or weekly frequency. These measurements could then have been compared to the simulation's output to better determine the model's parameters. This calibration method would however require a significant investment of time and resources, however it should be considered essential if the tool is to be used more generally. A similar method was described in Hsiao et al. (2009) where a maize crop model was parameterised using data recorded over 6 years, fitting the data for the crop's above ground biomass and leaf area index.

The model of the crop development used within the simulation can only be considered an approximation, although it was able to be used to demonstrate the function of the tool to evaluate the field readiness.

## 4.2. Evaluation of the assessment method

Other methods exist for determining trafficability and workability from field inspections. Earl (1996) calibrated tensiometers' measurements with expert inspections to create a method for predicting trafficability and workability for tillage, while the workability of a crop can be inferred from the inspection of the plants. However these methods require fields being physically visited before decision can be made, which is impractical by modern farming practices. Therefore methods to determine the readiness of field for operations on the dates of execution were limited to methods that included simulation.

The presented tool also offers the advantage over other tools by combining an estimation of trafficability and workability for different operations into one tool. It is of pivotal importance a minimal number of operation management tools are presented to farm managers to encourage participation (Sørensen et al., 2010b), if farm managers are forced to learn/use multiple tools adoption will be slower.

De Toro and Hansson (2004) presented two methods to evaluate field operations. The first, the *Aver. Work* method, utilised average workday probabilities and a formula for timeliness costs given proposed by ASAE Standards (2000). Similar methods utilising average workday probabilities are described in Van Elderen and Kroeze (1994) and Wijngaard (1988). The second method presented in De Toro and Hansson (2004), the *Daily Work* method, used a simulated data and assessed the workability of the fields for the operations and the delay from a specific date until the operation was executed. The *Daily work* method was determined to offer a better estimation of the timeliness costs of an operation's execution as it could handle the evaluation of a sequence of operations and utilised a more detailed methodology.

Much of the methodology of the de Toro and Hansson (2004) *Daily Work* method is similar to the methodology employed in this study, with simulated data being used to estimate conditions and limits being applied to determine field readiness. However in the Daily Work method, the field readiness for spring operations was based solely on the soil workability, ignoring the trafficability. The soil workability was determined by applying an empirically derived threshold limit on the simulate soil moisture content, only limiting the soil from being too wet. The readiness for the harvest operations was determined by calculating the number of "maturation days" for the crop. This was based on the daily temperature and photoperiod using a model of a similar crop.

The methodology employed in this study considers both the trafficability and the workability when determining the field readiness, furthermore when the workability of planting is calculated the soil temperature is also considered rather than just the soil moisture. These methods present a progression in the methodologies of calculating field readiness.

Another criticism of the *Aver. Work* method and the timeliness equation (ASAE Standards, 2000) was that it was unable to deal with the chain effects that delayed tillage might have on harvest. By including the information of previously executed operations as part of subsequent simulations the tool is able to reproduce these effects leading to a more realistic model.

### 4.3. Assessment of operations execution

From the analysis of the results it would appear that the readiness of the fields for tillage was easier to estimate than the readiness for harvest. Figure 5.6 shows that in both spring 2012 and 2013 the operations were executed shortly after, or slightly before, the whole field was ready. Figure 5.4 also shows that in spring 2012 either 100% of the field was ready on the execution date or 0% of the field was ready, meaning that the variation in the soil types in the field had little effect on the readiness. This indicates that the fields are likely to be unready due to the soil temperature, which is more consistent across the fields, rather than the soil moisture. The readiness of the soil for planting also considers the temperature over the two weeks after the execution date. Farm managers would have had to rely on weather forecasts on or before the dates of execution which may have provided erroneous information.

While Figure 5.6 shows that in spring 2013 all of the operations were executed after the first ready date, Figure 5.4 shows that approximately 15% of fields were partially unready when the operations were executed. This would be a worst case scenario from an operation management perspective as not only has the operation been executed at an inopportune time, but an opportune time has been missed earlier.

In 2012, the harvest operations seem to be quite sporadic when compared to the simulated dates. Figure 5.4 shows that according to the model 75% of the fields were harvested when less than 100% of the field was ready. Figure 5.6 also shows that while most of the field were harvested early, there was a large variation, with some fields being harvest 60 days early and others 40 days after the first ready day had passed. The 2013 harvest appears to have generally been executed more in line with the simulated dates. Most of the 2013 operations, over 90%, were executed after the field was ready, however there was again a large variation. The parameterisation of the crop development will have had an impact of the simulation of the first ready day for harvest, and could be the reason why there is so much variation between the day difference for the harvest operations in 2012 and in 2013.

## 5. Conclusions

The demonstrated FRD tool and the methods of employing it were used to assess the operational execution data at 93 fields in 4 seasonal periods over 2 years. Actual execution data was compared against simulated data to qualify the aptitude of the farm managers to execute operation in a timely manner. Two criteria are

suggested as quantitative measures for the assessment of the execution of the operation. The readiness at the time of execution is an indication of the evaluation of the status of the field on the date of execution. The difference between the execution date and the field's first ready date is an indicator of how well the farm manager exploited the field's window of opportunity to execute the operation. Both of these criteria offer a good means to assess the timeliness of the operations execution. A further step could be to combine the two criteria using a weighted equation to get a single quotient to measure an operation's timeliness.

A practical application of the assessment of the execution of the operation could form the basis for an incentive scheme to encourage farmers to adopt sustainable farm practices. The two criteria provide a simple means by which farmers can demonstrate their aptitude at executing operations in a timely fashion. The assessment could also identify farm managers who regularly execute operations at inopportune times and who could benefit from extra support developing their operational plans.

An additional feature of the field readiness decision tool is that if forecast weather data is available, it can be used to produce machine work plans which exploit fields' readiness windows. This is especially useful to farm managers when allocating multiple machine resources to multiple fields. Also, the impact of future climate change could be elaborated in terms of operational constraints and possibilities for future farming practices, and assist individual farmers, or the greater farming industry, to adapt and evolve.

In order for the tool to be fully utilised a more representative parameterisation of the crop would be needed. This could be achieved by closely monitoring the development of the crop under real field conditions in a number of different areas. The accuracy could also be increased with the integration of in field sensors to monitor soil moisture, temperature and crop development. This would allow the tool to utilise real data and decrease the reliance on simulated data. However the installation of these systems would be expensive and could impact the profitability of the crop making it infeasible for the average farmer.

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# Chapter 6 Coverage planning for capacitated field operations under spatial variability

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## Abstract

Operations involving the collection or dispersion of material are executed by machines with a limited capacity that must unload/reload. Furthermore, the spatial variability of yield or demand increases the complexity of the planning for these operations. When there is no knowledge of the spatial variability, or when intelligent machines make adjustments due to real-time conditions, a new intelligent planning system is needed. A real-time planning system is presented that monitors the capacity change and generates an optimal coverage plan for operations. The system was tested on the Lego operations test platform as a prelude to full-scale testing, utilising a colour map to represent the spatial variability. When the demand is known the planning system produced a solution that is 17%, on average, improved from the conventional coverage, in terms of the total travelled distance, while when demand was unknown the improvement in the total travelled distance was 7%, on average.

## Keywords

route planning; Lego test platform; real-time optimisation; operations management.

## 1. Introduction

Research has shown that the in-field logistics of agricultural machinery can be improved significantly by using methods from the fields of operations research and artificial intelligent. Jensen et al. (2012) showed how methodologies from robotics path planning can be used to optimise the paths driven by transport units in grain harvesting. Bochtis and Voggioukas (2008) presents a method of optimised coverage of fields in parallel passes (B-patterns) using adapted methods and algorithmic approaches developed for the well-known travelling salesman problem (TSP), giving up to 19% increase in the area capacity (ha/h) (Bochtis et al., 2013). Bochtis and Sørensen (2009) showed how a variety of the field operations planning problems can be cast to different instances of the well-known vehicle routing problem (VRP). In real-life field operations,

in general, by integrating the data collection and planning tools, and by employing fast optimisation algorithms, operational plans are able to be adapted to the encountered situation to ensure the efficient execution of the overall operation. On the other hand, various farm management information systems (FMIS) have been proposed and/or developed which use collected data for supporting off-line decision making for field operations (Sørensen et al., 2010). However, due to the non-deterministic nature of field operations often key operational parameters may change from those estimated by the FMIS so that operational plans need to be modified in a real-time frame.

The objective of the presented work was to develop and demonstrate a planning system for capacitated field operations with re-planning capabilities. A series of tests were conducted on a dedicated test platform, which is able to execute the real-time generated route plans and demonstrate the results. The presented method regards the planning for output material flow and input material flow field operations which involve the collection (e.g., harvesting) or the dispersion (e.g., fertilising), respectively, of material within a field area. The complexity of planning in these types of operations lies

- a) in the limited load capacity of the machines
- b) to the spatial variability of the yield or the input demand.

When there is not prior knowledge available on the spatial parameters, such as when the spatial variability has not been mapped or when intelligent machines vary the application rate due to real time conditions encountered, a new intelligent planning system is needed.

## 2. The planning method

### 2.1. Spatial configuration planning

In a first step, field and vehicle features, and operational parameters are used to generate the spatial configuration of the field area. This process regards the determination, in a geometrical sense, of the headland passes and field work tracks. The notion of the controlled traffic farming was implemented meaning that the vehicle is restricted to move solely on the pre-defined field work tracks or on the headland passes. The driving distance between the entrance/exit location and all field work tracks ends, and the distance between each pair of field work tracks ends are calculated and stored in a cost matrix. The cost matrix along with the commands for following each path are compiled into a 'Path File' and passed to the planning system.

## 2.2. The field coverage planner

The purpose of the field coverage planner is to determine the traversal sequence of the tracks under the criterion of the minimisation of the non-productive travelled distance. The implemented function works in three steps:

1. the agricultural problem is transformed into a VRP
2. a VRP solver finds an optimised VRP solution
3. the VRP solution is transformed to a solution suited for the execution of the agricultural operation

## 2.3. Modelling the capacitated field operation problem

The computer-based optimal planning of field operations requires an exact description of the feasible actions of the machine and the optimality criteria. The operation that is modelled is harvesting, where the harvester does not unload on-the-go but instead has to travel out-of-field in order to unload. This is a case that often occurs in rice harvesting and in cotton harvesting. The location where harvester unloads, called 'the depot', is reachable through one or more field gates. As each track is worked completely, the planning function simply requires the accumulated capacity value of the machines temporal hopper. The minimisation of the total travelled distance is chosen as the optimality criterion of the planning, as this is correlated with the amount of fuel and time spent. As mentioned above, the planning function requires as input the travel distances between all combinations of pairs of tracks ends and the two field gates. Furthermore, it requires the harvester's hopper capacity ( $C$ ) and the demand of each individual track,  $d_i$ ,  $i \in T$ , where  $T$  is the set of tracks defined in the spatial configuration process.

As driving is restricted to follow either the headland passes or the tracks, the paths of the machine can be described by a sequence of waypoints corresponding to the field gates and endings of the tracks. Thus, the planning function output is a sequence of these waypoints grouped in a sequence of tours. In each tour the machine begins at the depot, works a number of tracks and returns to the depot to unload.

The capacity demand of each track, which is related with the yield, is not known exactly before the operation is executed. Estimates of the track demands are used to make an initial plan. However it is likely that the actual demands are different, causing the initial plan to be either suboptimal or even unfeasible. To solve this problem, online planning features are employed in the field coverage planner, where the planning function is called back as new information about the track demand is revealed.

## 2.4. Casting the field operation problem as a VRP

Using a transformation identical to one described in Bochtis and Sørensen (2009), the field area coverage problem is transformed into a capacitated VRP (Laporte, 2007), denoted CVRP. In CVRP a set of  $n$  customers

are given, each with individual demands, and a vehicle with a certain capacity starting at a depot must serve all customers. Furthermore, a cost matrix describing the travel cost between all the customers and the depot is defined. In a feasible route the vehicle starts and ends at the depot and visits a sequence of customers whose total demand does not exceed the capacity. The problem is to find a set of feasible routes that minimise the total travel cost.

The field operation problem is transformed into the CVRP by representing each track end with a customer of demand  $d_i/2$ . The distance from a customer to the depot and between the customers is provided by the cost matrix constructed in the spatial configuration process. CVRP solvers typically support the use of fixed edges, which enables one to specify that the solution must contain a certain sequence of visiting a group of customers. In the transformation, fixed edges between customers correspond to track ends of the same track.

As the online planning approach requires plan updates throughout various stages of the operation, the planning function must be able to plan according to various “starting states of the operation”, i.e., it must be handled that:

1. some tracks are already worked
2. the hopper is not completely empty
3. the machine is driving on a track (it is not located at the depot)

Each time a re-planning occurs the customers that correspond to tracks that have been prior worked are not included in the updated CVRP to be solved. The case of the current location of the machine is more complex as the CVRP general methodology assumes that the vehicle always starts at the depot. This is handled by introducing a ‘dummy’ customer corresponding to the track end (or field gate) that the machine is currently heading towards. The demand of the dummy customer is set identical to the capacity used when the machine has reached that track end (or field gate). Furthermore, a fixed edge between the depot and the dummy customer is specified. This ensures that the solution, i.e., a set of tours, contains a tour where the dummy customer is either the first or the last customer in a sequence. Figure 6.1 summarises how the field coverage planning problem is transformed to a CVRP problem.

