CRANFIELD UNIVERSITY

SVEN PEETS

SPECIFICATION, DESIGN AND EVALUATION OF AN AUTOMATED AGROCHEMICAL TRACEABILITY SYSTEM

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Abstract

Traceability through all the stakeholders in food production is an issue of increasing importance, being specifically required by the regulations for food safety and quality (EC 178/2002), and for compliance with environmental protection. The agricultural market perceives a need for systems and technologies to automate the currently manual process of producing records of agrochemical inputs loaded into a spraying machine.

A novel prototype Automated Agrochemical Traceability System (AACTS) to identify and weigh agrochemicals as they are loaded into crop sprayer has been designed, constructed, fitted to a machine and evaluated with commercial operators. The functional blocks of the system are a 13.56 MHz RFID reader, 1.4 litre self cleaning weighing funnel mounted on a 3 kg load cell, a user interface with a screen and three user command buttons (Yes, No, Back), and a progress bar made of 8 coloured LED's (green, amber, red). The system is able to trace individual agrochemical containers, associate the product identity with national agrochemical databases, quantify the required amount of product, assist the sprayer operator and control workflow, generate records of sprayer inputs and interoperate with (recommending extensions to) task management standards as set out in ISO 11783-10.

The evaluation of the quantity weighing has demonstrated that with such a system, the principal noise component is in the range of 33–83 Hz, induced by the operating tractor engine. A combined 3 Hz low pass digital filter with a second stage rolling mean of 5 values improves performance to allow a practical resolution of 1 gram (engine switched off) to 3.6 grams (sprayer fully operational) with a response appropriate to suit human reaction time. This is a significant improvement over the ±10 grams of the work of Watts (2004).

An experiment with 10 sprayer operators has proved that in the majority of cases (92%) an accuracy equal or better than ±5% is achieved regardless of dispensing speed. The dispensed amounts (100.36% of target) and recorded (100.16%) are in accordance with prescribed values (100%; $LSD_{(5\%)}$ 2.166%), where amounts dispensed by manual methods (92.61%) differ significantly from prescribed and recorded value (100%). The

AACTS delivers a statistically similar work rate (211.8 s/task) as manual method (201.3 s/task; Δt = 10.5 s/task; $LSD_{(5\%)}$ 28.2 s/task) in combined loading and recording cycle. Considering only the loading time (181.2 s/task) of manual method, the difference is 30.6 s/task ($LSD_{(5\%)}$ 30.1 s/task). In practice this difference is believed to be marginal compared to the time required to load the water, random external events during the spraying session and in time moving, checking and storing paper records.

The integrated weighing funnel concept is another significant improvement over previous work. Using this system, the mean duration of measuring per container for all tasks (34.0 s) is approximately half the time (68.5 s) achieved by Watts (2004). The AACTS was rated to be safer than the manual method regarding operator health and safety and risk of spillage. All operators who evaluated the AACTS were interested in purchasing such a system.

The work confirmed that an RFID system was an appropriate media for agrochemical identification performing more than 250 product identification operations during operator tests without failure, with a speed of operation <1 s per cycle and reading distance of 100 mm. A specific format for RFID tag data is proposed for adoption, using low cost tags, that combines item level traceability with identification of products independently without access to worldwide databases.

The AACTS follows ISO 11783 task management logic where a job is defined in a prepared electronic task file. It is proposed to extend the ISO 11783-10 task file to integrate the records provided by AACTS by handling the tank loads as individual products resulting from loading task and allocating them to spraying tasks.

It is recommended to produce a production prototype following the design methodology, analysis techniques and performance drivers presented in this work and develop the features of user interface and records of tank content into software for ISO 11783-10 cabin task controller to deliver business benefits to the farming industry. The results with RFID encourage the adoption of RFID labelling of agrochemical containers.

The reader may wish to read this thesis in parallel with Gasparin (2009) who has considered the business and industry adoption aspects of the AACTS.

Publications

The results of this work have been presented on European and international conferences on precision agriculture. The following papers have been published:

Peets, S., Gasparin, C. P., Blackburn, D. W. K., Godwin, R. J. (2009) RFID tags for identifying and verifying agrochemicals in food traceability systems. *Precision Agriculture*. Online First (in press).

Peets, S., Blackburn, D. W. K., Gasparin, C. P., Godwin, R. J. (2008) Development of an Automatic Agrochemical Recording System for Crop Sprayers. In: Proceedings of the 9th International Conference on Precision Agriculture, edited by R. Khosla. USA: Colorado State University.

Blackburn, D. W. K., Peets, S., Gasparin, C. P., Godwin, R. J. (2008) Application of Radio Frequency Identification for Agricultural Traceability Systems. In: Proceedings of the 9th International Conference on Precision Agriculture, edited by R. Khosla. USA: Colorado State University.

Gasparin, C. P., Angus, A., Cook, M., Peets, S., Blackburn, D. W. K., Godwin, R. J. (2008) Measuring farmers' preferences for systems that improve agrochemical traceability. In: Proceedings of the 9th International Conference on Precision Agriculture, edited by R. Khosla. USA: Colorado State University.

Peets, S., Gasparin, C. P., Blackburn, D. W. K., Godwin, R. J. (2007) RFID tags for identifying and verifying agrochemicals in traceability systems. In: Proceedings of the 6th European Conference on Precision Agriculture, edited by J. V. Stafford. Netherlands: Wageningen Academic Publishers, p. 801–808.

Gasparin, C. P., Peets, S., Blackburn, D. W. K., Godwin, R. J. (2007) Stakeholder Requirements for Traceability Systems. In: Proceedings of the 6th European Conference on Precision Agriculture, edited by J. V. Stafford. Netherlands: Wageningen Academic Publishers, p. 793–799.

A proposal for extensions to XML data formats is in preparation for consideration by the ISO 11783-10 standard committee at the November 2009 meeting. This has the support of a major committee member (AGCO).

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Last but not least a sincere thank you goes to my parents, Tõnis and Maie, for their endless support.

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Notation

AACTS	Automated Agrochemical Traceability System
AD	Auto dispensed
AR	Auto recorded
ASCII	American Standard Code for Information Interchange
ASP	Allocation stamp
BSI	British Standards Institution
CAN	Controller Area Network
DC	Direct current
Defra	Department for Environment, Food and Rural Affairs (in the UK)
DFT	Discrete Fourier' transform
DLV	Data log value
EC	European Commission
EPC	Electronic Product Code
EU	European Union
FAO	Food and Agriculture Organisation
FFT	Fast Fourier' transform
FIR	Finite impulse response
FMIS	Farm management information system
GPS	Global positioning system
HF	High frequency
IIR	Infinite impulse response
ISO	International Organisation for Standardisation
LED	Light-emitting diode
LF	Low frequency
LSD	Least significant difference
MD	Manual dispensed
MICS	Mobile implement control system
MRL	Maximum residue level
PAN	Product allocation
PCB	Printed circuit board
PDT	Product
PDV	Process data variable
PSD	Pesticides Safety Directorate
RFID	Radio Frequency Identification
TC	Task controller
TIM	Time
TSK	Task
TZN	Treatment zone
UHF	Ultra high frequency
UID	Unique identifier
USB	Universal serial bus
VT	Virtual terminal
WHO	World Health Organisation
XML	Extensible Markup Language

1. Introduction

1.1. Background

Agriculture and food technology have developed very significantly with the general advance in technology. The current era of globalisation and information technology has set new goals, such as providing consumers with verified information about the quality and safety of food, however, equally important is proof of compliance with environmental protection schemes. Traceability – the ability to identify the origin and processing history of a food product by means of records – is the key to meet the required standards of safety and quality of a food product in the supply chain.

A series of requirements and recommendations relating to traceability have been set in force (EC 2002, BSI 2005a, Anon 2006). According to a common standard (BSI 2005a) all companies in the food chain must be able to identify their incoming materials and suppliers and also the receiver of the outgoing product, i.e. traceability one level up, one level down. Recent research (McBratney et al., 2005) points out that “product tracking and traceability should be a major new focus of precision agriculture research, particularly to provide the tools on-farm to initiate the process”.

A farm is the primary production facility in food production supplying the food processors with raw material or super markets directly with fresh produce. Lupien (2005) indicates that all parts in the food chain should have control systems in order to assure the quality and safety of food products. One weak link in chain can result in unsafe food, which is dangerous to health. A farm has a range of inputs to the crops grown such as plant protection products to repel pests or fertilisers to promote yield. The use of agrochemicals, a subset of plant protection products, is under high public attention (Miles et al., 2004) because of the high risk to health and environment.