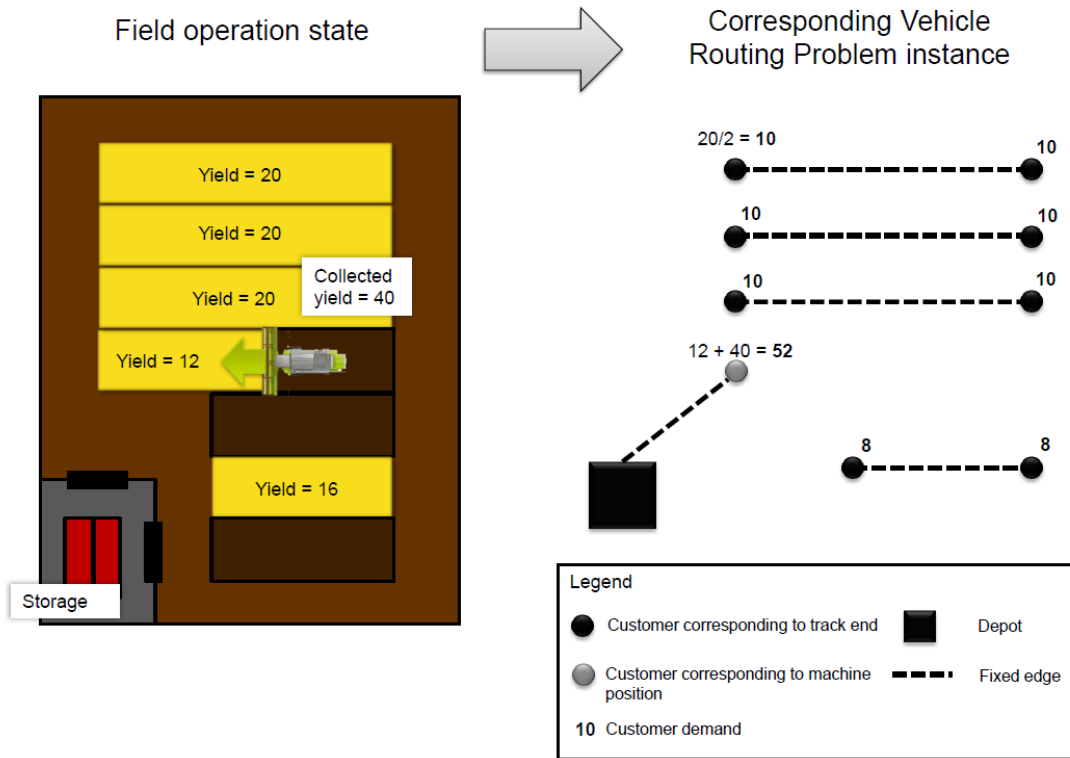


Figure 6.1: Example of how harvest operation is transformed into a VRP instance

It is straight forward to transform the VRP solution to a sequence of working the tracks (see Figure 6.2).

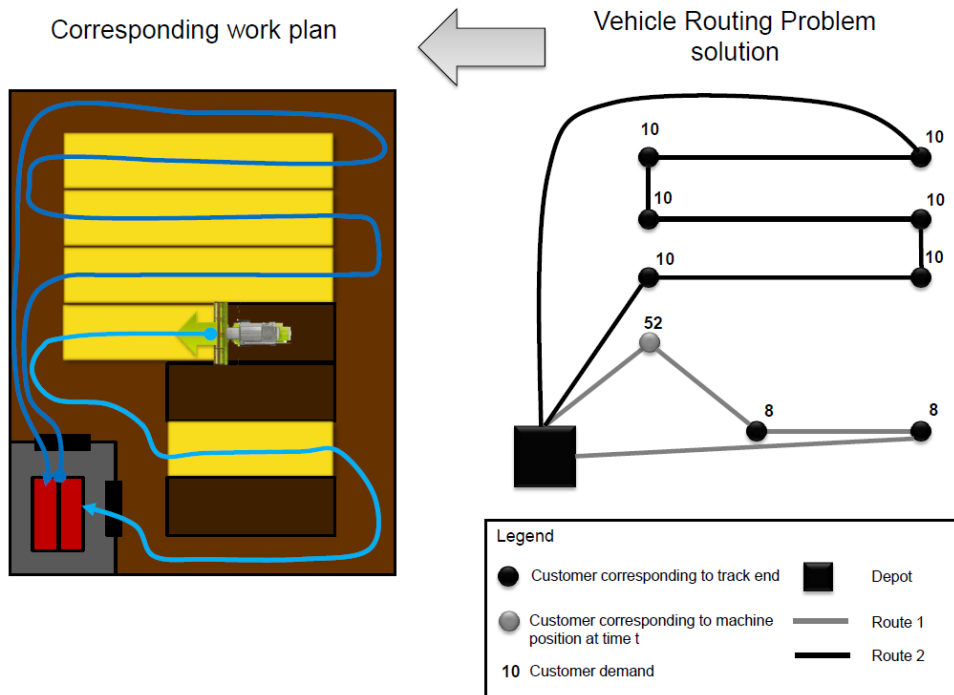


Figure 6.2: The solution of the VRP is transformed into a work plan

## 2.5. The implemented CVRP solver

A standard solver in the open source library ‘vehicle routing problem heuristics’ (VRPH) was modified to obey the single fixed edge between the dummy customer and the depot (Groër et al., 2010). The standard solver in VRPH uses a constructive heuristic to generate a feasible solution, and improvement heuristics to improve the solution [for an introduction to the VRP and overview of solvers see Laporte (2007)]. The constructive heuristic is a variant of the Clark-Wright (CW) savings algorithm (Yellow, 1970) further modified to obey the specified fixed edges. The improvement heuristic is a meta-heuristic characterised by allowing the search for solutions beyond the first local minimum encountered. This type of meta-heuristic is a version of the record-to-record travel algorithm. In Groër et al. (2010) it is reported that the specific solver produces solutions on benchmark problems which are, generally, within 3% of the best-known solutions.

## 3. Architecture of the testing system

The testing system includes the following parts; the spatial configuration system, the coverage planning system which generates an initial plan and optimise the operation while it is executed, and the operation test platform. The operation test platform utilised was the Lego Operation Test Platform which includes a Lego Mindstorm micro-tractor (Edwards et al., 2013). The micro-tractor behaves as a full sized automated tractor capable of receiving and executing driving commands, and relaying its position and sensor values. A colour sensor was used to mimic a yield sensor measuring the amount of material collected by the harvester. Different coloured patches were placed within the working area to create spatial variation in the yield that can be observed and relayed by the micro-tractor. Figure 6.3 and Figure 6.4 show the outline of the system architecture of both the planning system and operation platform.

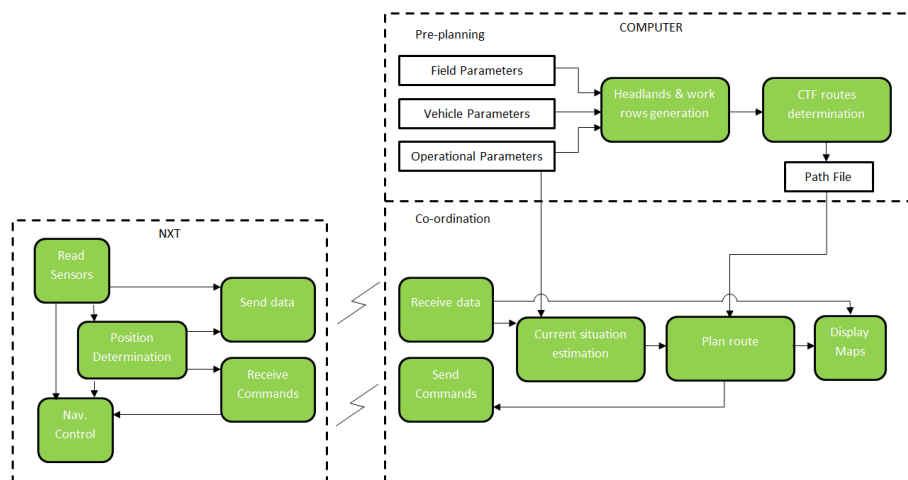


Figure 6.3: System Architecture

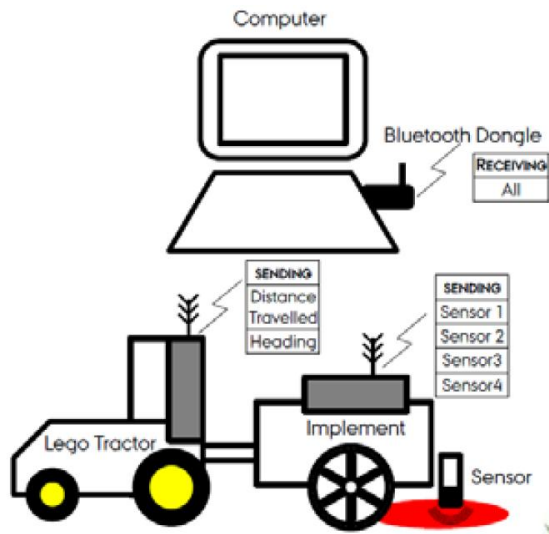


Figure 6.4: Lego Mindstorm micro-tractor

The track end sequence produced by the planning methods lists the order of way points (either track ends or field gates) the machine must visit. At the end of the current track, the track end sequence is queried, ensuring that the most recent results of the online planning are utilised. Commands are sent to the machine describing how to navigate from the current track to the next track and then how to work the next track. Alternatively if the machine must return to the depot commands are sent to navigate from the end of the current track to one of the field gates. Once the commands are sent the next track is 'locked in' as the current track and cannot be changed.

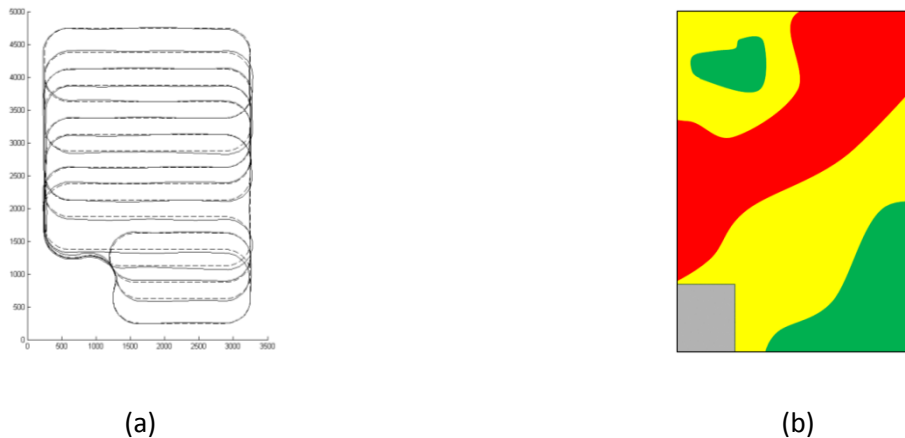
#### 4. Experimental results

In order to compare the performance of the optimised field coverage planner (GO) with the conventional planning, the human operator planning abilities were modelled with a type of greedy algorithm (NF). The algorithm works iteratively, selecting the next nearest unworked track with a material demand that, once added to the current hopper level, does not exceed the hopper capacity. When the hopper is full, a return to the depot is planned. The algorithm continues in this way until the working of all unworked tracks has been planned and completed.

For testing purposes, a small test area of 3.5 m by 5 m was used which corresponds to an area of 0.34 ha when scaled up from the micro-tractors dimensions. The working width of the micro-tractor was set at 250 mm, which corresponds to 3.5 m in real life dimensions. The depot was placed in the corner of the working area where the microtractor had to return to unload the collected material. Figure 6.5(a) shows the

headland and the field work tracks. Figure 6.5(b) shows the actual yield map within the test field, with red depicting high yield, yellow average yield and green low yield.

The field was tested using both the method of conventional planning and the method of optimal planning, and in the cases where the demand was known prior to the operation and when it was revealed during the execution of the operation. The test runs were duplicated seven times for each method and averages were taken. The results are given in Table 6.1.



**Figure 6.5:(a) Geometric representation of the test area (b) Graphical representation of yield spatial variability in the test field**

The results show that the plans generated by the GO method are superior, in terms of the total travelled distance, to the plans generated by the NF method in both cases of a priori known track yields and track yields that are revealed during the execution of the operation. When the demand is known the GO method results to a solution that is on average 17% shorter than the one resulted by the NF method, while in the case where the demand is unknown the GO method generated path is 7% shorter than the NF generated one. GO is expected to perform better than NF because the method decides what track to work next by considering the cost executing all remaining tours (a tour consist of working a number of tracks and returning to the farm for emptying). NF on the other hand decides what track to work next by considering what the nearest track is, and it does not consider that the machine has to travel back to the farm nor that it needs to work the rest of the tracks.

The results also show that both methods perform better when the demand is known. This is intuitive as when the demand is estimated the plans can vary greatly as the demands change. An example where the conventional planning can lead to non-optimal plans is the case where a distant track is selected to be the subsequent track to be worked because the nearest track has an overestimated demand that exceeds the capacity. Similarly the optimal planning method can also be affected. Further study investigating the effects



of over or under estimation of the track demands on both planning methods is needed to fully understand the effects on their performance.

**Table 6.1: Results of tests runs**

	Method	Overall Path Length (m)
Demand Estimated	NF Method	108.99
	GO Method	101.06
Demand Known	NF Method	106.31
	GO Method	88.13

## 5. Conclusions

A real time method for optimal coverage planning for capacitated field operation was presented. The method has been compared with the conventional planning method and it was found that the resulted savings were 7.3% and 17.1% for two experimentally tested scenarios. Also it was found that both optimal and conventional planning produced better results if the spatial variability of the parameter under question (e.g., crop yield) was known prior to the operation. In practice, however, to determine the spatial variability would involve the crop being inspected which could incur costs that out weight any savings gained.

The presented approach provides a range of advantages for testing algorithmically generated plans for outdoor operations such as agricultural field operations. Especially in the case of field operations full-scale testing is both costly and time consuming. On the other hand, solely computer simulations can lead to false estimations since a number of assumptions are considered for both executional environment and machine sensing and actuating. The proposed system can be used by managers (in farm level or industry level) for generating and test beyond simple route plans, also mission plans and multiple-machinery cooperation strategies. This is a crucial advantage especially in the case of field robots where there are a number of safety concerns associated unmanned vehicles.

The test platform allowed the chance to compare the methods operated within the same field and with the same spatial variability, an opportunity which would not have been an option in a real world field testing. Since both methods have been demonstrated and operational savings can be clearly seen, the next step would be to conduct prototyping and full scale testing.

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# Chapter 7 General Discussion

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In the following chapter, the conclusions of the previous chapters are reconsidered and appraised within the perspective of the research goals as a whole. The advances in the state of the art are evaluated and contextualised.

## 1. Conceptual Model of the field readiness decision support system tool

The focus of Chapter 2 is the development of the architecture and internal structure of the field readiness decision support system tool which would be further elaborated and utilised in the following chapters. Any new tool produced to handle some, or all, of the tasks of farm management would need to integrate into the existing system, dominated by human operators and other biological and abstruse entities. As such a methodology was needed that was able to capture the behaviour of the physical world, that by definition is complicated and unsystematic, and assimilate it into the system thinking world so it can be manipulated to produce a rational model of the system. By basing a new tool on the current practices of the individuals executing the operation management tasks it was hypothesised that it would increase the intuitiveness of the tool and increase its adoption by others.

The method chosen to capture the intrinsic information held by the perceived end user of the tool was the Soft System Methodology (SSM). The SSM utilises directed interviews between actors, i.e. people who execute actions within the system, and a researcher to create a model of the system that can be developed further to offer solutions to systematic problems. The exchange of information between the actors and the researcher is important to increase the shared understanding of the system.