Thus the ability to prove good agricultural practice and compliance with food safety and environmental protection regulations is very important for the farmers in terms of business benefits. Accurate traceability records gathered in a robust way are the proof of the above. Contemporary agricultural crop sprayers have the capability to control precisely the application of agrochemicals, vary the rate spatially, and produce "as applied maps" (Miller 1999 and 2003a). The development and adoption of ISO 11783 data communication standard has provided a common platform for exchanging data between farm management information system, tractor task controller and implement controller.

However, there is a gap in the ability to automatically generate records of sprayer inputs. Product identification and quantification remain a manual process subject to human errors and bias. Conventional methods of record keeping are paper based and post-event (Defra 2006). This method has a low level of confidence for providing trace-ability because it is open to operator error, it can be easily tampered with, and it is not easily integrated into electronic data management systems according to Miller (1999).

In order to achieve comprehensive and reliable traceability, integrated automated data acquisition is required – an approach suggested by Auernhammer (2002). The ability to automatically monitor agrochemicals loaded into a sprayer tank has several significant benefits and implications in addition to traceability according to Miller et al. (2008): improved control of the application process to reduce drift and match target, availability of reliable records for post application analysis concerning efficacy and safety factors.

A prototype system consisting of a separate weighing platform incorporating load cells and RFID reader to create automatic records of sprayer inputs with minimal operator intervention has been demonstrated by Watts et al. (2003) and Watts (2004). The results proved the feasibility of the method and suggested improvements such as in signal processing, resolution, work rate and integration into the sprayer's hardware and software to make it more robust and readily implemented.

The engineering development of the Automated Agrochemical Traceability System (AACTS) in this work has been carried out in parallel with the PhD study by Gasparin (2009) who focused on the analysis of the factors related to the market requirements and farmer's perception of the AACTS. The research programs were funded by AGCO Corporation, Douglas Bomford Trust and Patchwork Technology Ltd.

1.2. Aim

To develop a system that can assist in the loading and automatic recording of agrochemical inputs as a primary input of food product traceability. The system will deliver the required performance while operating in a farm environment to meet the goals of operator, food and environmental safety.

1.3. Objectives

1) To develop a prototype system to integrate the identity and quantity of agrochemicals as an initial "input" record for traceability systems.
2) To integrate the prototype system with appropriate hardware and software to meet the required performance.
3) To evaluate the system in terms of speed, efficiency, safety, resolution, accuracy, and operator satisfaction.
4) To make recommendations for system improvements to further meet the requirements of operators.

1.4. Outline methodology

1) Conduct market requirement analysis with stakeholders in the food chain in conjunction with Gasparin (2009) with the focus on aspects of on-farm agrochemical application.
2) Investigate and update the automatic recording system and traceability concept proposed by Watts (2004) and specify the revised performance requirements.

3) Produce an integrated prototype system with the appropriate technical development for improved user safety, accuracy, resolution and ergonomics as requested by the market.

4) Extend the existing standard (ISO 11783-10) to encode the unique identifier of agrochemical containers (RFID) and records of tank content.

5) Evaluate the capability of the designed system for use on farms.

6) Make recommendations for further system improvements and potential routes to market.

The overall program of work for the development of automated agrochemical traceability system was conducted both in this work in engineering aspects and by Gasparin (2009) in market perception and acceptance aspects.

The development of the system follows the structure of the farm traceability system as proposed in Figure 1-1 where the tasks are logically divided between farm computer, tractor controller and the prototype system. The AACTS delivers the functionality to automatically generate records of tank contents by using and complementing the functions of task controller and farm computer.

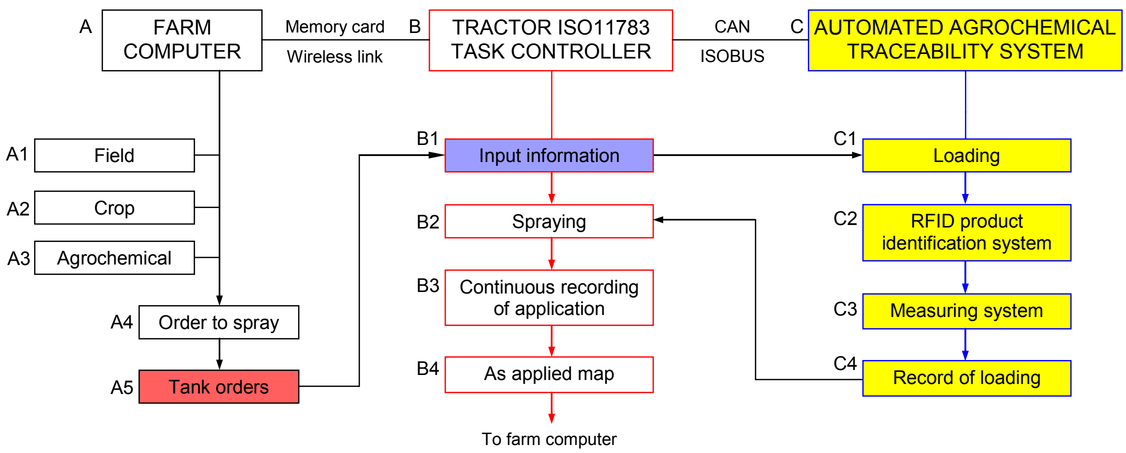


Figure 1-1 Outline of a data flow chart for on farm traceability

2. Review of the current state of the technology

2.1. Introduction

This review differs somewhat of a classic academic review. It covers the breath of technologies which help to deliver traceability. Whilst there is plenty of published material on traceability, the literature on the design of the agricultural traceability systems and automatic recording systems is limited. Concerning these particular subjects the most relevant previous work is that by Watts (2004) who describes the design, construction and evaluation of an early prototype system. Overall, this chapter reviews the requirements for traceability, food safety and quality which set the design specification for agrochemical traceability systems. The market requirements analysis included herein chapter identified the requirements of stakeholders relevant for the development of on-farm automatic recording systems.

2.2. Traceability

2.2.1. Definition

Food traceability is defined as the ability to trace the history of a product in a processing chain, i.e. to identify the farm – the origin of a food product, sources of all input materials and the location in the supply chain by means of records (Opara & Mazaud, 2001). According to ISO 9000:2005 (BSI 2005b), product traceability is defined as the ability to trace the origin of materials and parts, the processing history, and the distribution and location of the product after delivery. In the Codex Alimentarius by FAO/WHO (Anon 2006), traceability is defined as a tool that not by itself but rather in the right context improves food safety. By their design, traceability systems should be able to identify at any specified stage of the food chain from where the food came from and to where the food was sent. That can be described as one step up and one step down traceability.

The benefits of an automatic traceability system based on RFID technology for global supply chain were listed by Sahin et al. (2002). For example: reduction in the cost of labour, reduction in the losses of profit, more efficient control of the supply chain due to increased accuracy of information, better tracking and tracing of quality problems, and better management of product recalls and customer safety.

2.2.2. Drivers

The main drivers for traceability are regulation, the retailer and the consumer. Traceability is mentioned and generally outlined in Article 18 of EC regulation 178/2002 which has been in force since 1^{st} January 2005. The ISO 22000 standard (BSI (2005a) specifies internationally harmonised requirements for a food safety management system which is applicable to all organisations involved in the food chain, and specifies that organisations shall have traceability systems in place. Souza-Monteiro & Caswell (2008) and Gasparin (2009) point out that the leadership of retailers is a driving force for the adoption of traceability systems across the supply chain.

2.2.3. Projects related to traceability

The importance and actuality of traceability has been an impetus for a range of projects to investigate the market requirements and to provide harmonised traceability principles and practice. Those particularly recent and relevant to this work are briefly reviewed below.

Cristal

Project Cristal (Communicating Reliable Information and Standards to Agriculture and Logistics) (http://cristal.ecpa.be, 8 Oct 2008) was initiated by the European Crop Protection Association (ECPA) to develop standards and guidelines to facilitate the implementation of electronic commerce within the European agrochemical industry (Debecker 2001). Cristal standards cover the contents and use of bar codes in consumer units, and electronic data interchange messages between organisations in the distribution chain. The standard does not specify unique identifiers for consumer units.

GlobalGAP

GlobalGAP (formerly EurepGAP) (http://www.globalgap.org, 8 Oct 2008) started as a retailer initiative in 1997 to react to the growing concern of the consumer regarding product safety, environmental and labour standards. Primarily driven by European supermarkets, the organisation has developed comprehensive harmonised farm assurance standards covering crops, livestock and aquaculture to lay down the Good Agricultural Practices. Currently the organisation has members in more than 80 countries worldwide.