The SSM has been previously used to initiate a participatory approach to develop other agricultural based information systems (Fountas et al., 2015; Sørensen and Bochtis, 2010; Sørensen et al., 2010a). The number of people involved in the interview process in Chapter 2, 2 agricultural contractors and 2 farm managers may seem low, however compared to other studies a small group of individuals is the normal practice; Sørensen et al. (2010a) conducted interviews with farmers from 4 farming systems in their study, Sørensen and Bochtis (2010) does not specify the number of individuals interviewed, van Meensel et al. (2012) had a supporting group of which only 3 were farmers, although Fountas et al. (2015) did conduct a total of 30 interviews. An argument in support of a small group size is that regional variations in agricultural practices and attitudes can affect the design of an FMIS (Nikkilä et al., 2010). Also due to the small group size, an intimate relationship was developed between the researcher and interviewee. This is an important, and often overlooked, outcome of a participatory approach. The communication conduits were maintained and

the interviewees were often called upon to offer their practical opinions on ideas which were developed during the remainder of the thesis. In fact the real world example described in Chapter 4, was based on a situation faced by one of the interviewed agricultural contractors in Chapter 2.

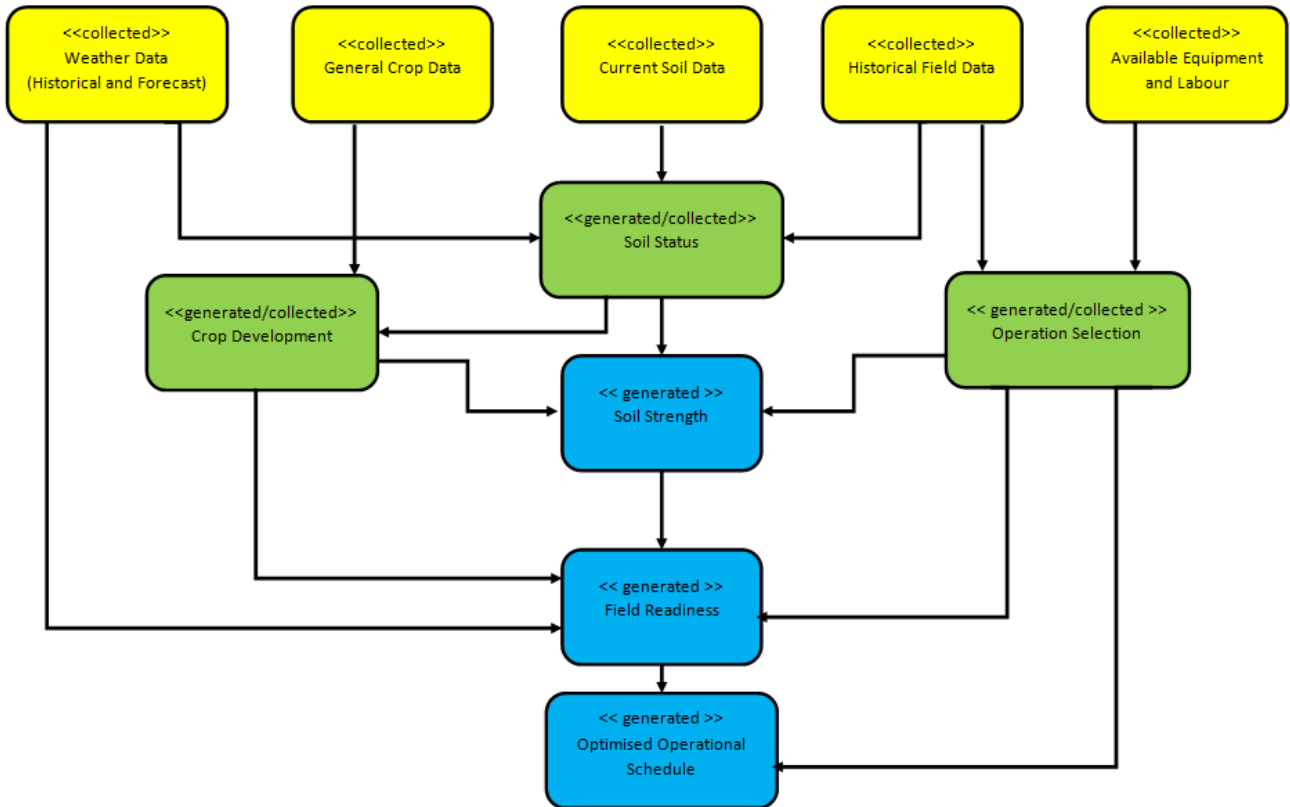


Figure 2.4: The proposed Field Readiness DSS

The conceptual model depicted in, Figure 2.4, contributes to the state of the art of Farm Management Information Systems (FMIS) by representing a clear model of the required components of a tool to estimate field readiness and assist farm managers in planning activities. An overall FMIS was outlined in Sørensen et al. (2010a), of which the field readiness decision and operational planning are subsystems. The conceptual model presented as a first step in development, Figure 7.1, highlighted the processes in a FMIS but lacked the specification of the data to be collected or generated. The purpose of a conceptual model it to convey domain knowledge from users of the system, i.e. the farm managers, to the computer scientist, from which a functional system can be built (Checkland, 1981)

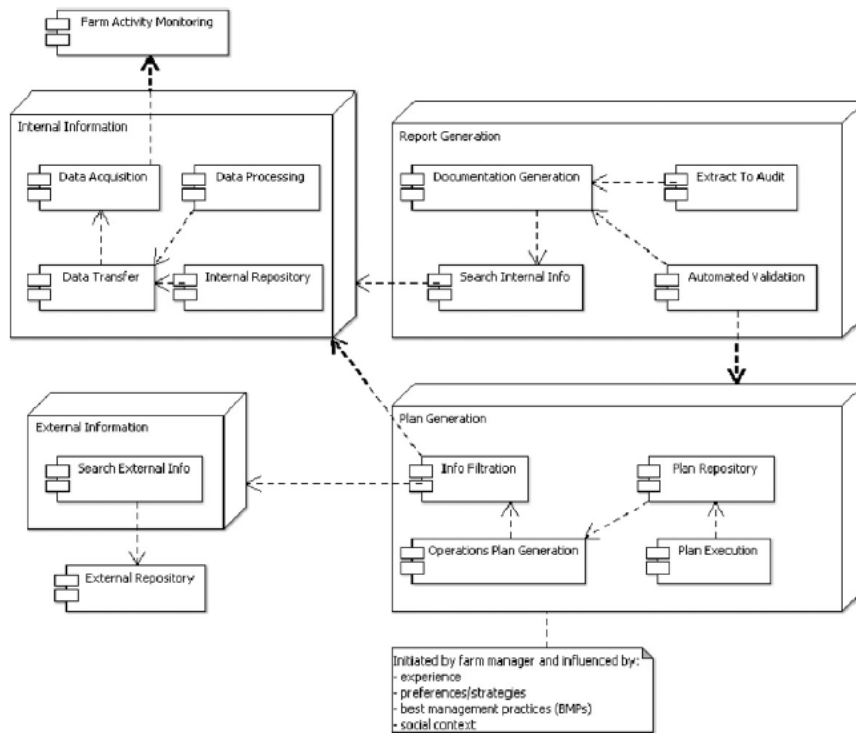


Figure 7.1: The concept of the FMIS to be developed, Sørensen et al. (2010)

The conceptual model in Chapter 2, Figure 2.4, addresses a specific part of a FMIS by describing the information requirements, Table 2.2, and providing a structure to be developed into a usable tool. This conceptual model was then used as the basis of the continued development of the tool through Chapters 3, 4 and 5.

## 2. Evolution of the conceptual model

Chapters 3, 4, and 5 describe the continued and incremental development of the field readiness decision support tool and provided practical examples of its implementation. In Chapter 3 methods are introduced to determine the trafficability of soils and the workability of a specific operation type, tillage. These methods are used to demonstrate the estimation of the average number of ready days for a real field. Additional methods to determine workability, for the planting and harvest of maize, are introduced in Chapter 5, expanding the functionality of the tool. Again real fields are used, in conjunction with simulations, to assess the management actions of real farm managers. In Chapter 4 the final module of the conceptual model, Figure 2.4, is tackled when algorithms are presented which create work plans based on a field's readiness estimation. The optimisation algorithms described in Chapter 4 can be parameterised to result in solutions of varying optimality based on the computational time available to find a solution.

In Chapter 3 the concept model, Figure 2.4, is refined, with a modified version of the model being presented as Figure 3.1. Some datasets are more clearly specified, as to their particular application in Chapter 3, while others are omitted for later development. In Figure 3.1 the Weather Data dataset was modified to only include historical data as the application in Chapter 3 assessed the field readiness of a location in previous years. The Soil Status dataset, which was sourced as either collected or generated in Figure 2.4, was specified as generated. As the application considered previous years, and recordings of the status of the soil had not been made, this dataset had to be generated using the DAISY (Abrahamsen and Hansen, 2000) simulation. The Operation Selection dataset, which again was sourced as either collected or generated in Figure 2.4, was specified as collected. This was because the operations were already selected as part of the experimental setup to be conventional tillage and minimum tillage. Three datasets were removed as they were not yet needed within the remit of the experimental setup, these were the General Crop Data, the Crop Development and the Optimised Operational Schedule.

## 2.1. Trafficability

Methods for the generation of the datasets defined as generated in Figure 3.1 are described in Chapter 3. A requirement of the method for determination of the trafficability of the soil was that it must be implemented remotely and utilise easily obtainable data. As such, the empirical equations from Schjønning et al. (2006) were used as these linked the parameters required to model the soil tyre interface as a super ellipse to the standard physical descriptions of a tyre (Keller 2007). The stress distribution within the area of the super ellipse was then described using a power-law function in the driving direction and an exponential function across the driving direction (Schjønning et al., 2008). This was an improvement on other methods for describing the soil stress under a tyre that relied upon uniform distributions of stress within the soil tyre interface (Kirby, 1994; Kirby et al. 1997; Berli et al., 2003).

The propagation of the stress within the soil profile was modelled using the Söhne summation procedure (Söhne, 1953), Equation 3-5. An important variable within Equation 3-5 is the concentration factor, so called as it dictates the stress concentration below the high pressure regions of the soil tyre interface. The relationship of the concentration values 4, 5 and 6 corresponding to hard, firm and wet soils was modelled using Equation 3-6, which relates the concentration factor to soil water potential. Terrainimo (Stettler et al. 2014) uses a similar method to estimate the concentration factor, although it utilises a discrete scale between 4 and 6 rather than a continuous scale. Keller and Lamandé (2010) reviewed the challenges posed by modelling the stress propagation in the soil profile and found a range of concentration factors being used between 4.6 and 7.7 which is similar to the range of 4 to 6 as used.

The estimated stress at 50 cm below the soil surface was limited to 50kPa (Schjønning et al., 2012), with the soil being determined as trafficable if equal or below this limit and not trafficable if the limit was exceeded. A similar conclusion was also offered by Keller et al. (2012). Stress – strain measurements were taken during wheeling experiments utilising Danish and Swedish soils at field capacity. The results suggested a limit between 31 and 49 kPa as an upper threshold to avoid non-plastic deformation of subsoil layers. This would offer a more cautious estimation of trafficability and would mean the results of the trafficability method within the tool would be an over estimate. Other methods (Söhne, 1953; Petelkau, 1984; Rusanov, 1994) proposed limiting the pressure on the surface of the soil, however these methods were not investigated as they did not account for the effects of soil moisture and more modern methods offered more analytical solutions.

It was important that the stress within the soil profile could be determined analytically and remotely. Other methods such as the installation of sensors would have been able to provide a more accurate measurement of the stresses within the soil profile however they would also be extremely expensive when multiple locations are considered.

The same method for determining the trafficability was also used in Chapter 5. All of the machines available to execute the operations in the experimental setup had the option to operate in a dual-wheel configuration, where extra wheels are fitted to the axles to spread the vehicle load. These configurations ensured that the soils were trafficable for most of the operational windows considered, as shown in Figure 5.3.

It should be noted that the 50-50 rule used to limit the stress within the soil profile (Schjønning et al., 2012) was defined to be used on soil near field capacity, however during harvest operations fields are rarely at or near field capacity. The soil moisture is accounted for in the calculation of the concentration factor, Equation 3-6. However it is possible that at much lower water contents, such as those experienced at harvest, soils are able to withstand higher levels of stress. More experimentation would be needed, including wheeling experiments, at more varied field conditions to determine if the 50-50 rule is applicable when considering soils not near field capacity, however until another rule is offered the 50-50 rule still provides a good guideline.

It is widely accepted that the stress propagation throughout the soil profile is affected by the wheel load, foot print of the tyre and the moisture of the soil. While the methods employed to estimate trafficability may not be infallible, they do account for these factors. As stated earlier it is outside the scope of this work

to devise new methods to determine trafficability, but rather to correlate previous work and integrate methods into the field readiness tool.

## 2.2. Workability

Methods to determine the workability for specific operations were described in Chapter 3 and Chapter 5.

### 2.2.1. Tillage

Chapter 3 introduced a method for determining the workability of soil for tillage. Dexter and Bird (2001) reviewed several methods of finding the workability of soil for tillage and suggested an upper (wet) limit, Equation 3-3, and a lower (dry) limit, Equation 3-4, of the soil water content, at which tillage could produce adequate results. In the application described in Chapter 3 these limits were used to constrain the simulated soil water contents so that the soil was only workable if all of the soil measurements down to the tillage depth were within the limited range. This method fits well with the requirement that methods should be analytical and able to offer a remote assessment. Also the binary nature of the assessment, i.e. soil water contents either being within the limited range or not, is compliant with the requirement of producing a binary variable for the optimisation of the operation scheduling at the next stage within the model.

Other methods for the assessment of soils for tillage include qualitative assessments made by farmers or advisers in the field (Ball et al., 2007; Shepherd, 2000) and quantitative assessments made in the laboratory (Utomo and Dexter, 1981). These methods all require the field to be physically visited to make the assessment, while the laboratory methods also require additional time after the field has been sampled. The methods also generally require special skills in order to make the assessment, which may lead to results being subjective to individuals making the assessment and their skill level. Both of these reasons make many of the other methods inapplicable to be used within the developed tool.

A review of methods to assess soil friability (“the ability of a mass of soil to breakdown into adequately sized aggregates”) (Munkholm 2011) also concluded that the water content of soil was influential on the soil friability and that defining a range of least limiting water contents was highly recommended. Mueller et al. (2003) proposed an alternative upper (wet) limit for tillage of  $0.7 \times \text{gravimetric water content at } -5\text{kPa}$ . If this limit had been used in Chapter 3 it would have lowered the upper limit and reduced the number of available ready days, as Figure 3.3 shows for autumn tillage the upper (wet) limit is often breached. Munkholm (2011) also stated that the lower (dry) limit may have been determined in a rather crude way, and that further investigation could lead to a lower (dry) limit which is more closely related to the tensile strength of the soil. In Chapter 3 the lower (dry) limit was rarely, if ever, exceeded, Figure 3.3, as during



autumn tillage the soil is more often too wet rather than too dry. Therefore changing the lower (dry) limit would have had a lesser effect on the results than changing the upper (wet) limit.