PETER

The objective of the PETER project (Promoting European Traceability Excellence & Research, 2006–2008) (http://www.eu-peter.org/, 22 Oct 2008) is to harmonise traceability practices by providing an international discussion forum and disseminating results of food and feed traceability research.

TRACE

Ongoing project TRACE (http://www.trace.eu.org, 22 Oct 2008) aims to improve the well being of European citizens by delivering added confidence in authenticity of food products. Within the project, cost effective analytical methods to enable determination and verification of the origin of food are being developed. Also, the consumer perceptions, attitudes, and expectations regarding production and traceability of food production systems are being assessed.

TRACEBACK

The objective of the TRACEBACK project (http://www.traceback-ip.eu, 22 Oct 2008) is to create a generic system for traceability and information handling within the entire food chain (from field to shelf). To achieve the objectives, the project will deliver a working traceability model. The work involves analysing the food chain to identify weak points with high risk of loss in quality of food product, development of sensors and devices for detecting and monitoring conditions that might cause loss of quality of food products, creating an information handling system, training potential users of the devices, and assessing economic feasibility.

Study of the acceptance of the on farm automated traceability systems

A research program to identify the factors that inform the development and the potential market uptake of automated agrochemical traceability systems at farm level has been carried out and described by Gasparin (2009) and Gasparin et al. (2007) and (2008). The investigation included face to face interviews with stakeholders of the food chain in order to identify their perceptions and requirements regarding traceability systems. The AACTS was evaluated against manual methods by questioning a group of sprayer operators participating in the trial of using such system. The farmer's perception towards AACTS, their willingness to pay and the potential market uptake were investigated. The results suggest automatic traceability systems have the potential to provide benefits through increased reliability, reduced errors, added value to the farm products and business, and competitive advantage from increased confidence in records.

Conclusions

The regulations require traceability from members of the food chain without specifying how it may be achieved (Gasparin 2009). There are many individual traceability practices despite previous effort to develop a common system. Records kept for local management and wider traceability are part of the same process, but are commonly not perceived as similar (Section 2.10.2). There is an opportunity to view traceability as an integral part of management information gathering rather than a separate additional cost process (Alfaro & Rábade 2009). For market acceptance of a standard, development of appropriate technology is required to drive adoption.

2.3. Food safety and quality

2.3.1. Consumer perceptions about food safety

Food hygiene standards and the use of chemicals, pesticides and additives were among the major consumer concerns about food safety identified in the study by Kidd (2000). The fact that the use of pesticides in food production is one of the main public worries is also supported by Miles et al. (2004). Van Rijswijk et al. (2008) found that consumers associate traceability with product quality and safety.

The general public perception of the technological risks of food are associated with a perceived lack of information from the government. The actual scientific risks do not correspond to the social perception of risks because the application of agrochemicals is very rigorously regulated and controlled (Defra, 2006). However, there is always a risk factor of an accidental event, for example an excessive amount of chemicals is applied to one small area. This may be unrecorded at the time and either not part of a test sample or be undetected in a test, remaining in the food chain with serious consequences. Direct recording of inputs and actions on the sprayer removes the issue of events being unrecorded at point of application. Information then exists to take preventative measures prior to contaminating bulk product. Subsequent traceability can help to increase the transparency of food processing technology, spot risks and improve communication with customers.

2.3.2. Regulations

The main objective of the food quality and safety regulations is the high level of protection of consumers' health from risks deriving from food (EC 2002). Principal risk factors are associated with hygiene and pesticide treatments. In the EU, a rigorous approach has been taken recently, food safety regulations have been strengthened since 2002 (Hardy 2007). The Regulation 178/2002 also referred to as General Food Law (EC 2002) provides the principles for the protection of human life and health, consumers' interests, animal and plant welfare and environment from risks of production, processing and distribution of food. Similarly, the Public Health Security and

Bioterrorism Preparedness and Response Act of 2002 (EPA 2002) sets the food security strategy in the USA, though the main focus is on deliberate adulteration of food.

EC Regulation 178/2002 establishes the European Food Safety Authority (EFSA) whose mission is to provide scientific advice and technical support to the legislator. In the European Economic Area a system called Rapid Alert System for Food and Feed (RASFF) is in operation which facilitates exchange of information between members. If a member of the network has detected a serious direct or indirect threat to human health arising from food or feed the notification about the threat and measures taken are sent immediately to all of the members.

A possible consequence of using agrochemicals in crop protection may be the presence of residues of active substances in the food produced from treated crops. Consumers may be directly exposed to agrochemicals through these residues in or on food. The EC Regulation No 91/414 (EC 1991) specifies that public health should be given priority over the interests of crop protection. This risk of exposure is controlled through the Maximum Residue Level (MRL) which is defined as the upper legal level of a concentration for a pesticide residue in or on food after the use of pesticides according to label conditions and good agricultural practice. Maximum Residue Levels are legally regulated, e.g. EC No 396/2005 (EC 2006b) in the EU or Food Quality Protection Act of 1996 (Anon 1996) in the USA. The smallest level of residue is determined by the capabilities of analytical detection methods, currently the lowest detectable level is 0.01 mg/kg (Hardy 2007). Food samples for the maximum residue analysis are picked from a range of points in the supply chain (supermarkets, retail depots, ports etc).

2.3.3. Requirements for record keeping of agrochemical application

Generally, record keeping is a legal requirement (EC Regulations 852/2004 (EC 2004) and 183/2005 (EC 2005a) on food and feed hygiene in the EU and Food, Agriculture, Conservation and Trade Act (Anon 1990) in the USA). Food business operators who apply plant protection products on plants used for food or feedstuff must keep records of treatments. An example of the required detail is given by Defra (2006):

- Date and time of application
- Site of application
- Crop sprayed and reason for treatment
- Products used with their name and registration number
- Dose of product per ha
- Application rate of the dilution per ha
- Total amount of product used
- Area sprayed
- Weather conditions
- Other relevant information

These records are currently mainly created manually from human memory post event with a "pen and paper" method. Automatic methods have clear potential to improve accuracy, remove possible bias and reduce time required.

2.4. Agrochemical products

2.4.1. Physical properties

Agrochemicals are mainly available in two forms: liquids and granules. Farmers generally prefer to use a liquid formulation because it is easier to measure out in small quantities (Matthews 2000). Agrochemicals are more extensively applied to the field as liquids than as solids. Dry formulations, such as wettable powders, are diluted or suspended in a liquid before being applied as liquid (Waxman 1998). Formulations are usually selected on the basis of convenience to the user, availability and price (Matthews 2000).

Bulk density of agrochemical products is in the general range of 0.4 to 1.271 g/cm^3 according to a range of common products selected at random from the market (Appendix A.1). Granules have bulk density of less than 1 g/cm^3 and may specify a range based on compaction of the material (e.g. 0.4 – 0.7 g/cm^3). A known bulk density allows equivalence in measurements taken with volumetric and gravimetric methods.

2.4.2. Packaging

The type and design of packaging is determined by the physical form of the product, chemical resistance, and storage and handling requirements. In order to minimise any operator contamination because of glugging or splashing whilst pouring wider necks are used (Miller 2003a). For such standardised containers, the smallest 1.0 litre has a 45–50 mm neck diameter, the sizes 3.0, 5.0 and 10.0 litre have a 63 mm neck diameter (Miller 2003a).

In the UK, maximum size is limited by the manual lifting guidelines (HSE 2004), being 25 kg when weight is lifted to elbow height with arms bent. The height for loading the induction hopper is 500–1000 mm above ground level (BSI 1996a) which corresponds to the requirements of safe lifting. Because of this limit, larger containers (e.g. 20 *l*) exist but are rare because they are difficult to handle manually. Granules may be contained within a water soluble package mixed directly into the sprayer.

Containers have crude graduation marks, some have incorporated an indicator tube for easier reading of marks. Some containers of liquid products have a measuring bottle included which enhances the accuracy and eases the measuring process, especially when only a small quantity is required from a large container, this also helps minimising spillage. However, they have difficulties with cleaning.

2.4.3. Water rates

Agrochemical products are chiefly sprayed on the field as a solution in water. The required water rate for the product is specified by the manufacturer and given on the label. Agrochemicals are conventionally sprayed at a rate of 151–200 *l*/ha (Garthwaite 2004). The current trend is to use lower rates such as 100–150 *l*/ha or even <100 *l*/ha. This allows covering larger area with one tank load and also cuts cost on water. It does however give increased consequences from misapplication of one tank load and from failures missing product and water.

According to the pesticide survey report (Garthwaite 2004) 78% of the UK arable area is sprayed with water coming from the normal mains supply.

Sprayer tank capacity can vary greatly in the UK as found by Garthwaite (2004):

- 11% having an <800 *l* tank,
- 23% between 801 and 1500 *l*,
- 39% 1501–2500 *l*,
- 27% having a main tank greater than 2500 *l*.

Miller (2006) notes that tank size is almost certainly 2000 *l* and makes two considerations:

- average tank size of partly trailed and self-propelled sprayers is more than 2000 *l*,
- many of them will not operate efficiently with less than 100–200 *l* in the bottom.

Sprayers that cover 71% of the sprayed area are fitted with auxiliary water tanks for cleaning and rinsing (Garthwaite 2004). The capacity of the sprayer tank is restricted by the maximum permitted weight specified for the tractor.

2.4.4. Application and dilution rates

According to Miller (2006), dilution ratio of agrochemical products ranges from a fraction of 1% to often 2% but never more than 5% by volume. Mean concentration is 1%.

Application rate is mostly given in *l*/ha for liquids and in g/ha for granules. To weigh liquids, dose has to be given in g/ha or information about bulk density has to be available to operator. Here is an opportunity for automation.

2.4.5. Review of the most extensively used agrochemicals

A review of the most extensively used agrochemical products was undertaken to examine the application rates and product packaging sizes.

The most extensively used active ingredients used on arable crops as given in Garthwaite et al. (2004) and their application rates according to (Tomlin 2003) are summarised in Appendix A.2. For each active ingredient a set of products were randomly selected (PSD 2006a, Whitehead 2006) and information about formulation type, application rate, and packaging investigated (Appendix A.3–A.6).

The following summary can be made based on the review of the products:

- Range of application rate 50 ml/ha to 5 *l*/ha / 280 g/ha to 3.1 kg/ha
- Range of container size 100 ml to 25 *l* / 50 g to 12 kg
- Common range of container size 1–10 *l*

Application rate of an agrochemical product can often be half or a quarter of the specified maximum rate (Walker, 2006). Thus, the minimum application rate can be taken to be 12 ml/ha or 12 g/ha.

2.5. Capabilities of current farm equipment

2.5.1. Agrochemical induction systems

Agrochemical products delivered to farms have to be transferred from their original package into an application system, i.e. the sprayer, in order to apply them on the field. Miller (2003a) has listed the following desirable criteria for the transfer of agrochemical products from their original containers into the sprayer:

- high work rate,
- low risk of contamination to the operator and environment,
- low residue in the packaging after transfer,
- easy removal of these residues (rinsing).

Work rate is a very significant factor. Miller (2003a) points out that "the time taken to transfer product is often quoted as a reason for not adopting systems that can reduce the potential for operator and environmental contamination during a transfer operation".

The most primitive method of loading the agrochemicals is by pouring them directly into the main tank of the sprayer. However, this technique has a high level of risk of operator and environmental contamination and requires physical effort and time particularly if the operator has to climb on the top of the tank carrying an opened agrochemical container (Miller 2003a). Thus, this technique has become less acceptable.

A range of agrochemical induction systems have been developed to enable the operator to load the products while standing on the ground. These systems are classified as open systems and closed-transfer systems.

Open system (induction hopper)

In Northern Europe, the most popular agrochemical filling system is the induction hopper (Miller, 2003a). In the UK according to Garthwaite (2004), 82% of the arable area is treated with sprayers using induction hoppers, while closed transfer systems account for less than 2%.

The induction hopper, also known as bowl, is a generic low height chemical insertion system (Figure 2-1). Induction hoppers are made of stainless steel or plastic. The main components of a typical induction hopper are a Venturi injector, a container rinse jet, a hopper rinsing bar, a lid, and valves to control the flow of material and rinsing systems as shown in Figure 2-2. Chemical is poured manually into the hopper and drains into a Venturi section where liquid from the sprayer pump is allowed to recirculate back through to the tank. This Venturi device generates a sufficient pressure difference to balance the height between the tank and the relatively low hopper. An arrangement of valves must be closed before switching off the sprayer pump or else the induction hopper is flooded with liquid from the main tank.

The hopper is compatible with any manually handled chemical package, and use of rinsing jets allows granules to be added into a continuously moving film of water to prevent adherence to the hopper sides. If measuring more precise than the graduation marks on the original packaging is required, dispensing into a suitable measuring jug is included prior induction hopper.

(a) (b) (c)

Figure 2-1 Various designs of induction hopper: (a) stainless steel, (b) plastic with a protruding container rinse nozzle, (c) plastic with a combination handle for discharge and rinsing (mechanical wire drive)

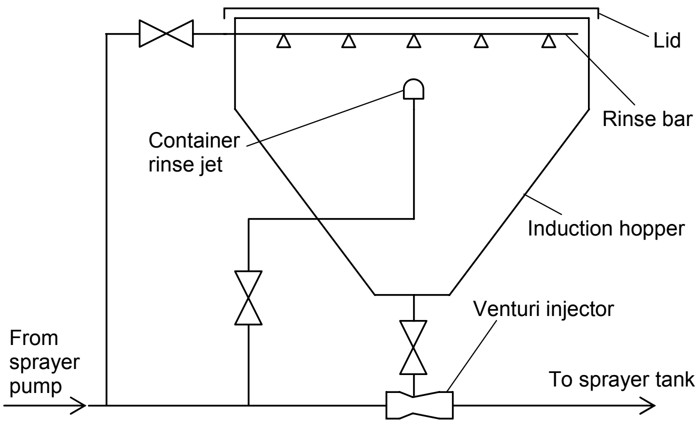


Figure 2-2 Layout of an induction hopper (adapted from Miller 2003a)

In order to spread best practice in design and ensure a low risk of contamination of the operator and environment a standard (BSI 1996a) has been developed which sets the following physical requirements for the induction hoppers:

- Minimum working volume of 15 *l*.
- Minimum diameter of the filling hole of 250 mm.
- Fitted with a lid.
- Height for loading between 500–1000 mm above the ground level.
- Minimum clearance zone around the hopper 500 mm.
- Fitted with a device to rinse containers.
- Minimum flow rate of 12 *l*/min of a liquid formulation.

- Minimum flow rate of 6 kg/min of a granular and powdered formulation.
- The manufacturers shall specify the range of sizes of container with which the induction hopper is designed to operate.

Further requirements concern the performance in terms of chemical resistance, leakage and potential operator contamination, residues within the hopper and the agrochemical product container.

Closed-transfer systems

One of the highest risk factors in dispensing agrochemicals is direct operator contact with the concentrated formulation (Matthews 2002, Miller 2003a). In order to reduce this risk a number of closed-transfer systems have been developed. The use of closed transfer systems on most toxic category pesticides has been a regulatory requirement in California USA since 1973 (Helms & Landers, 2001). However, the enforcement of the regulation was postponed until 1977 to allow the systems to be developed and become commercially available. In the UK, a standard specifying the performance requirements for closed-transfer systems of liquids has been introduced (BSI 1996b).

Based on the product extraction method closed-transfer systems are classified by Fong (2003) as follows:

- Suction probe
- Container puncturing
- Direct drop/gravity feed

Suction probe arrangement has a long tube which is inserted into the chemical (Figure 2-3a). In order to make it a closed system the tip of the probe has to be protected with a suitable shroud (Miller 2003a). Rinsing function can be added by means of a secondary tube enveloping the primary extraction tube (Fong 2003). Suction probe works only with liquids, integrated measuring cylinder is reported to have a resolution of 27 ml by graduation (Chemeasure by Cherlor Manufacturing).