If it was deemed necessary as the result of future experimentation to utilise different limits from those stated in Dexter and Bird (2001), then a new workability method could easily be included in the tool, either as an alternative which could be selected by the user or as a replacement if the previous method was deemed inaccurate.

### *2.2.2. Maize planting*

In Chapter 5 a method for the determination of the workability of planting maize was introduced. The workability is based on the soil temperature on the date of planting as well as during the following weeks. The topsoil temperatures on the date of planting and in the following 14 days were limited to being above 10°C in order for the soil to be workable for planting in accordance with the values stated in Saab (2009). In addition to the minimum temperatures, Saab (2009) also stated an optimal temperature of approx. 29°C. This was unable to be utilised in the definition of the workability for planting as the result of the assessment was required to be a binary variable. Because the implement used in the field operations described in Chapter 5 also engaged the soil to create, and close, a trench in which the seeds were planted, it was necessary for the soil to be workable for both planting and tillage. The same method was used in Chapter 5 as was used in Chapter 3 to determine the workability of soil for tillage. In Chapter 5 the workability for tillage was calculated to a depth of 7 cm, making the operations similar to the minimum tillage operation executed in Chapter 3.

Gesch and Archer (2005) also found a minimum temperature for the planting date, although at the slightly lower 9°C, and in addition to this a maximum temperature of 40°C is also stated. A maximum temperature limit was not applied in the definition of workability in Chapter 5 as it was not deemed necessary. However, as a future application of the tool could be to consider the effects of climate change and unusual scenarios a maximum temperature limit may also need to be included in the workability assessment.

A review, of which Saab (2009) and Gesch and Archer (2005) were not a part of, of temperature requirements of rice, wheat and maize offered temperature limits for various stages of development (Sánchez et al. 2014). The mean minimum temperature for the planting date and the following weeks calculated from the assimilated data was 10°C, also the mean optimal and mean maximum temperatures were 29.3°C and 40.2°C, respectively. The mean minimum temperature corresponds nicely to the value used in Chapter 5 indicating that the method offered a reasonable assessment of the workability for planting.

The workability for planting other crops was not considered within this study, as the operation in Chapter 5 provided an adequate example to prove the concept of how the workability would be determined. However, an extension of this work could be to include the workability of planting other crops within the tool. Sánchez et al. (2014) also included minimum, optimal and maximum soil temperatures for the planting of rice and wheat and how long after the planting date these temperatures must be maintained. It is therefore likely that if methods for determining the workability of planting other crops were needed, they would be similar to the workability determination for maize with some key parameters changed.

Other soil properties may also be required to be within defined limits, in a similar way to how the soil temperature was confined for the workability of planting maize. In the experimental setup in Chapter 5 a fertilisation operation was executed in the spring. This fertilisation operation was assumed to introduce a more than adequate supply of nitrogen into the soil, as is the practice of the farm managers within the experiment, therefore the crop experienced no nitrogen stress. Different crops could require different levels of nitrogen, or other chemicals such as phosphorus, within the soil therefore these limits would have to be specified within the workability assessment. Soil moisture might also be another soil property which could be influential on the workability assessment of planting other crops.

### *2.2.3. Harvest*

The workability of harvest was considered in Chapter 5 by assessing the phenological stage of the crop's development. The development of the crop was modelled in DAISY (Abrahamsen and Hansen, 2000) based on a generic Pioneer brand maize hybrid. The development rate parameter of the crop model was parameterised using a subset of the analysed fields. The field was assessed as workable for harvest when the crop reached the phenological stage value of 2, which in the model corresponds to fully mature. Additional crop modelling software was not investigated for modelling the crop as DAISY had already been integrated into the tool to model the soil column. To introduce a separate piece of software to run parallel to DAISY and model the crop development would have seriously impaired the tool and would likely have significantly increased the computational time, as information would need to be passed between the two models via the tool. As a high computational time would limit the tools usability to the end user, alternative crop modelling software was not sought after.

DAISY was also used in a Chinese study to model water dynamics under a maize/winter wheat double cropping system (Kröbel et al., 2010). A separate program, UCODE\_2005 (Lamers et al., 2007), was used to automatically parameterise the model, adjusting parameters such as the development rate and the hydraulic properties of the van Genuchten equation. This was implemented in order to limit the users'

interaction with the model. The parameterisation was shown to improve the results, although the main focus on the study was the water dynamics rather than the crop development.

The parameterisation of the crop model in Chapter 5 would have been better served if more data had been available pertaining to the crop. Only two points were available for the parameter calibration, the planting date and the harvest date. Also while it was assumed that the harvest date corresponded to the first date the crop reached maturity, there was some ambiguity concerning this. To increase the fidelity of the crop model, observations of the crop should be made throughout the growing season with a high frequency, measuring such datum as the crop's development, leaf area index and weights of the plants' roots, stem and cob, etc.

As with the planting operation, only the harvest of maize was considered, as the demonstration in Chapter 5 was deemed adequate. DAISY has a number of generic crop parameterisation available for standard crops. These could be used to determine the workability of harvest for other crops, although as with the crop model for maize, they would need to be parameterised. For many crops the workability assessment will be determined in the same way as shown in Chapter 5, by stating that the crop is workable for harvest if the phenology of the crop is equal to 2, that is the crop has reached maturity. However some crops are harvested before they reach maturity, for example the optimal maturity of grass when it is harvested for silage is dependent on the required use of the silage (Kuoppala et al. 2008). Therefore the limit of the phenological stage could be a parameter of the operation.

### 2.3. Operations' Scheduling

The methods for the scheduling of the operations and the optimisation of resource allocation presented in Chapter 4 represent a considerable advancement in the state of the art. The algorithms of Basnet et al. (2006) were used as a base, however these algorithms were modified to include functionalities which changed how they were implemented in order to account for the field readiness. Also, the limitation that operations could not be started until all of the machines arrived at a location was removed so as not to hinder the operation's execution. These modifications mark a significant improvement of the algorithms, creating a more precise representation of the real world scenario to be used to produce work plans used for fleet management.

Fountas et al. (2015) described a FMIS with the modification of having the farm machinery at its focus rather than the farm manager, in an effort to make the process of farm management more automated. A conceptual model was also presented with a field robot at its core, the main difference between an automated tractor and a field robot being that a field robot does not require a local human operator. The

paradigm shift away from having a human at the centre of the FMIS to having a machine as its focus further solidifies the need for a subsystem that produces machine work plans in respect of a field's readiness, similar to those shown in Figure 4.7. The scheduling algorithm of Chapter 4, Algorithm 1, provides a solution to a task which is vital to the continued development of farm management information systems.

Optimisation algorithms were also presented in Chapter 4, Algorithm 2 and Algorithm 3, which vary the input variables, related to machine allocation and field order, to produce near optimal solutions based on overall execution time. The modified optimisation algorithm, labelled the Look Forward Algorithm (LFA), Algorithm 3, could be parameterised as to the extent of which the search space was examined. This allows control to be exerted over the level of optimality desired from a solution and the time available to compute a solution. One of the initial goals of the thesis is to be able to offer planning decision support at different planning levels, each of which has different requirements as to the level of optimality desired of the solution and the time available. The utilisation of the LFA with adjustable parameters at each planning stage will fulfil this requirement and produce the fleet and machine work plans.

### **3. Planning stages**

One of the initial goals was to develop a tool capable of assisting farm managers with the decision processes within the planning stages of operations management. Throughout Chapters 2 to 6, many of the tasks associated with the different planning stages have been demonstrated with practical examples.

#### **3.1. Strategic Planning**

The tasks involved in the strategic planning stage place focus on the long term planning of the farm. As such many of these tasks involve adherence to regulations. The adherence to regulations was outside the scope of this thesis as it had been tackled previously (Nikkilä et al., 2010; Nikkilä et al., 2012). Other tasks of the strategic planning stage involve the selection of the crops to be grown at locations and the consideration of machine fleet sizes to execute the establishment, maintenance and harvest of the crop.

Fleet sizing is the task of comparing the work able to be executed by the machines within the fleet to the amount of work that is required, and adapting the machinery complement accordingly (Sørensen et al., 2010b). If there is too much work to be completed by the fleet then more machine must be purchased, leased, or contracted from an agricultural contractor. However, if there is too little work to be completed by the fleet, then the execution of the fleet will be inefficient and machines may need to be sold. In order to estimate how much work a fleet can execute an estimation of the average number of ready days for an operation must be made (de Toro and Hansson, 2004). Chapter 3 is an example of an estimation of the number of days available during autumn for tillage. Table 3.4 shows the average yearly ready days for three

types of soil and for a field which contains all three soils. If an area was associated with the soils and if the working capacity of a machine to execute the tillage was known then an appropriate number of machines to handle the work load could be determined. It is typical that historical weather data is used to estimate the average yearly ready days, and that many decades worth of data are considered in the estimation. In Chapter 3 only 11 years of historical data were used, however with the recent revelations of climate change, it may be prudent to consider shorter time scales as representative of the conditions to be expected.

### 3.2. Tactical Planning

Tactical planning covers a period of 1 or 2 years, or 1 or 2 growing seasons (Sørensen et al., 2010b). This is also the time scale covered in Chapter 5, considering operations during 2012 and 2013. Although the focus of Chapter 5 was to assess the management actions of farm managers in a retrospective manner, it could also be interpreted as an example of how to plan operations over a two year period in a prospective manner. During the tactical planning stage a limitation is that weather forecasts are not available on such long term scales, and instead recorded weather data must be used to make initial work plans. If operations were to be planned at the fields involved in the study in Chapter 5 for 2014 and 2015, then the utilisation of the tool could provide estimates of when each field is first in a state of readiness for operations to fully utilise the window of opportunity.

### 3.3. Operational Planning

Chapter 4 described an example of operational planning to create achievable work plans, in the form of fleet plans, Figure 4.6, and individual plans for machines, Figure 4.7, within an established scenario. The daily readiness of fields for different operations is shown in Chapter 3 and Chapter 5, in Figure 3.8 and Figure 5.3 respectively. Although the daily readiness was calculated during the examples using recorded weather data, the assessment methods used would be unchanged if forecast weather would be used. The creation of forecast weather data is outside the scope of this work as it is assumed that it would be available from an outside source, via an overlying FMIS or an online provider. As long as the forecast weather data was available in the same format as the recorded weather data, which is also likely if they are being produced by the same source, then the operational planning process would be the same.

Operational planning is implemented in the days and weeks preceding the execution of the operations, therefore the computational time to find an optimised work plans it only confined to hours or even days. As such the optimisation algorithm described in Chapter 4, Algorithm 3, could be parameterised with large

values, so that a large amount of the search space can be investigated and results near to the optimal solution can be found.

### 3.4. Execution

An example of how field operations are planned and replanned during execution was shown in Chapter 6. For many operations the infield coverage paths are dependent on the spatial variability of soil and crop properties within the field. In Chapter 5 it was shown that due to the spatial variability of the soil within a field, the crops may be ready for harvest at different times within the same field. As a result the crop yield is also likely to vary throughout the field. At the operational planning stage an estimate must be made for the amount of time needed to execute an operation at a given location, Chapter 4 Table 4.3. In the scheduling algorithm presented in Chapter 4, Algorithm 1, this was calculated as proportional to the area of the field and the number of machines being utilised. However, as can be seen in Chapter 6, the execution time was not only dependent on the area of the field, it was also dependant on the spatial variability, the knowledge of the spatial variability and the strategy employed to create a coverage plan. As such any estimation of the execution time based solely on the field area is likely to be erroneous.

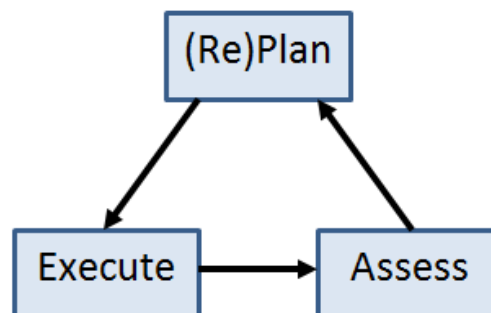


Figure 7.2: Process of execution planning

In Chapter 6 the process of the execution planning followed these steps; the plan was constructed and commands were sent to the tractor; the tractor, in executing these commands, moved and received new information about the yield in the field; the field was reassessed in response to the new information gained from the tractor and the tractor's and field's statuses were updated; considering the updated field and tractor a new plan was generated. This process is summarised in Figure 7.2.

This process has also been applied to the operation scheduling algorithm in Chapter 4 in work which is yet to be finalised and published. The result of the operational planning stage is a work plan for individual machines and the fleet based on the most up to date forecast before the execution is begun. The scenario being scheduled is described by the parameters in Table 4.1 and the variables in Table 4.2. Since the

operational planning stage has already supplied the plan, the machine allocation and the locations' order parameters have already been finalised. At this point the scheduling algorithm can be executed to produce the work plans, however as soon as the execution begins, things begin to change.

New parameters are introduced which account for this change such as; the amount of work remaining for an operation at a location, the distance from the current position of each machine to all fields, and how setup for an operation a machine is when it is at a location. The weather forecast may also change, which would affect the readiness variable for each operation at each field. With the inclusion of the new parameters and the slight modification of the equations, Equations 4-1 to 4-14, the scheduling algorithm can provide a work plan from the concurrent scenario while the operations are being executed. Not only would this account for the differences in working times caused by infield variability, but it could also account for machine breakdowns. The computational time to find a new optimised solution would be limited by the frequency with which the new information can be obtained. This is likely to be within the range of minutes or hours. As such, small values could be used for the parameters of the optimisation algorithm in Chapter 4, Algorithm 3, so that solutions can be found quickly.

## **4. Real world applications and Future Work**

In addition to the tool being used to assist farm managers plan operations' execution a different planning stages, as described above, there are other real world situations where the tool can be applied.

### **4.1. Assessment of fleet managers' actions**

In Chapter 5 the execution dates of operations were assessed using two criteria based on the readiness of the field at execution and the earliest ready date. However during the analysis it was stated that no limitations were placed on operations due to fleet sizes. While this is a valid assumption, as no information was available concerning fleet sizes or which fields would be serviced by which fleets, it could offer another explanation as to why a field may be unready at execution, or if an operation is executed after the field's first ready day.

In Chapter 4 the real world example contained three operations being executed, which is a similar scenario to the Autumn period described in Chapter 5 when the harvest, heavy tillage and fertilisation operations were executed, Table 5.2. In the real world example in Chapter 4 there were also five locations requiring the operations and a fleet of five machines, two of which can execute the first operation, another two which can execute the second operation, and the final machine which can execute the third operation. Due to the interdependency between the operations and the limit of the amount of work each machine can do

in a day, operations were delayed. The delay may not have been what was best for the individual fields, but it resulted in the over best performance of the fleet.