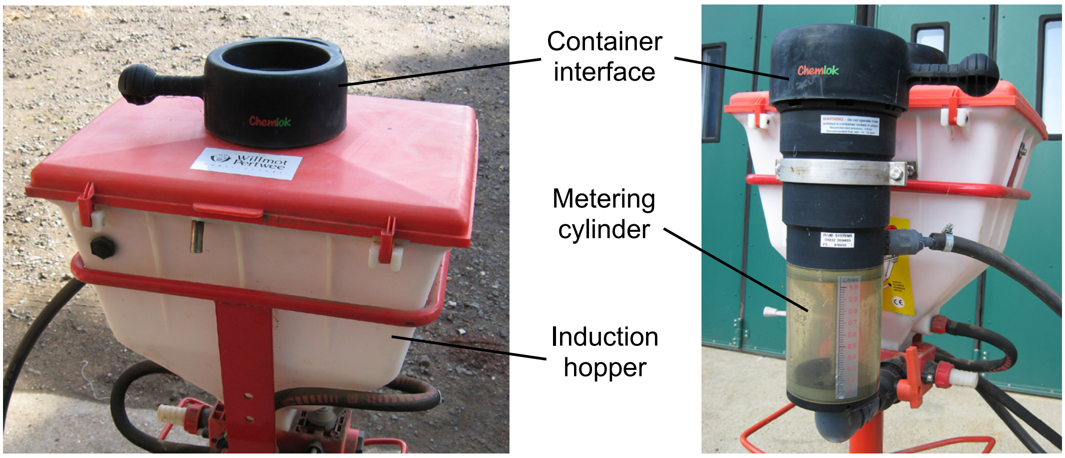
(a) (b)

Figure 2-3 (a) Suction probe and (b) container puncturing device (Fong 2003)

Container puncturing (Figure 2-3b) works by placing the original packaging into a sealed larger box and activating a spike to breach the container. Rinsing can be arranged by leading the water into container through spikes (Miller 2003a). This extraction method is not suitable for glass containers and the whole container contents must be loaded, part packs cannot be used.

Gravity feed system is based on a valve/coupler arrangement creating a sealed connection between the container and induction device (Figure 2-4). The product is transferred into the sprayer from inverted container by controlling the valve. Dispensing of part containers is possible with a resolution of 28 ml as reported for specialist measuring cylinder (Accuductor by Sotera Systems). A rinsing function may be built into the coupler. This system is limited to containers designed for a particular interface.

Although, the closed-transfer systems have been commercially available for three decades, a number of problems are still reported (Fong 2003): non-standard container interfaces, problems with container rinsing, measuring difficulties and system complexities. Cost, complexity and speed of operation are the reasons for slow commercial uptake in the UK (Miller 2003a).



(a) (b)

Figure 2-4 Closed transfer system Chemlock: (a) integrated into the lid of the induction hopper, (b) into the stream feed with a measuring cylinder

Direct injection

In a direct injection system the agrochemical is dispensed directly from its original packaging into the stream of water within the line to the nozzles without diluting and mixing it into the tank in the first place (Frost 1990). The advantages of direct injection are reduced need for decontamination of the sprayer and disposing of unused dilution, reduced risk of operator contamination because of the closed system, flexible patch spraying or variable rate spraying if more than one product is switched to the injection system (Miller 2003a and Landers et al., 2000). However, to cope with the wide range of application rates of formulated products at least three pumps are required which has influence on the system cost (Miller 2003a).

2.5.2. On-field application systems

Contemporary sprayer controllers (Figure 2-5) have the capability to control precisely the delivered dose, although across the application boom (tolerance of nozzle discharge rate ±5% specified by BSI (1989)) and record actions with the onboard controller (Miller 1999). Existing protocols such as ISO 11783 enable electronic data exchange between tractor task controller and farm management information system.

(a) (b)

Figure 2-5 (a) A dedicated sprayer controller, (b) sprayer screen on an ISO 11783 console

By the method of controlling the delivered dose sprayers can be classified as constant rate and variable rate (Miller 2003a). In case of constant rate the field is treated with a uniform application rate by adjusting the total volume output rate or the amount of chemical concentration in the spray liquid (direct injection metering) depending on the forward speed. The availability of satellite navigation systems such as the Navstar GPS (Global Positioning System) on agricultural crop sprayers enables the electronic controller to associate the time, location and output rate to produce an "as applied map" (Miller 2003b). This may be produced in-cab or back on farm computer (Figure 1-1).

The impulse for development of spatially variable rate application came from research findings which demonstrated the distribution of weed is commonly not uniform across the field, thus spatially variable application reduces cost (Godwin et al. 2003) and environmental burden (Miller 2003a). A spatially targeted pesticide application approach requires according to Miller (2003b): detection module to identify the target; decision module to relate the target with required treatment, an application module to deliver the required dose to the target.

All three functions can be realised on a single spraying vehicle. Alternatively detection can be separated from application using a treatment map approach (Figure 2-6).

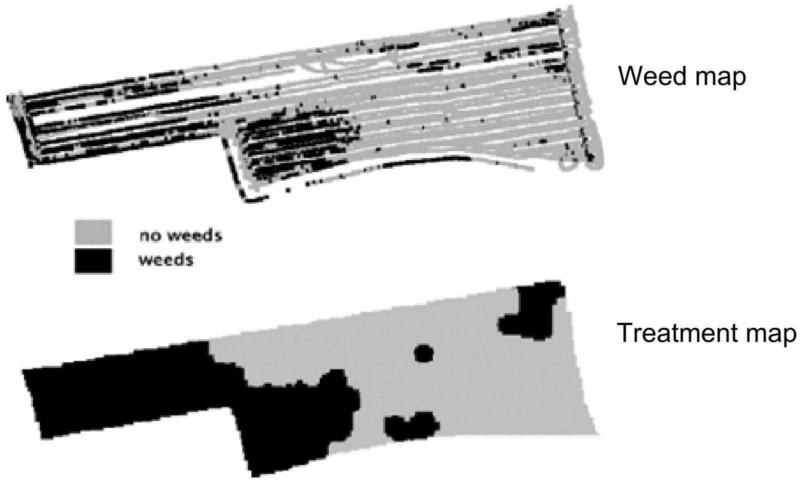


Figure 2-6 Mapped weeds transferred into a treatment map (Miller 2003b)

The application technology is required to deliver high work rate, uniform deposits at target level, high levels of drift control and effective pest control (Miller 2007). The ability to automatically record the identity and amount of chemical inserted into the sprayer tank has implications not only for automated traceability systems (Miller 2003b) but also for the development and implementation of improved sprayer control algorithms (Miller et al. 2008; Miller & Butler Ellis 2000).

2.5.3. Farm management information system

Farm management PC software presently available offers a comprehensive set of features: job planning, management of resources (products, machinery, and workers), finances, field records, spatial data (maps), data analysis and interface with the mobile implement controller. Many of the software packages such as Greenlight by Muddy Boots and SentinelActive by Farmade emphasise the traceability functionality and provide also agronomical functions such as checking the compliance of the spray plan against registered agrochemical products. A regularly updated database of nationally registered pesticides is supplied (e.g. ProCheck by Muddy Boots).

It is a legal requirement to maintain traceability records for at least 3 years (Defra 2006). These records can be kept locally on a farm computer. However, that suggests issues with reliability as the farm PCs are often not maintained at a required level (Price 2008).

These problems can be overcome by placing the records automatically off farm on a professionally maintained central network server. Internet based solutions for storing and managing farm records are currently available such as WebTrack by Patchwork Technology Ltd. These services may in the future be extended to serve as “data clearance house” to provide information to other relevant parties in the food chain. Modern data acquisition technology allows rapidly collect large of amounts of data. These “raw” traceability records have to be turned into a meaningful summary, a function that can be provided by the “data clearance house”. Data reduction is beneficial because stakeholders are interested in a yes/no format summary which indicates whether the food product complies with the requirements (Section 2.10.2). Detailed data has to be available in case of a problem.

The traceability regulations do not specify how the organisations in the food chain have to demonstrate traceability. Thus there are many inter-organisation traceability systems in place which have to be linked together for higher efficiency. One way is to implement a common data standard for data that leaves and enters the farm. Efforts have been made in this direction such as the AgroXML format (http://www.agroxml.de, 23 April 2009) or the TraceCore XML format (http://www.trace.eu.org/ft/doc/Brochure Tracecore_Final.pdf, 23 April 2009).

2.6. ISO 11783 data network and communication

2.6.1. General overview

Electronics and information technology have an important role in improving the efficiency and automating tasks of agricultural machinery. Therefore modern agricultural machines and implements are controlled by electronic processing units. These units have the ability to communicate with each other. This is highly relevant for any automatic system to record agrochemical inputs, which should relate to existing developments in on-vehicle agricultural communications.

It was recognised that smooth communication requires a standardised network (Auernhammer & Speckmann 2006). The ISO 11783 standards define an open inter-connected system for on-board electronic systems for agricultural equipment (Figure 2-7).

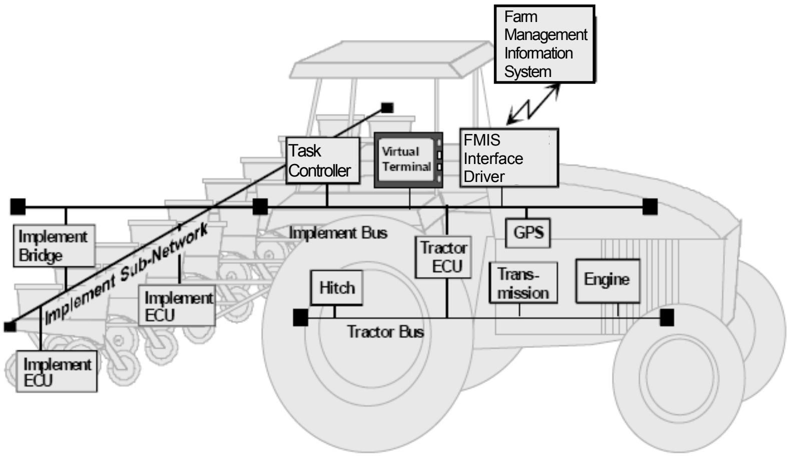


Figure 2-7 ISO 11783 network on tractor (after Goering et al. 2003)

The ISO 11783 serial control and communications data network (ISOBUS) is based on Controller Area Network v2.0B with data frames of 29 bit identifier and 64 bit data field. The BUS operates at a speed of 250 kbit/s. The ECUs responsible for a complete functionality of a device or a service communicate through the BUS by messages. All together the standard consists actually of 13 parts. Regarding this work, the following are more relevant:

- Part 6: Virtual terminal for ECUs to interact with an operator (BSI 2004g).
- Part 10: Task controller and management information system data interchange (ISO 2008).
- Part 13: File server (BSI 2007a).

A free library IsoAgLib (http://www.isoaglib.org, 23 April 2009) is provided as an open source project contributed to widely across the industry to facilitate the development of ISO 11783 applications.

2.6.2. Task management

Part 10 of ISO 11783 (ISO 2008) defines the task management, communication between task controller and electronic control units, and data transfer between farm management information system (FMIS) and mobile implement control system (MICS).

FMIS is the complex of farm computer and management software. MICS refers to devices that are coupled by ISO 11783 network. A task controller is the primary electronic control unit (ECU) on the MICS responsible for sending, receiving and logging of process data. It has links with FMIS and electronic control units of implements.

The central atomic data management unit that comprises the agricultural resources, products, and operations is called task. Tasks can be generated on the FMIS and MICS. In ISO 11783-1 (BSI 2007b) task is defined as an execution of work on one field, for one farm. A maximum of one task can be active concurrently on a single task controller.

The main objectives of the task management are the management of farm resources and field activities (ISO 11783-10:2008). Data transfer between FMIS and MICS is bidirectional: planned task is sent to the MICS and resulting logged data back to the FMIS (Figure 2-8). In the planning stage farmer allocates resources to a field. The data is converted into a standard XML format and transferred to task controller on a tractor through wireless link or on a memory card. Optionally, the task data can be assigned to implements. Task controller sends messages to implements according to the planned task file and logs data values recorded from a particular processing operation. The collected data is sent back to the farm computer and converted into a standard XML file. Finally the completed task data is converted into desired format for further usage or storage.

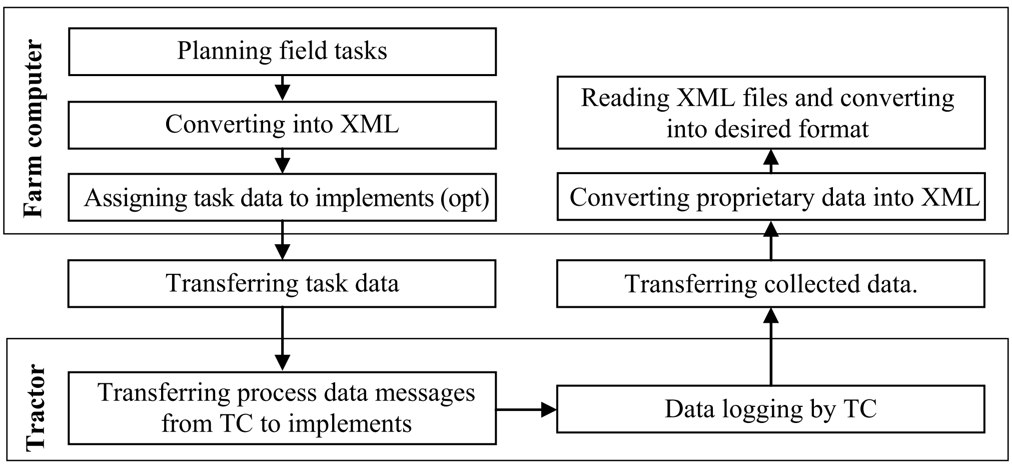


Figure 2-8 Workflow of the task management (adapted from ISO 2008)

2.6.3. Task file

The ISO 11783 task file is based on the Extensible Markup Language (XML) where the elements represent the real world objects. XML is a hierarchical structure consisting of elements and their attributes to exchange a wide variety of information (http://www.w3.org/XML/, 19 August 2008).

The main task file contains the root element ISO_11783_TaskData, coding data, and a number of tasks. Inside the main file, there can be references to sub task files which may each contain a single XML element. During the execution of tasks the files are modified and binary data appended by MICS. MICS is not allowed to change or delete the coding data. However, it can add new coding data elements.

2.6.4. Data transfer between task controller and farm computer

Communication between FMIS and MICS is based on standardised XML data transfer files, Figure 2-9. The task controller interface driver is responsible for sending task data to the task controller in proprietary or XML format. The task controller converts data from the transferred task file into process data messages which contain commands and values to control the relevant implement ECUs on ISO 11783 network.

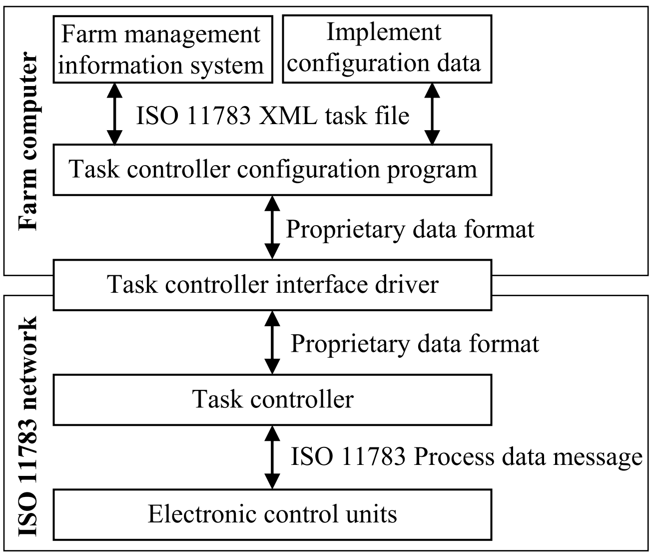


Figure 2-9 Entities and interfaces of task management (adapted from ISO 2008)

2.7. Review of Radio Frequency Identification (RFID)

2.7.1. Brief history

Recently RFID technology has become popular for the identification of items in the management of global supply chains. The history of exploring RFID dates from 1948 when Stockman published a paper titled "Communications by means of reflected power" which is considered the beginning of RFID research (Landt, 2005). These resulted from the developments conducted in the 1940's when a similar technology to RFID was used to identify airplanes as friend or foe (Domdouzis et al., 2007). The first widespread commercial use of RFID was electronic article surveillance with "1-bit" tag to counter theft in stores developed in the late 1960s.

2.7.2. Operating principle

A simple RFID system consists of a passive transponder (e.g. 76×48 mm rectangular thin flexible inlay) and an active reader as shown in Figure 2-10. The reader and transponder communicate over a wireless non-line-of-site radio frequency link (Finkenzeller, 2003). The interrogator (often called reader) transmits a radio wave which activates the transponder and in reply the transponder, using the energy of the received radio wave, responds to the interrogator.