To validate the scheduling algorithm within the developed tool a further experiment could be made which includes the information on how many machines were available to execute operations on a group of fields. A common practice of fleet management is to keep all of the machines together and execute operations in one field at a time, however as demonstrated in Chapter 4, this is not the most efficient use of resources. An experiment comparing the machine work plans created by the tool against the actions executed by a fleet under a fleet manager's control could validate that the scheduling algorithm is able to offer good solutions. The created work plans and the executed actions would both be assessed by the same criteria proposed in Chapter 5, as well as an additional criterion evaluating the utilisation of the fleet such as the total costs of the execution or the total machine hours expended.

## 4.2. Impact of climate change

Climate change will affect the way in which farmers are able to produce crops over the coming decades (Vermeulen et al., 2012). Today's farming practices are well suited to the current climate, however it is unknown how they will be affected by progressive climate changes, particularly if they are accompanied by changes to government policies (Williams et al., 2007). As the situation changes the intrinsic knowledge of the farm manager will be devalued, and the need for a tool to assist in decision making will increase.

The impacts of climate change may not all be detrimental to a farm manager. Lui et al. (2013) considered the impact of climate change in China over the past 30 years to examine the effect on yield. Using simulations it was shown that had farming practices stayed the same, yield in the area would have fallen. However due to sowing dates being moved to early in the year, as a result of milder spring weather, yields were increased. This demonstrates how farm managers were able to exploit climate change to their advantage.

New climate change models offer predictions of seasonal, and even daily, weather on increasingly smaller spatial resolutions (Knutti and Sedláček, 2013). In both Chapter 3 and Chapter 5 recorded weather data was used to estimate what the trafficability, workability and readiness of fields would have been. In both cases the recorded weather is provided in CSV files and interpreted by the tool using predesigned interfaces, as described in Appendix 1. Climate change models could be used to create simulated weather records which could be utilised in exactly the same manner as shown in Chapter 3 and Chapter 5, to demonstrate how field readiness will be affected and how opportunities can be exploited.



### 4.3. Incorporate more workability assessments

The workabilities of tillage (Chapter 3), planting and harvesting (Chapter 5) have been considered in this thesis. They were judged as three labour intensive and time sensitive operations which could benefit from being scheduled in accordance with a field's readiness. Sørensen et al. (2010b) also included spraying, fertilisation and irrigation as important operation to consider. These three operations, along with the three operations already considered in this thesis, were the main focus of the development of a FMIS in the European FutureFarm project (Chatzinikos et al. 2009).

To further the development of the tool the spraying, fertilisation and irrigation operations should be examined to incorporate methods for determining their workability. The workability assessments for these operations should be able to be made utilising data already available within the tool, such as weather data, soil status and crop status. In Pesonen et al. (2014) a crop management system was developed to assist with planning spraying operations. Wind speed is viewed as an important parameter to monitor, with operations being halted if the wind speed is too high. Parsons et al. (2009) also included a weed development model within its decision support system, which estimated when will be the most opportune time to execute a spraying operation.

### 4.4. Links to live data

The main conduit for entering data into the current implementation of the tool is either loading comma separated variable (CSV) files using predefined interfaces or by manually inputting data into the developed graphical user interface (GUI), Appendix 1 Figure 0.1. Both of these methods are labourious and would take up much of a farm manager's prescribed office time. Lawson et al. (2011) stated that farm managers have an increasing amount of office work to complete, and sited this as a driving factor as to why FMIS should be more widely adopted. Integration of the tool into a FMIS would allow for information to be passed between the systems so that it would not need to be entered in more than one place.

An alternative step to integrating the tool into a FMIS would be to link the tool directly to online sources of data. Many different technologies are available to the modern farmer to map the spatial variability of their fields, and to monitor temporal variations (Mulla, 2013). Van der Keur (2001) integrated soil water contents measurement (taken using in situ time domain reflectance probes) into the DAISY model. A similar technique could be used with the current tool in order to provide an accurate starting point for simulations during the operational and execution planning stages.

# Chapter 8 Conclusions

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In confronting the task of creating optimised machine work plans in accordance with a field readiness the following key conclusion were made;

- A conceptual model of a field readiness decision support system was created as a result of applying the Soft System Methodology and direct interviews with farm managers and agricultural contractors. This conceptual model provides a framework for the development of a tool to be used to estimate field readiness and assist in the tasks of operations management.
- Field readiness is a conjunction of a field's trafficability and workability. These properties are independent of each other and dependant on the machinery being used, the operation being executed and the local environment (field/weather conditions). An estimation based only on one property, rather than both, is inadequate to describe the readiness of a field.
- An analytical method is presented to determine trafficability, based on limiting subsoil compaction, using the physical description of agricultural tyres and wheel loadings. Methods are also presented to determine the workability for tillage, planting and harvest operations. All of these methods are integrated into a field readiness tool which can be implemented at the different planning stages encountered by a farm manager performing operations management. The methods analyse different data, which are made available within the structure of the tool. The tool and methods are demonstrated using real soils and real weather to initiate simulations of fields' conditions.
- The field readiness is shown to be an important parameter in the creation of work plans, so that operations can be executed efficiently and in a non-damaging manner. An algorithm is presented that can schedule multiple machines executing consecutive operations at multiple locations. The scheduling algorithm extends the state-of-the-art, incorporating many features of the real life scenario that is the subject of operational planning, so that the created work plans are realistic and actionable. Optimisation algorithms are used alongside the scheduling algorithm to find the near optimal allocations of resources to produce efficient plans. It is also possible to parameterise one of the optimisation algorithms to offer varying degrees of near-optimality at the expense of the computational time required. This is essential for its utilisation at the different operations management planning stages
- It is shown to be necessary to include real-time planning at the execution planning stage, so that work plans can be adaptive to variable conditions that may be encountered. Machines may need to replan how they execute their own operations and this may trigger a need to replan the whole fleet's execution.
- Outside of operation planning, the developed tool has been shown to have additional applications such as assessing the aptitude of farmers to execute operations in an efficient manner or helping farmers to adapt in the face of climate change.

## Chapter 9 References

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# Appendix 1 A summary of the final tool

## 1. Introduction

As part of the PhD study, a tool was developed to be used to handle relevant data for the field readiness decision, and create work plans that could be executed by specified machinery. The tool was developed from the initial conceptual model that was constructed using the involvement of perceived end users, i.e. farm managers and agricultural contractors, as described in Chapter 2. The tool is still at the prototype stage of development and is to be used solely as a research tool rather than a commercial product. As such the tool was programmed in Matlab as the researcher was extremely comfortable working with the programme, allowing for rapid prototyping and modifications of the tool. Matlab also supports interaction with other languages so that modules could be run in other programming languages while Matlab controlled the administration of the tool. Due to the researcher experience in Matlab, other programming languages were not considered as viable options for the main part of the tool.

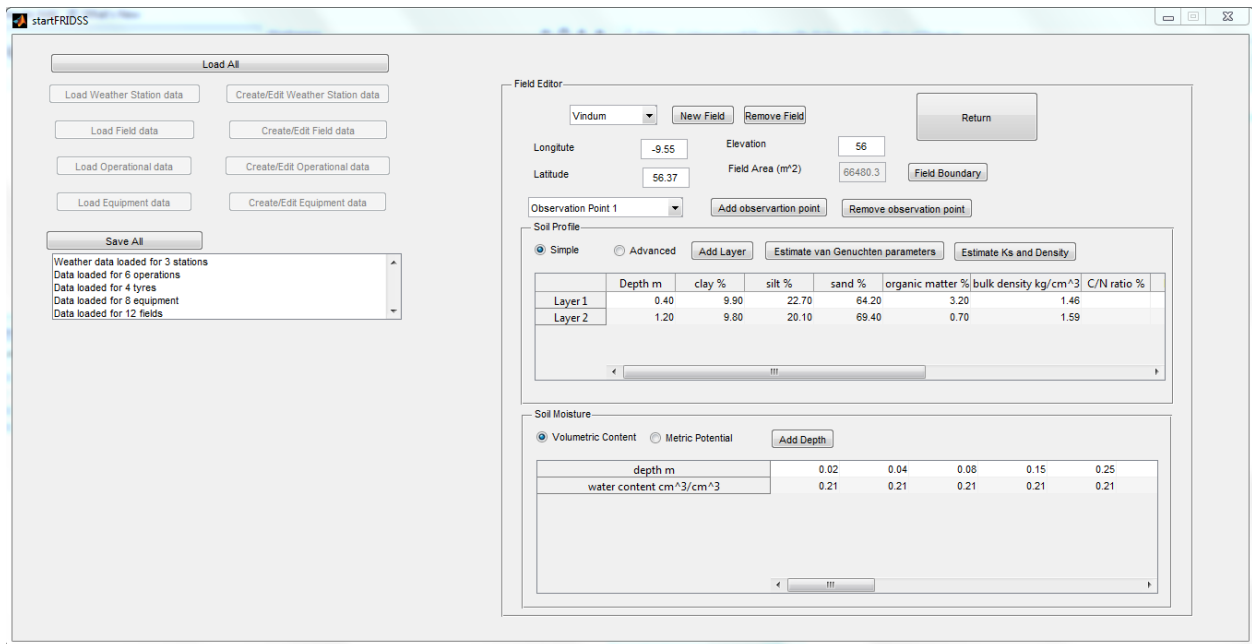


Figure 0.1: Example of the GUI showing the field editor

Since the tool is not connected to an existing Farm Management Information System (FMIS), all of the data used for the readiness evaluation must be inputted by the user, either by manually inputted data into the graphical user interface (GUI) or by loading in files where applicable. The GUI, Figure 0.1, also offers the ability to review and edit information already loaded into the tool. The data within the tool is segmented into 4 main areas, this segmentation is carried through to the GUI with each area is visualised via a separate

user input panel and editor. In Figure 0.1 the Field Editor is shown as an example, this editor can be used to input, view and edit data pertaining to the field such as soil profile layers and the soil moisture content. The field data is explained in more detail in section 1.2.

The 4 main data areas are; weather station data, field data, operation data, and equipment data. There is connectivity between the areas, such as each piece of equipment has a set of operations it can execute, but largely the areas can be thought of separately. In the following sections each area is described in more detail using an object orientated description, explaining the class objects within the areas of the tool and their properties and methods.

## 1.1. Weather station data

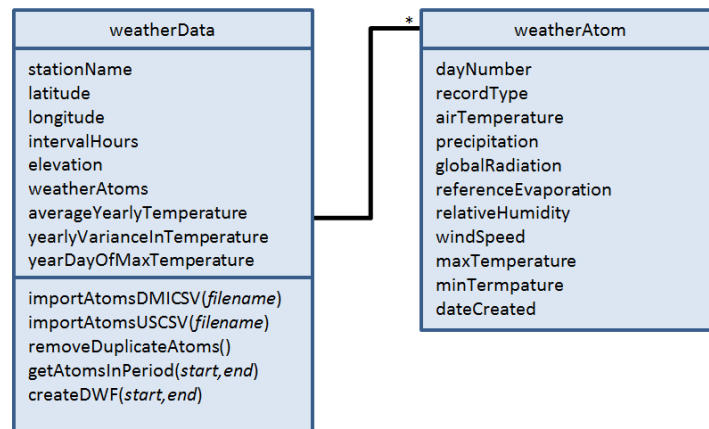


Figure 0.2: Class diagram of weatherData and associated classes

The data pertaining to the weather is described in two classes, Figure 0.2. The first is weatherData which is used to describe the location where the weather recording has taken place (this is usually a weather station). The second class, weatherAtom, describes individual recordings of weather.

### 1.1.1. weatherData

The stationName is an identifying name given to the weatherData so that it can be recognised. The latitude, longitude and elevation describe the global positioning coordinates of the station, these can be important when estimating the day length at a location. The intervalHours is the number of hours between each recording made by the station, typically this is either 1 hour or 24 hours. The weatherAtoms is a set of weatherAtom. In case there is any missing data with the weatherAtoms of a station, the temperature can be estimated using a simple sine wave and the values for the averageYearlyTemperature, yearlyVarianceInTemperature and yearDayOfMaxTemperature. There are a number of methods for the weatherData class. Both the importAtomsDMICSV and importAtomsUSCSV, read in comma separated

variables (CSV) files to create and append a set of weatherAtoms, with importAtomsDMICSV reading national weather files produced by the Danish Meteorological Institute, DMI, and importAtomUSCSV reading files from the US. Future developments of the tool will include live links to online sources, such as DMI, so that weatherAtoms can be imported directly. The removeDuplicateAtoms method assesses all of the weatherAtoms for the weatherData and finds weatherAtom that have the exact same observationDateTime and recordType, and keeps the weatherAtom that has the latest dateCreated property (these properties are explained in the next section). This is to ensure duplicate data is not stored and only the most recent data is retained. The getAtomsInPeriod returns all of the weatherAtoms between two dates. The weatherData can have quite a large set of weatherAtoms so it is often useful to only use a portion between two dates rather than using the whole set. Finally the createDWF converts the weatherData and weatherAtoms between two dates into a file format that can be read by the simulation engine of the tool, DAISY.

### *1.1.2. weatherAtom*

The weatherAtom is a record of the weather experienced at a location, quantified by specific physical weather data. The observationDateTime is the date and time that the record represents, it is expressed in the Matlab datetime format which converts a date and time into the number (and fraction) of days passed since January 1, 0000. The recordType states what type of record the weatherAtom is, the recordType is limited to only three types; recorded, forecast and average. Within the tool these types are considered hierarchical such that recorded data is the most accurate representation of a weatherAtom for a given time, followed by forecast, followed by average. Therefore, when a weatherAtom is needed for a specific date and time, a recorded recordType is sought after first, followed by forecast and then average. The dateCreated is the date and time when the weatherAtom was created. The other properties in the weatherAtom all relate to the physical observations (or predictions) of the weather, the units of which are as follows; airTemperature °C, precipitation mm, globalRadiation W/m<sup>2</sup>, referenceEvaporation mm/h, relativeHumidity %, windSpeed m/s, maxTemperature °C and minTemperature °C.

## **1.2. Field data**

The field data, Figure 0.3, describe the field area where operations are executed. A farm may have multiple fields for which the operations are scheduled.