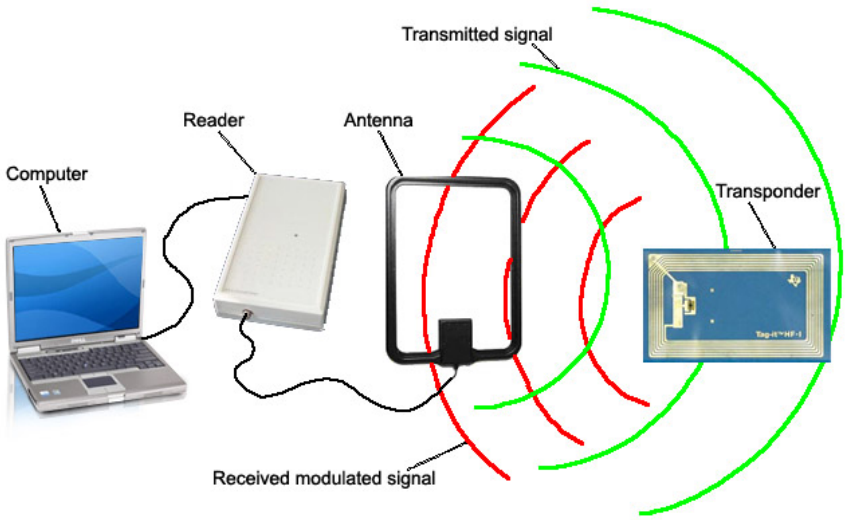


Figure 2-10 A basic RFID system

Key features of RFID can be summarised in the following:

- Non-line-of-sight – RFID tags do not need to be visible for reading or writing.
- Robustness – tags can be encased to protect from the environmental damage.
- Read distance and speed – high speed reading from long distances.
- Anticollison – simultaneous reading of multiple tags.
- Programmability – ability to write information to tag in addition to only reading data.

2.7.3. Frequencies

RFID systems generate electromagnetic waves and are therefore classified as radio systems. The interference with nearby radio and television broadcast, mobile phone, marine, aeronautical and mobile radio services is not permitted. With regard to other radio services, RFID operates in several different radio bands: 0–135 kHz, 13.56 MHz, 433 MHz, 900 MHz (UHF), and 2.4 GHz (microwaves) (Finkenzeller 2003; Knospe & Pohl 2004) as shown in Figure 2-11. All of these, except 0–135 kHz, belong to the worldwide reserved ISM (Industrial-Scientific-Medical) radio bands. There is some inconsistency over the international UHF (Ultra High Frequency) spectrum allocation: the band 865.6–867.6 MHz is available in Europe, 902–928 MHz in USA, and 952–954 MHz in Japan. HF has its advantages such as penetration through water and relative insensitivity to electromagnetic noise.

Ward & van Kranenburg (2006) and Domdouzis et al., (2007) have analysed the features of RFID frequencies, the results of that are presented in Table 2-1.

There are differences in the permitted radiated power which limits the read range at UHF 900 MHz. The strictest permitted power is in Europe, corresponding to a read range up to 2 m. In the US, the permitted radiated power is higher, where the range is up to 5 m (Anon 2004).

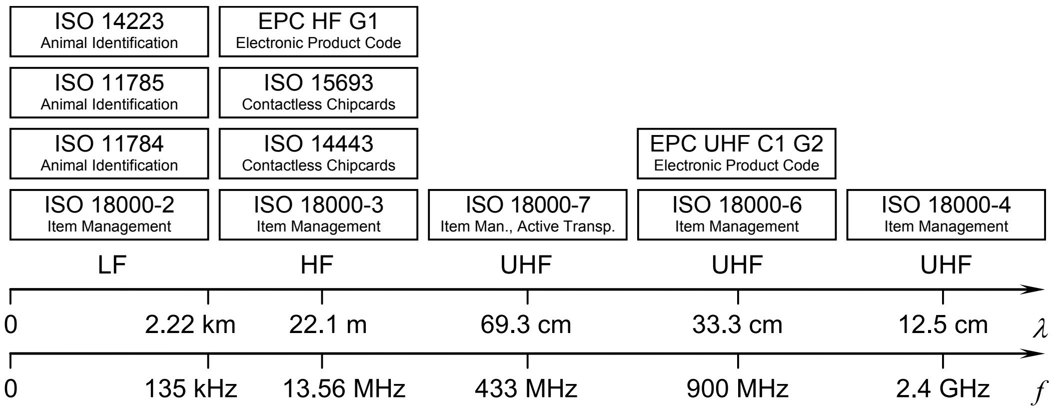


Figure 2-11 RFID standards, frequency bands, and wavelengths (Adapted from Knospe & Pohl, 2004)

Table 2-1 Features of RFID frequencies

Feature	**Frequency**			
	0–135 kHz	13.56 MHz	433–900 MHz	2.4 GHz
Maximum read range	0.5 m	1.5 m	433MHz=100m 900MHz=5 m	10 m
Data transfer	1 kb/s	25 kb/s	100 kb/s	100 kb/s
Coupling reader–tag	Inductive	Inductive	Backscatter	Backscatter
Penetration through water and metal	Water = yes Metal = no	Water = yes Metal = no	Water = no Metal = no	Water = no Metal = no
Typical use	Animal ID, car immobilisers	Smart labels, access and security	Logistics (item labelling)	Moving vehicle toll

2.7.4. Standards

The main advantages of developing international standards for RFID systems are following: to ensure international inter-operability among tags and readers manufactured by different companies, to reduce the cost due to compatibility and to aid the worldwide market growth of RFID systems (Finkenzeller 2003; Wu et al. 2006).

RFID standards such as those shown in Figure 2-11, are being jointly developed by ISO (ISO TC23/SC19, JTC1/SC31, JTC1/SC17) and GS1 EPCglobal (http://www.epcglobal inc.org, Brussels, last accessed 2008-08-21). The GS1 EPCglobal is an industry driven organisation which is leading the development of standards for Electronic Product Code (EPC) with a focus on UHF RFID applications for item identification in global supply chains. ISO have defined a set of standards for animal identification and contactless chip cards, and proposed a new 18000 standard range for item management. The EPC UHF Gen 1 standards were superseded by UHF Class1 Gen 2 standard.

Code structure and technical concept of animal identification tags is defined by ISO 11784 and 11785. ISO 14223 advances the animal ID allowing writing and write protecting of data blocks (Finkenzeller 2003). The tags operate in low frequency band below 135 kHz.

The vast majority of the contactless chipcards currently on the market conform to ISO 14443 proximity range up to 15 cm or ISO 15693 vicinity range up to 1 m (Finkenzeller 2003). Both standards cover 13.56 MHz and define physical characteristics, memory structure and communication protocols.

The ISO 18000 series specifies the air interface, collision detection mechanisms and the communication protocol for item management tags. In the future, ISO 18000-3 will completely incorporate ISO 15693 (Anon 2004). The GS1 EPCglobal has published requirements and protocols for EPC system. Class 0 tags have the functions of being factory programmed and read by the interrogator. Higher class tags provide additional functionality, e.g. security functions. The Class 1 tags in the HF band are compatible with ISO 15693 and ISO 18000-3 (Knospe & Pohl 2004) and EPC UHF Gen 2 is harmonised with ISO 18000-6 to provide interoperability of readers and tags.

2.7.5. Electronic Product Code

The Electronic Product Code (EPC) is a family of coding schemes for universally identifying physical objects in the supply chain (Thiesse & Michahelles, 2006). The EPC was developed for unique identification on the item-level in contrast to GS1/EAN/UCC (European Article Number / Uniform Commercial Code) barcode number which distinguishes the manufacturer and type of product. EPC accommodates existing naming schemes and is open for new schemes. The total length of EPC is 96 bit and it is structured hierarchically starting with the header which declares the type of the EPC and followed by data defined by the type (Figure 2-12).

016.3700.123456.100000000			
Header	Manu-facturer	Product type	Serial Number

Figure 2-12 Structure of the EPC general identifier

The various EPC elements (hardware and information services) are linked into an infrastructure called the EPC network (Figure 2-13). The distribution of information in the network works in the following manner: the RFID reader passes the EPC number to a local information system, which then uses the hierarchical Object Name Service (ONS), which is based on the design of the Internet service DNS (Domain Name System). ONS enables the computer system to locate information in the distributed database on the network about the object carrying an EPC and to request access to that information, such as the production time of an item (Sarma et al. 2001). Thus, using the existing RFID and Internet technologies results in a network of information – EPCglobal Network – that traces individual product movement in supply chains in real time.

The main benefits of the EPC are immediate identification of an item, greater accuracy in tracking, and improved efficiency and visibility in supply chain, which all enables the organisations to be more responsive to customers.