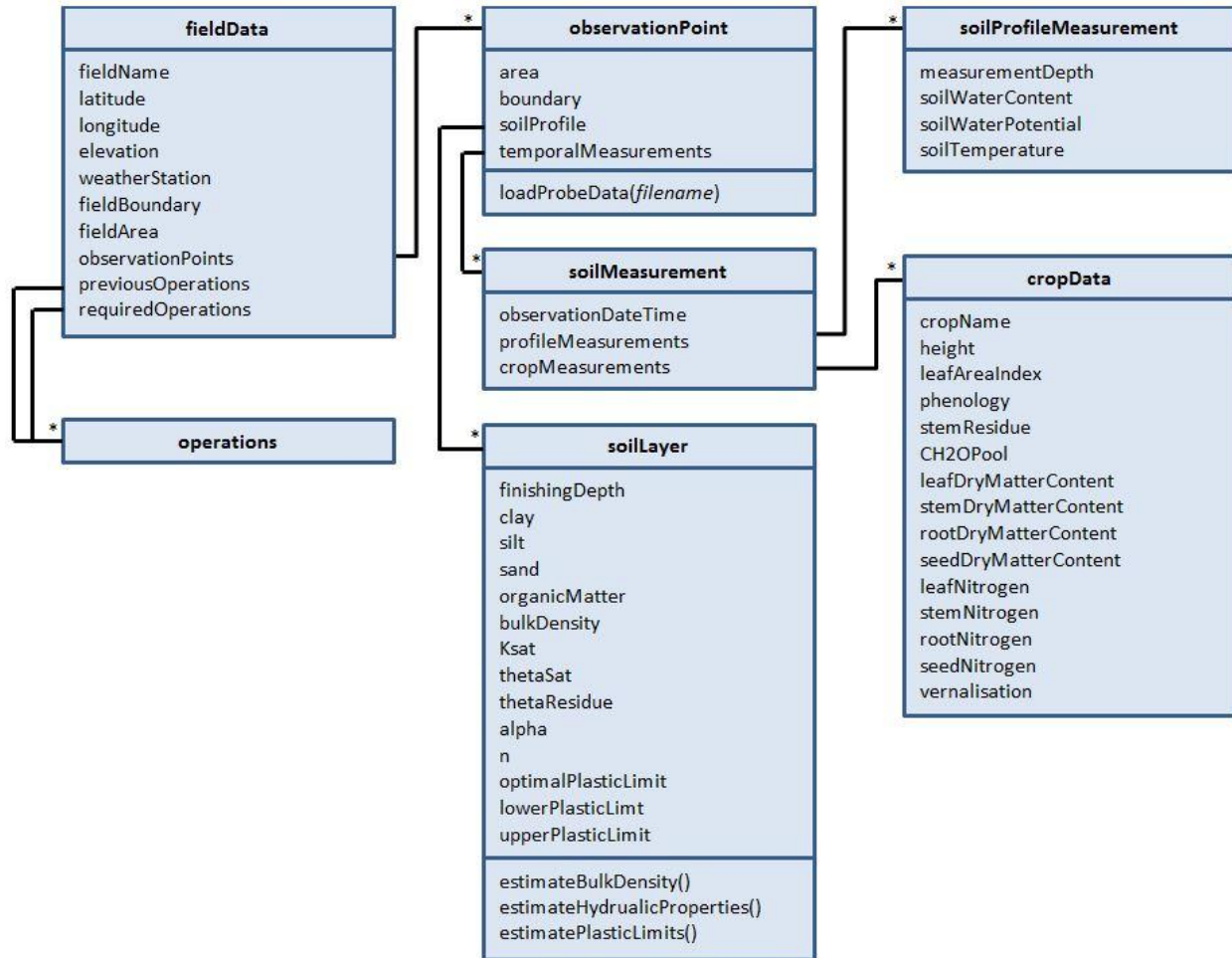


Figure 0.3: Class diagram of fieldData and associated classes

### 1.2.1. fieldData

The fieldName is used to identify the field. The latitude, longitude and elevation are the global positioning coordinates of the centre of the field. The weatherStation is the nearest weather station to the field, and is used when determining the weather experienced by the field. The fieldBoundary and the fieldArea are the shape and size of the field, respectively. The observationPoints are the points at which the field will be observed. There must be at least one point in the field where the soil and crop are observed, although it may also be the case that many points within a field are considered. Finally previousOperations are operations that have been executed on the field in the past, and requiredOperations are operations that need to be scheduled to be executed on the field. The operations class is explained later.

### 1.2.2. observationPoint

The observationPoint represents each of the observation points in the field. The area and boundary properties describe the area of the field that the observation point represents. Under the paradigm of precision agriculture (PA) this might be labelled as a management zone. Management zones are used so

that operations can be modified in accordance with spatial variance, to ensure maximised efficiency. The soilProfile describes the soil layers within the soil, these soil layers are a sequence of soilLayer of increasing depths. In the simulation engine of the tool, DAISY, the soil is modelled as a one dimensional column with the soil properties varying according to the depth beneath the surface. The temporalMeasurements are a set of measurements of the observation point at specific time.

There is also a method defined with the class diagram of the observationPoint. The loadProbeData method is used to create a set of soilMeasurements from data recorded by online soil probes. During the development of the tool, the John Deere CropSense soil sensors were used to monitor the variations in soil moisture throughout the soil profile. Data relating to the soil moisture over time could be downloaded from the John Deere website, in the form of a CSV file, and then the loadProbeData method could be used to read the CSV file directly into an assigned instance of observationPoint. An application programming interface (API) was not available from John Deere so the data could not be read by the tool directly, however it is foreseen that this will be available in later developments.

### *1.2.3. soilLayer*

The soilLayer describes an individual layer within the soil profile. Many of the properties of the soilLayer are likely to be unchanged over time. The finishingDepth is the lower boundary of the layer within the soil column, the upper boundary will be the surface if it is the first layer or else the lower boundary of the proceeding layer. The clay, silt, sand and organicMatter describe the textural composition of the soil layer. These are fractions by weight, such that the summation of the clay, silt, sand and organicMatter properties total 1. The bulkDensity is the grams per cm<sup>3</sup> of the soil. The Ksat is the saturated hydraulic conductivity which is a measure of how water flows through saturated soils and is expressed in cm/h. The thetaSat, thetaResidue, alpha and n properties are the hydraulic properties of the soil specifically related to the soil's water retention curve (van Genuchten, 1980). The optimalPlasticLimit, lowerPlasticLimit and upperPlasticLimit all relate to the malleability of the soil. They represent the soil moisture limits when soil is just right, too dry and too wet respectively, for soil engaging operations.

There are three methods for the soil layer, the first estimateBulkDensity uses the clay, silt, sand and organicMatter in a pedotransfer function to estimate a value for the bulk density. The second method estimateHydraulicProperties estimates thetaSat, thetaResidue, alpha and n. They can either be estimated using a pedotransfer function from the clay, silt, sand, organicMatter, and bulk density (as described in Wösten et al. (1999)) or if measurements of the soil water content at different soil water potentials are available then a regression formula can be used to fit this data to the water retention curve. The final

function `estimatePlasticLimits` estimates the `optimalPlasticLimit`, `lowerPlasticLimit` and `upperPlasticLimit` from `Ksat`, `thetaSat`, `thetaResidue`, `alpha` and `n` using equations defined in Dexter and Bird (2001)

#### *1.2.4. soilMeasurement*

The `soilMeasurement` is a measurement of the status of an observation point at a given time, the measurement may be from a sensor network, a direct observation or a simulation. The `observationDateTime` is the date and time of the observation, or simulation of the observation. The `cropMeasurements` describe the crop (or crops) that are planted at the observation point. The `soilProfileMeasurements` is a set of measurements (or the results of a simulation) within the soil profile. The `soilMeasurement` do not necessarily correspond with the `soilProfile`, i.e. there may be many measurements within a single soil layer.

#### *1.2.5. cropData*

The `cropData` class describes the current state of development of a crop at the observation point. The `cropName` identifies the crop, and the rest of the properties describe the biologic development of the crop. Many of the properties may be difficult to quantify in the field and may involve portions of the crop being taken to a laboratory to be studied. It may also be possible in future developments of the tool to define methods to estimate difficult to quantify properties using the properties which are easier to measure, such as height, phenology and leaf area index. The simulation engine used in the current implementation of the tool, DAISY, models all of the properties of the `cropData` class.

#### *1.2.6. soilProfileMeasurement*

The `soilProfileMeasurement` class is a record of status of the soil at a given time and at a given depth within the soil profile. The `measurementDepth` is the depth at which the measurement (or simulation of a measurement) is taken. The `soilWaterContent` is the fraction of the containing volume of the soil that is water, it is measured in  $\text{cm}^3/\text{cm}^3$  and is between 0 and 1. The `soilWaterPotential` is another measure of the soil moisture which is related to the energy state of the water within the micro pores of the soil, it is measured in kPa and is always negative. The `soilTemperature` is the temperature of soil in  $^{\circ}\text{C}$ .

### **1.3. Operation data**

The `operations` class, Figure 0.4, defines and parameters of the operations that can be executed on the fields by the equipment. There is an overlap between the operation data and the equipment data, as how an operation is executed may depend on the equipment being used. This must therefore be taken into consideration as the operations are defined. Parameters that are defined for an operation are considered to be default parameters, which can then be overridden by redefining the parameters for a specific piece of

equipment i.e. the parameters of a specific piece of equipment take president over the defaults of an operation, if they are duplicated. This will be further clarified later.

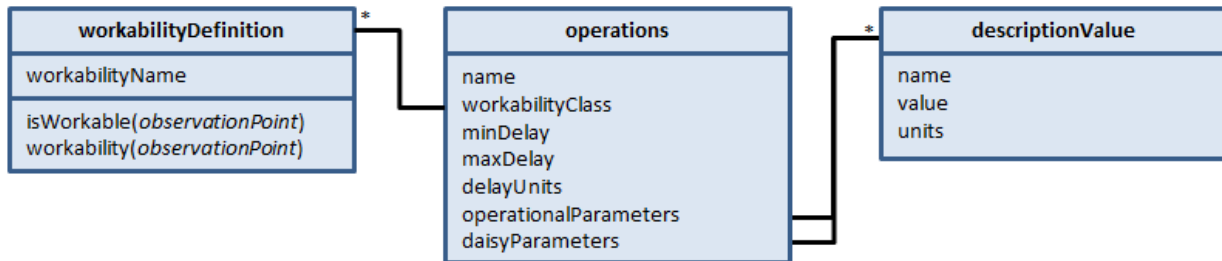


Figure 0.4: Class diagram of operations associated classes

### 1.3.1. operations

The operations class is the definition of the operations that can be executed. The name is an identifying name given to the operation. The workabilityClass is a definition of what type of operation the operation is i.e. tillage, fertilisation, harvest, etc. The minDelay and maxDelay are the minimum and the maximum amount of time, respectively, that must pass after the operation has been executed, before the following operation can be executed. The delayUnits is the units used to define the two previous properties, typically either hours or days. The operationalParameters and the daisyParameters are both similar in that they define the way in which the operations are executed, but the daisyParameters are specifically written in a language interpretable by the simulation engine, DAISY.

### 1.3.2. workabilityDefinition

The workabilityName is the identifying name given to the workabilityDefinition. There are two methods for the workabilityDefinition, these methods are defined individually for each instance of the workabilityDefinition class. `isWorkable(observationPoint)` returns a Boolean value and is used to designate if at a given time an observation point within a field is workable or not. Similar to the `isWorkable(observationPoint)` method, the `workability(observationPoint)` method returns a quantitative value of the workability at a given time for an observation point, within the range of 0 to 1.

### 1.3.3. descriptionValue

The descriptionValue class is used to describe various parameters of the operation. The name is the identifier of the descriptionValue, also for the daisyParameters in the operations class the name property is written in the syntax of DAISY. The value is the value of the description, and the units is the units the value is expressed in.

## 1.4. Equipment data

The equipment data, Figure 0.5, describes the piece of equipment used to execute operations. This could be a combination of a tractor and implement or a single integrated machine. A piece of equipment may be able to execute multiple operations, however if the implement is changed a new equipment must be created.

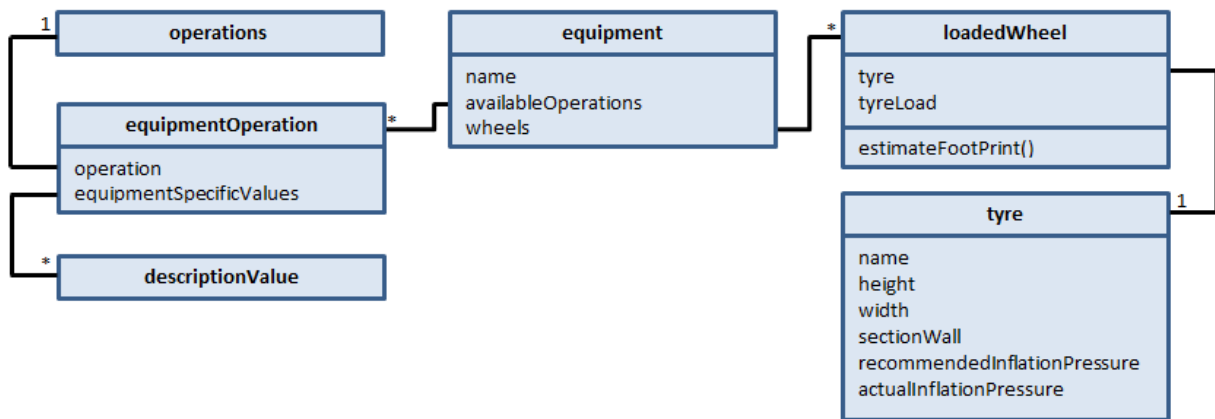


Figure 0.5: Class diagram of equipment and associated classes

### 1.4.1. equipment

The equipment class defines the combination of tractor and implement used to execute operations in the fields. The name is the identifier of the class. The availableOperations is a set of operations that the piece of equipment is able to execute. The wheels is a set of tyres and loads expressing how the weights of the tractor and the implement are transferred to the soil.

### 1.4.2. loadedWheel

The loadedWheel class describes the individual loading of the tyres of tractor and any implement which is also trailed. The tyre is the tyre that is on the wheel and the tyreLoad is the load, in kN, that is carried by the tyre. It should be noted that tractor, and implement, loads are often expressed as axle loads but there can be two, or even four, wheels per axle. Therefore care should be taken when setting these properties.

There are three methods for the loadedWheel class. `estimateFootPrint()` is used to estimate the stress distribution within the soil-tyre interface of the footprint of the tyre for a given tyre and load, which is vital when estimating the stress propagation through the soil profile beneath the tractor or implement. The footprint of the tyre is assumed to be a super ellipse given by Equation 0-1, where  $x$  is the direction across the direction of travel and  $y$  is direction of travel, Keller (2005).



$$\frac{x^n}{a} + \frac{y^n}{b} = 1 \quad 0-1$$

The stress within the soil tyre interface is then confined to the bounding circumference and interior area of the super ellipse,  $\Omega$ , Equation 0-2

$$\Omega = \{x, y \mid \frac{x^n}{a} + \frac{y^n}{b} \leq 1\} \quad 0-2$$

The distribution of the stress within in the footprint is given by Equation 0-3, where  $\sigma(x, y)$  is the stress at point  $(x, y)$  in  $\Omega$ ,  $L$  is the load,  $f$  describes the variation of the stress in the direction of travel, Equation 0-4,  $g$  describes the variation of the stress across the direction of travel, Equation 0-5.  $C$  is a function of the parameters  $\alpha, \beta, a, b, n$  defining an integration constant such that the integration of  $\sigma$  over  $\Omega$  is equal to the load,  $L$ .

$$\sigma(x, y) = L * C(\alpha, \beta, a, b, n) * f(x, y) * g(x, y) \quad x, y \in \Omega \quad 0-3$$

$$f(x, y) = 1 - \frac{x^\alpha}{l_x y} \quad 0-4$$

$$g(x, y) = 1 - \frac{y}{w_y x} * \frac{1}{g_{max}} * e^{-\beta * (1 - \frac{y}{w_y x})} \quad 0-5$$

$$\beta \leq 1: g_{max} = e^{-\beta} \quad 0-6$$

$$\beta > 1: g_{max} = \frac{e^{-1}}{\beta} \quad 0-7$$

$$l_x y = a * \left(1 - \frac{y}{b}\right)^{n \frac{1}{n}} \quad 0-8$$

$$w_y x = b * \left(1 - \frac{x}{a}\right)^{n \frac{1}{n}} \quad 0-9$$

An example of the stress distribution is shown for a Nokian ELS Radial 800/50R34 tyre, Figure 0.6. The magnitude of the stress distribution, which is proportionate to the wheel load, is shown by the colour ranging from red for high stress to dark blue for zero stress.

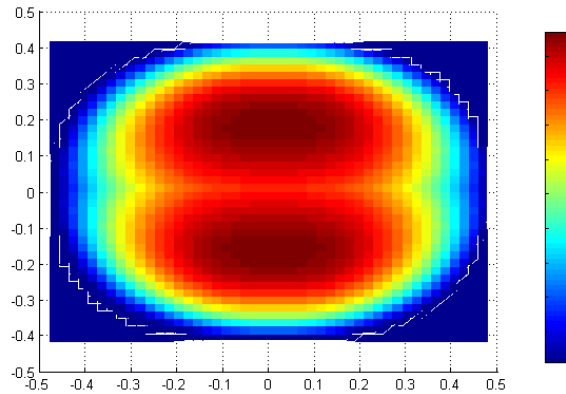


Figure 0.6: Example of the stress distribution in the soil tyre interface

For each tyre it is necessary to determine the  $\alpha$ ,  $\beta$ ,  $a$ ,  $b$  and  $n$  parameters. Schjønning et al. (2006) establish empirical equations for  $\alpha$ ,  $\beta$ ,  $a$  and  $b$  as well as an estimation of the area of the tyre footprint, Equations 0-10 to 0-14, using the physical dimensions of the tyre, as given in the tyre class.

$$\begin{aligned}
 a &= -2.96 + 2.56*W - 0.591*D + 2.12*S/W - 0.344*\ln \frac{aP}{rP} + 0.00141*L & 0-10 \\
 & & 0-11 \\
 b &= 0.049 + 0.457*W & \\
 A_{EST} &= -5.76 + 7.38*W + 1.03*D - 2.57*D*W + 1.96*S/W - 0.426*\ln \frac{aP}{rP} + 0.00294*L & 0-12 \\
 \alpha &= -2.22 + 4.7*W - 1.24*D + 3.65*S/W - 0.792*\ln \frac{aP}{rP} - 0.00395*L & 0-13 \\
 \beta &= -2.72 + 3.68*W + 1.35*S/W - 0.731*\ln \frac{aP}{rP} - 0.00561*L & 0-14
 \end{aligned}$$

In the above equations the properties of the tyre class are referred to as,  $W$  is the width,  $D$  is the height,  $S$  is the sectionWall,  $aP$  is the actualInflationPressure and  $rP$  is the recommendedInflationPressure, the tyreLoad from the loadedWheel class is  $L$ .

Finally to determine the  $n$  parameter the estimated area of the tyre footprint  $A_{EST}$  is compared with the formula for the area of a super ellipse, Equation 0-15. A recursive algorithm is implemented to estimate  $n$  for the above calculated  $a$  and  $b$ , given that the area is equal to  $A_{EST}$ .

$$Area = 4 * a * b * \frac{\Gamma \left(1 + \frac{1}{n}\right)^2}{\Gamma \left(1 + \frac{2}{n}\right)} \quad 0-15$$

### 1.4.3. tyre

The tyre class describes the tyres on the equipment. The name is the identifier of the class. The height, width and sectionWall are the properties of the tyre which are used by tyre manufactures when selling tyres. The recommendedInflationPressure is the inflation pressure recommended by the manufacture to

perform field operations, and the actualInflationPressure is the inflation pressure that the tyre is actually inflated to.

#### 1.4.4. equipmentOperation

The equipmentOperation is a correlation of an operation that the equipment can execute, and any operational parameters that are unique to the equipment. The operation is an operation which has already been defined, and the equipmentSpecificValue is a set descriptionValue.

### 1.5. Operation Plans

The operationalPlan is the main output of all the planning stages, Figure 0.7. The operationalPlan contains all the information and methods required to initiate the plan generation and estimate the outcomes of prescribed operations.

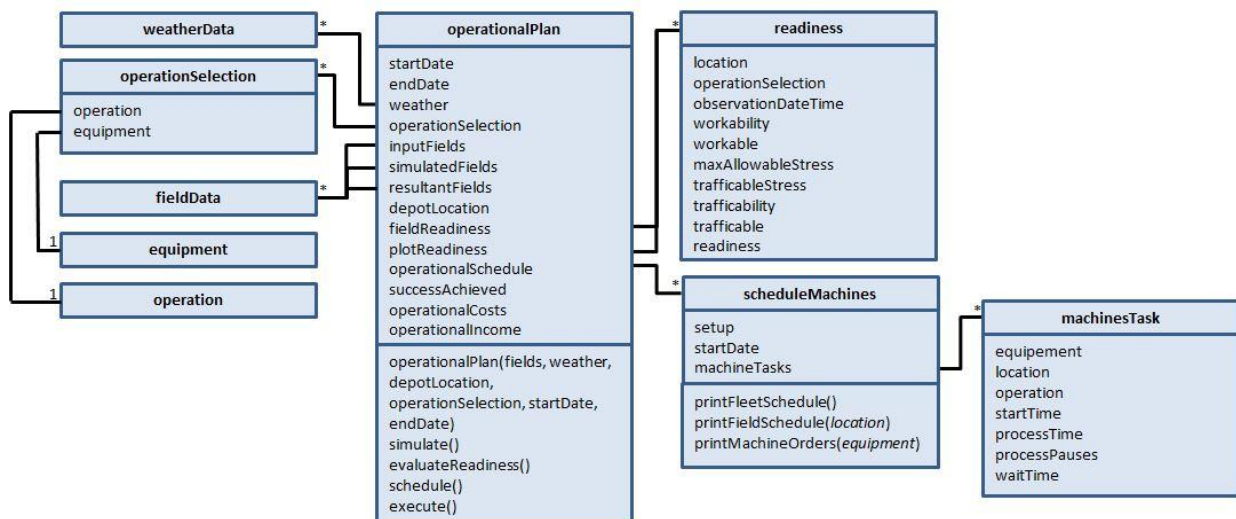


Figure 0.7: Class diagram of operationalPlan and associated classes

#### 1.5.1. operationalPlan

The startDate and endDate are the start and end of the period the operationalPlan covers. These are expressed in the Matlab datetime format. Typically an operationPlan will only cover a part of the growing season, such as tillage and planting or harvest, rather than the whole growing season in order to make the scheduling of operations simpler. The period between the start and end dates is known as the operational window. The weather is a set of all of the weatherData that might be needed within the operationalPlan. The weatherData is filtered using the getAtomsInPeriod method of the weatherData class as only weatherAtoms which are between the start and end dates are needed for a particular operationalPlan. The

operationSelection is sequence of operations that need to be performed within the operational window and the equipment desired to execute the operations. The inputFields is the set of fieldData's that describe the fields where the sequence of operations will be executed. The simulatedFields is the same set of fieldData stated as the inputFields, however the soilMeasurements at the observationPoints describe the status of the fields that is expected during the operational windows without any operations being executed. The resultantFields is the same set of fieldData stated as the inputFields, however the soilMeasurements at the observationPoints describe the status of the fields that is expected before, during and after the execution of the desired operations at the scheduled times. The depotLocation is the base where all of the equipment must start and return to after their jobs are completed. The location of the depot must be specified as the scheduling of the operations estimates the time taken to travel to and from the fields and this must be accounted for.

The plotReadiness and the fieldReadiness are the descriptions of the readiness of the individual observation points within the fields and the whole field, respectively, over the operational window for the specified operations executed by specified equipment. The operationalSchedule is the schedule of when and where the operations are executed and by what equipment. The successAchieved is a single binary variable that is used as a measure of whether all of the operations could be executed at all of the locations while ready within the operational window. The operationalCosts and the operationalIncome are the total cost and total income, respectively, incurred during the execution of all the operations at all of the locations.

There are five methods for the operationalPlan class. The first is the constructor method, `operationalPlan(fields, weather, depotLocation, operationSelection, startDate, endDate)`. This is used to build the operationalPlan and specifies all of the input parameters required. The `simulate()` method simulates the response of the fields, in inputFields, to the weather. The results are stored as simulatedFields. The `evaluate()` method evaluates the readiness of the simulatedFields to the operations specified in operationSelection. The result of each simulatedFields to each operationSelection is stored as plotReadiness and fieldReadiness as described. The `schedule()` method schedules the execution of required operations, in operationSelection, at the fields, in inputFields. The results are stored as the operationSchedule. The `execute()` method is similar to the `simulate()` method, however the scheduled operations are executed within the simulation. The results are stored as resultantFields.

### *1.5.2. operationSelection*

The operationSelection is the correlation of an operation with a piece of equipment that can execute the operation. In the operationSelection class both properties have a 1 to 1 relationship as each

operationSelection directly matches a single operation to a single piece of equipment. Both the operation and the equipment will have operational parameters already described for them, if there are any operational parameters that are duplicated between the equipment and the operation then the operational parameter of the equipment will take president.

### *1.5.3. readiness*

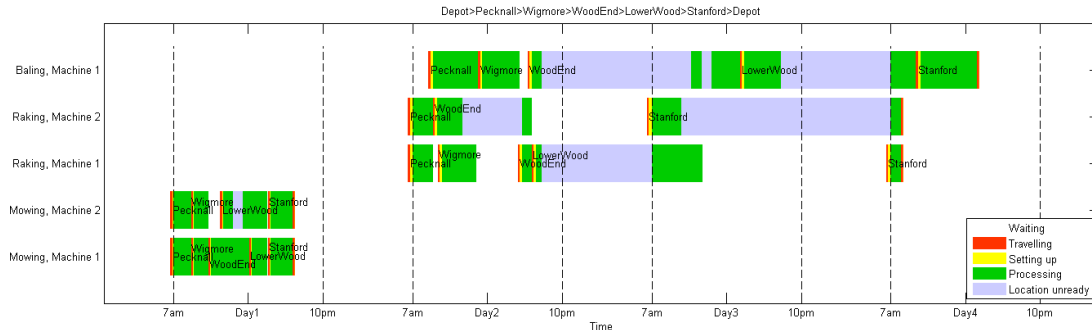
The readiness class is the measure of the readiness of a single observationPoint, or the whole field, at a given time. It can be used to calculate the number of ready days within an operational window, determine if operations were executed on ready days or for future scheduling of operations. As mentioned earlier the readiness is the combination of the workability and the trafficability. The workability assessment is governed by the operation that is being considered to be executed, while the trafficability is based on the equipment.

The location is a reference to either the field or the observation point within a field for which the readiness assessment is for. The operationSelection is the specific operationSelection (from the sequence of operationSelection in the operationPlan) for which the readiness assessment is for. The observationDateTime is the date and time the readiness assessment represents. The workability is quantitative value based on how workable the location (be it an observation point or a whole field of observation points) is for the operation. The workability is between 0 and 1. The workable property is a binary value of how workable the location is, 0 being not workable and 1 being workable. The maxAllowableStress is the maximum level of stress allowed at a depth of 50 cm below the soil surface. As default this is set to 50 kPa to adhere to the Schjønning 50/50 rule (Schjønning et. al. 2012). The trafficableStress is the stress caused by the loadedWheel of the equipment at a depth of 50 cm, if there is more than one wheel of the equipment being considered then it is the maximum stress of all the loadedWheel's at 50cm. The trafficability is a quantitative measure of how trafficable the location is, i.e. it is the maxAllowableStress minus the trafficableStress. The trafficability has a minimum of 0. The trafficable property is a binary value of the trafficability. If the trafficability is greater than 0 the trafficable is 1, else it is 0. The readiness is a binary value of whether the location is both trafficable and workable, it can be expressed as a conjunction of the trafficable and workable properties.

### *1.5.4. scheduleMachines*

The scheduleMachines class represents the orders given to the equipment to execute the operations. The setup property is a structure that summarises much of the important data from the operationalPlan expressed in a format needed to create an optimised operational schedule. The algorithms used to create the optimised operational schedule are explained further in Chapter 4. The startDate is the date that the

equipment begins executing the operations, i.e. the date and time when the first machine leaves the depot location, this may be later than the operationalPlan startDate but not earlier. The machineTasks is a set of individual tasks given to the machines, or their operators.



**Figure 0.8: Example of a fleet schedule (from Chapter 4)**

There are three methods for the scheduleMachines class all of which produce outputs so that the operations can be interpreted and execute by human operators. The printFleetSchedule() method prints a Gantt chart of when and where each machine will be executing their operations over the operational window. This would be useful to the fleet manager who must comprehend the entire fleet’s movements. An example of a fleet schedule Gantt chart is shown in Figure 0.8. The printFieldSchedule method prints a Gantt chart for a specified location, showing when the different operations will be executed there. This would be of use if the field, or farm manager, was not the fleet manager, as is the case then an agricultural contractor execution operations on many independently run farms. The printMachineOrders is a list of orders directing at machines human operator to execute operations at specified locations at specified time, Figure 0.9.

```

Machine No: 1
Operation: Raking
Orders:
Date: Day 2
    06:34 Drive from Depot to Pecknall
    06:45 Setup Implement
    07:00 Begin work at Pecknall
    09:03 Finish work at Pecknall
    09:35 Drive from Pecknall to Wigmore
    09:45 Setup Implement
    10:00 Begin work at Wigmore
    13:27 Finish work at Wigmore
    17:36 Drive from Wigmore to WoodEnd
    17:45 Setup Implement
    18:00 Begin work at WoodEnd
    18:58 Finish work at WoodEnd
    18:58 Drive from WoodEnd to LowerWood
    19:09 Setup Implement
    19:24 Begin work at LowerWood
    20:00 Pause work at LowerWood overnight
Date: Day 3
    07:00 Resume work at LowerWood
    12:06 Finish work at LowerWood
Date: Day 4
    06:34 Drive from LowerWood to Stanford
    06:45 Setup Implement
    07:00 Begin work at Stanford
    08:04 Finish work at Stanford
    08:04 Drive from Stanford to Depot

```

Figure 0.9: Example of list of orders for a machine (from Chapter 4)

### 1.5.5. *machinesTask*

The *machinesTask* describe individual commands given to a machine, or its operator, to execute an operation at a location. The *equipment* is a reference to one of the machines in the fleet that will execute the operation. The *location* is a reference to the field where the operation will be execution. The *operation* if a reference to the operation that is to be executed. The *startTime* is the date and time at which the equipment must start executing the operation at the location. The *processTime* is the time it is estimated it will take to execute the operation. The *processPauses* describe any time when the operation must be paused due to the location being unready. The *waitTime* is the total time that the equipment must wait at the location while it is unready.

## 2. Levels of planning

The tool is designed to be used by farm managers for operations management. Operations management is broken down into a series of planning stages; tactical planning, operational planning, and execution planning. Figure 0.10 shows when, and how often, the tasks of the planning stages are initiated. Operational plans are created at each planning stage from the available data spanning a predefined time in the future. The goal of each planning stage is to produce a plan for how operations will be executed at specific locations. However at each planning stage different data are available with varying levels of certainty. It is often the task of the planning stages to produce multiple *operationalPlans* which are refined into a single plan, either automatically or requiring some user input.

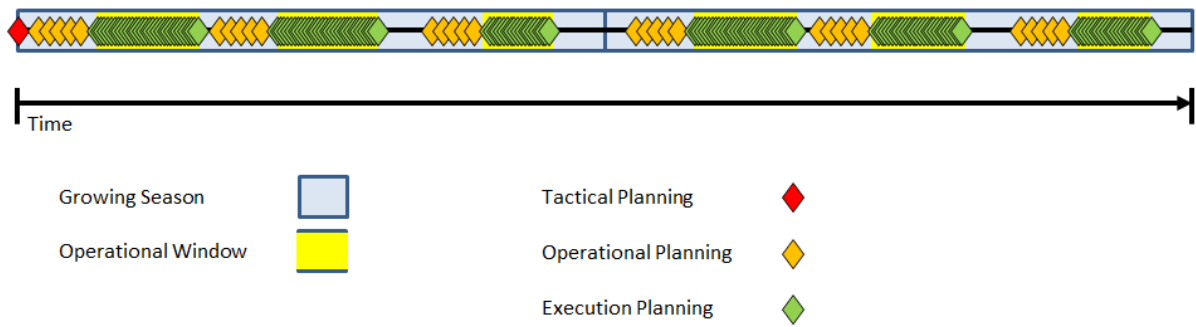


Figure 0.10: Representation of when planning stages are initiated

## 2.1. Tactical Planning

Tactical planning covers the planning of 1 -2 growing seasons, evaluating machine types, crops, and operations. Each operationalPlan object only covers a portion of the full growing season, typically the operations of the establishment, maintenance or harvest of a crop. Therefore the main aim of the tactical planning stage is to produce a sequence of operationalPlans, to be used as a guide for the operations in the upcoming season(s). Since tactical planning happens at the beginning of the season, there are no time constraints placed on the execution time of the tool. As such many different scenarios can be evaluated and their resultant operationalPlans assessed for their fitness for purpose.

### 2.1.1. Available Information

#### Weather Types

The weather used during the tactical planning stage has a large impact on the plans which are developed. However since the planning covers a large window, accurate forecasts would be impossible to obtain. Instead, in order to promote confidence in the resultant operationalPlans a number of different sets of weather forecasts can be used to determine a robust plan. A simplistic approach would be to use previous years' weather as an example of what the coming years' weather might be. A more sophisticated approach would be to develop pessimistic or optimised forecasts to test what effect these might have on operationalPlans. Each set of weather forecasts is used to create a unique operationPlan.

#### Fields

The set of fields, for which the operations are being planned at the tactical planning stage, can still be considered as open to be adjusted. For example a farm manager could want to evaluate the benefits of renting extra land and needs to assess if the present fleet of equipment could cope with the increased work load, or if it would be necessary to increase the fleet size or machines' capacities. This could also apply to contractors who would like to evaluate taking on a new customer. Another way fields could be modified in



the tactical planning stage is to be split into different management zones. Traditionally fields have been thought of as static areas which cannot be changed, but after examining how operations are being planned to be executed it may be prudent to divide a field into a number of management zones so operations can be tailored to the specific parameters/conditions of that zone.

### Operations

One of the major decisions made at the tactical planning stage is what operations will be executed. Each growing season covers the establishment, maintenance and harvest of a crop within a field. The crop that is to be grown may already be selected or there may be a number of different crops being evaluated. In either case the choice of crop leads to a number of sequences of operation which could be executed to give the same result of a harvested crop, although the specific operations in the sequences may be different.

### Equipment

The equipment needed to execute the desired sequence of operations is another important decision made at the tactical planning stage. Purchases of equipment are a large investment and there is a need to justify the purchases and ensure that the equipment will be optimally utilised. Each operation to be considered within the tactical planning stage must have a piece of equipment that can execute the operation. However it may also be the case that multiple types of equipment are capable of executing the same operation, therefore an evaluation can be made as to the ideal fleet configuration.

#### *2.1.2. Plan evaluation*

The combination of the options from each data area detailed above (weather, fields, operations, and equipment) results in a number of operationalPlans being produced. From these plans an optimal plan must be selected, and it may also be prudent to select a number of back plans in case changes within the growing season(s) cause the optimal plan to become unfeasible.

Each of the operationPlans could be presented to a user, who could select the desired plan (and backups) using their expert knowledge. However, if a large number of operationPlans are produced, or if a user with expert knowledge is not available, an automated evaluation of the operationPlans can be utilised instead. The criteria under which the plans are assessed are as follows;

#### Ready days for a sequence of operations

The number of days when the fields are ready for the operations is important to examine when evaluating operationPlans. Figure 0.11 shows an example of when a single field is ready for 3 operations over a 15 day period. The highlighted cells indicate that the field is ready, while the blank cells indicate that the field is not ready. Moreover, since the operations must be executed in sequence, then for the field to be ready for

operation 2 there must be a time when it is earlier ready for operation 1 and later ready for operation 3. The minimum number of machines of a certain type can be inferred from the number of ready days using Equation 0-16, where the field area is stated in hectares and the machine operational capacitance is stated in hectares per working day.

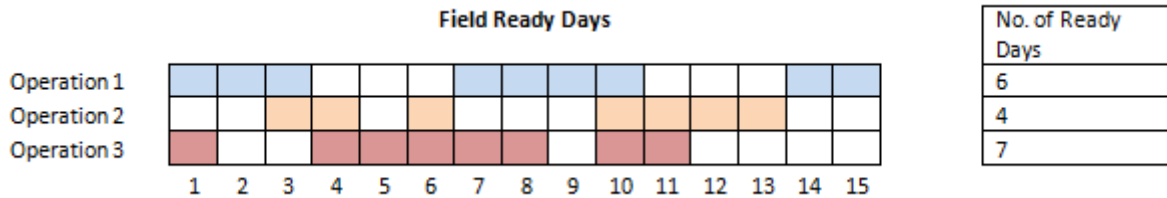


Figure 0.11: Field ready days for 3 operations over a 15 day period

$$\frac{\text{No. of ready days} * \text{machine operational capacitance}}{\text{field area}} = \text{minimum no. of machines} \quad 0-16$$

### Operational costs and revenues

The operational costs and revenues are calculated based on the work plans produced. Each operation and equipment has its own associated costs. These can be either fixed costs or variable costs. The costs of a specific operation or equipment are stated in the operationalParameters. Revenues are generally only associated with harvest operations, when the crop can be sold. The assumed market price of the crop is also one of the operationalParameters of the operation. The costs and revenues are calculated for each operationPlan and presented to a user.

## 2.2. Operational Planning

The result of the tactical planning stage is a sequence of operationPlans which cover the entire growing season(s) considered. Each of the operationPlans in the sequence is evaluated at the operational planning stage in the weeks preceding the operational window.

The purpose of the operational planning stage is to refine the operational plan produced at the tactical planning stage using updated data which has a higher level of certainty. The purpose is also to assess if the execution of the operationPlan remains within the performance parameters set forth at the tactical planning stage. If an operationPlan’s execution no longer produces the desired results there is a need to modify the plan.

### *2.2.1. Available Information*

#### Weather

The operational planning stage is initiated a relatively short time before the operational window, when operationPlan is due to be executed. Therefore there should be more confidence in the forecast weather data that is available. It may still be prudent to examine the impact of optimistic and pessimistic forecasts, however these are likely to be less divergent than at the tactical planning stage and their impact on the result will be decreased.

#### Fields

The fields that are included at the operational planning stage are now definite. If changes have to be made to the fields, i.e. adding or removing fields, it would necessitate that the planning would return to the tactical planning stage.

Updated information concerning the field status, such as the soil moisture content, crop development, ect., may be available to be collected from the actual fields. Adding this updated information will have an impact and lead to the production of a more accurate operationPlan.

#### Operations

The operations are largely considered as definite, as subsequent operationPlans in the result of the tactical planning stages rely upon certain operations having been executed. However if changes within the operational planning stage cause the results of the operationPlan to fall outside of the performance parameters, then changes may need to be introduced. For example if an unexpected weed becomes present in a crop in a field, an extra spraying operation may be required to ensure the crop develops as desired.

#### Equipment

The equipment is considered as definite at the operational planning stage. Any purchase decisions are made at the tactical planning stage (or at the earlier strategic planning stage) and machine breakdowns are dealt with within the execution planning stage. Only major breakdowns resulting in a piece of equipment unexpectedly being scrapped would necessitate change, which would then need the planning to revert to the tactical planning stage (or strategic planning stage) to ensure an informed choice was made about the equipment's replacement.

### *2.2.2. Plan evaluation*

Since the operationPlans proposed as a result of the tactical planning stage have already been evaluated as the “best” plans, the evaluation at the operational planning stage is predominately to ensure that plans are still executable. If the new work plans produced by the operationPlan no longer fulfil the requirement of the performance parameters, then backup plans from the tactical planning stage may need to be considered.

## **2.3. Execution Planning**

The execution planning is performed within the operational window of an operationalPlan. The purpose of the execution planning stage is to react to changes that affect the operationalPlan and more specifically the machine schedules, in order to modify the instructions given to individual machine operators. The execution planning is executed on a daily, hourly or even minutely time scale to provide an updated executable operationalPlan.

As the execution planning is performed within the operational window of the operationalPlan, this will result in a portion of the operational window being in the past, while a portion is in the future. This removes much of the planning flexibility, as events that have already happened aren't able to be changed. The purpose of the execution planning is to deal with unanticipated events, such as weather changes and machine breakdown, so that the operationalPlan can still produce results within the limits of the performance parameters. Also as the execution planning must produce an operationalPlan for the immediate future, the replanning must be able to be executed fast.

### *2.3.1. Available Information*

#### **Weather**

As stated some of the weather within the operational window will have happened in the past, at the time the execution planning is performed, as such this will be recorded weather which will be unchanging. Also since the execution planning's main purpose is to produce machine schedules for the immediate future, the weather forecasts available should be relatively accurate. It is not necessary to examine the impact of different weather forecasts, which will also allow for the execution planning to be performed more quickly than previous planning stages.

#### **Fields**

As with the operational planning stage, it may be possible to update the fields' statuses with collected data. This will increase the confidence that can be placed in the produced operationalPlan.

## Operations

During the period of the operational window some of the operations may have already been executed or initiated on some of the fields. Therefore it is not possible to change the operations within the execution planning stage, although changes can be made to the operational parameters of the operations if their execution is not having the desired effect.

## Equipment

Breakdowns, and the subsequent replacement of equipment, will have a large effect on the operationalPlan. Initially breakdowns may only affect the individual orders being given to machine operators, so that machines can be rerouted to cover work. However if a breakdown causes an operationalPlan not to be able to comply with the limits of the performance parameters, it may be necessary to bring in a new piece of equipment. It is also likely that more than one option is available to replace the broken down equipment and a decision must be made.

### 2.3.2. Plan evaluation

The plan evaluation at the execution planning stage is highly automated, with user input only required for high level decisions. This is because changes happen quickly at this stage and there is not time to consult a user. Also the user may be operating a machine that is currently executing an operation or otherwise occupied.

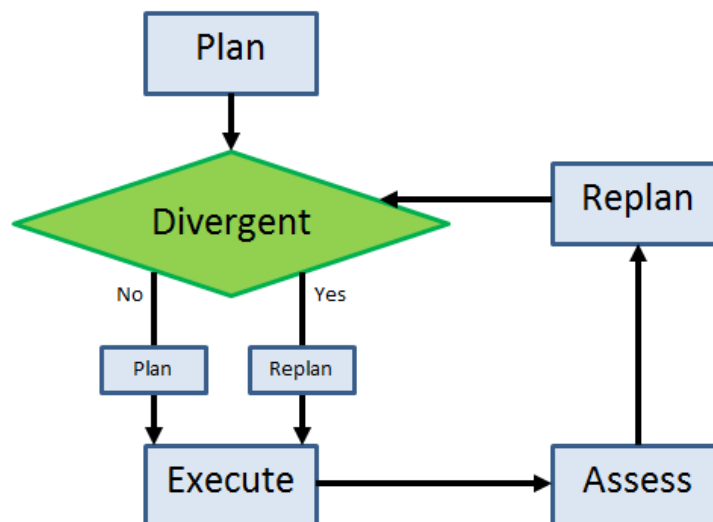


Figure 0.12: Scheme of the plan evaluation at the execution planning stage

Initially the operationPlan produced by the operational planning stage is used to create the work plans for the individual machines. These work plans are executed by the machines, thereby changing their individual status and the status of the fields where the operations are being executed. The updated machine and field

statuses are reassessed to create a new representation of the current scenario. Using the updated scenario a new operationalPlan is created. The new operationalPlan is compared with the previous operationalPlan to determine if the plans are divergent, i.e. if there is a significant difference in how the operations are executed between the two operationalPlans. If the operationalPlans are divergent, then the new operationalPlan is taken as the new current operationalPlan and new work plans are issued to the individual machines. If the operationalPlans are not divergent then the old operationalPlan remains the current operationalPlan and new work plans are not issued. The process of this evaluation is summarised in Figure 0.12