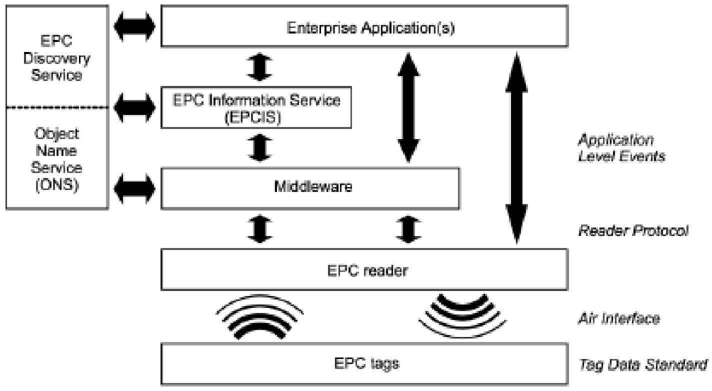


Figure 2-13 Architecture of the EPC network after Thiesse & Michahelles (2006)

The Electronic Product Code was the creation of the Auto-ID Center, a consortium of global corporations and university laboratories. Since 2003 the development and world-wide adoption of the EPC technology is managed by the GS1 EPCglobal, a joint venture between GS1 (formerly know as EAN International) and GS1 US (formerly the Uniform Code Council).

The EPC family incorporates currently the following identifiers according to the standard (EPC Global 2008):

- General identifier (GID).
- GS1 Serialised Global Trade Item Number (SGTIN).
- GS1 Serial Shipping Container Code (SSCC).
- GS1 Serialised Global Location Number (SGLN).
- GS1 Global Returnable Asset Identifier (GRAI).
- GS1 Global Individual Asset Identifier (GIAI).
- GS1 Global Service Relation Number (GSRN).
- GS1 Global Document Type Identifier (GDTI).
- US Department of Defence Identity Type.

2.7.6. Interrogators (readers)

The interrogator is usually called reader whether it reads and writes or only reads data (Finkenzeller 2003). Readers can have built-in or separate antenna, packaged as a PCB module, housed unit or hand held device, Figure 2-14. Reader's main functions are to activate the data carrier (transponder), structure the communication sequence with the transponder, perform anticollision (if exchanging data with more than one transponder) and authentication, and transfer data between the application software and transponder.

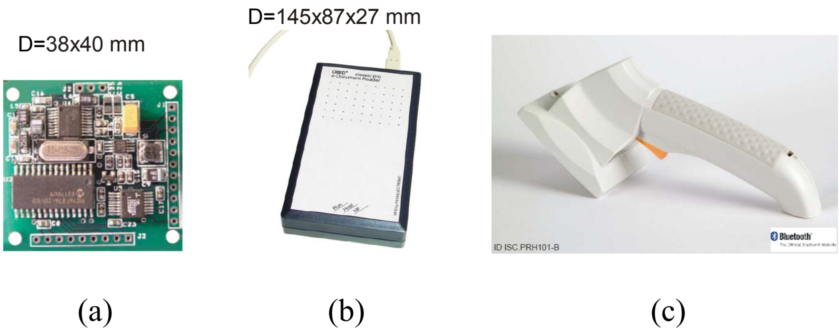


Figure 2-14 Various RFID readers: (a) PCB module, (b) housed unit, (c) hand held unit

2.7.7. Transponders

The data carrier in a RFID system is the transponder which consists of an integrated circuit microchip and coupling device, and has the ability to respond to radio waves transmitted from the RFID reader in order to send, process, and store information.

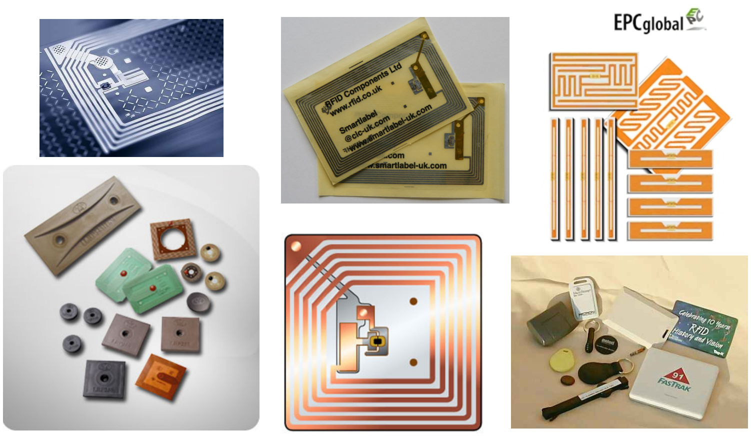


Figure 2-15 A selection of RFID labels

Every RFID label carries a unique read only serial number defined at manufacture e.g. 16 hexadecimal numbers for ISO 15693 transponders. In addition, there is a user definable read-write memory of between 64 bits to 8 kilobytes structured into a number of blocks where bytes are individually programmable as hexadecimal data words (Finkenzeller, 2003). The retail and logistics industries favour low cost small (e.g. 96 bits user memory) tags which serve as unique "number plates". The unique number is used to relate to details held in larger external databases (Thiesse and Michahelles, 2006).

A passive tag does not have an internal power source, it operates with the energy of the radio wave emitted by the reader. The vast majority of inductive coupling tags are passive. Typical read-write ranges of passive inductive coupling tags are up to 1 m. Passive backscatter coupling tags operate in UHF and microwave band and have ranges up to 3 m.

Active backscatter tags incorporate a battery which supplies the microchip and keeps the stored data. However, the battery never provides power for the data transmission, this relies entirely on the energy of the electromagnetic field received from the reader (Finkenzeller 2003). Active tags have a larger memory capacity and achieve read ranges up to 15 m.

2.7.8. Unique identifier of RFID transponders

A unique identifier (UID) is used to address each RFID transponder uniquely and individually worldwide. The UID is set permanently at the tag manufacturer so that it cannot be modified in later use. The UID comprises of a header, integrated circuit manufacturer code and a serial number as shown in Figure 2-16. The manufacturer of the tag is responsible for assigning unique and unambiguous serial number to the tags. The serial number is used by the collision arbitration algorithm which facilitates time efficient communications between the reader and tags in case where more than one tag is in the radio field.

MSB LSB

64 57	56 49	48 1
'E0'	IC Mfg code	IC manufacturer serial number

Figure 2-16 UID format according to ISO 15693-3:2001

The length of the UID is 64 bit (10^{19} combinations) according to a range of standards (BSI, 2001, 2004a, 2004b, 2004c, 2004d, 2004e, EPC Global, 2005) and 32 bit according to BSI (2004f). However, the allocation of bits for manufacturer code and serial number within the UID varies between 16–8 and 32–48 bits accordingly. The header is normally 8 bits.

2.7.9. Disposal and recycling of RFID tags

With increasing number of RFID labels in circulation the question of disposal of RFID labels becomes important. Currently there is little information or literature about the end of the life issues related to RFID transponders. The issue of recycling and environmentally safe disposal of RFID devices has been raised for debate in the Commission of the European Communities (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52007SC0312:EN:HTML). According to the case study by Wäger et al. (2005) where potential impacts of smart labels on municipal solid waste recycling and disposal have been assessed, specific recycling processes of RFID labels to recover used materials would not be feasible. Smart labels could potentially impact waste stream by dissipation of toxic and valuable materials and interruption of established recycling systems.

2.7.10. Cost

An indication of market prices of RFID components from a recent market survey is given in Table 2-2. The cost of labels and tags depends significantly on volume with discount for large volume orders. Memory capacity has also an effect on price. The readers and antennas are offered as PCB modules or encased. Interrogators and antennas can be integrated into one unit such as small handheld device or large gate arrangement.

Table 2-2 The starting retail prices of RFID interrogators, antennas and labels (16 April 2009, http://www.rfid-webshop.com; http://www.buyrfid.com)

Product	HF 13.56 MHz	UHF 868/915 MHz
Interrogator	£65	£332
Antenna	£152	£87
Label	£0.51	£0.23

2.7.11. Comparison to barcodes

In comparison with barcodes RFID has several advantages as given in Table 2-3. The main difference is that barcodes have to be in direct line of sight to the scanner, RFID labels on the contrary are read over non-line-of-sight radio link which makes RFID very reliable and robust for use in agriculture where surface contamination is a significant issue (Watts 2004). Secondly, barcodes have to be individually scanned whereas RFID enables simultaneous multiple reading of labels which saves time and thus reduces cost.

Table 2-3 Comparison between RFID and barcode

Criteria	Barcode	RFID
Transfer method	Visible to reader	Non-line-of-sight
Reliability*	90% at <10% surface contamination	>99%
Read errors	Yes	No (checksum)
Simultaneous multiple reading	No	Yes
Traceability	Type of product	Unique item

* – After Watts (2004)

RFID achieves virtually 100% reliability, the built in checksum algorithm reduces and identifies read errors whereas with barcodes erroneous readings occur more frequently. The unique serial number component of an RFID tag adds the important conceptual difference of identification of individual items. Barcodes only identify the type group of an item.

2.7.12. Market trends

Both the worlds largest retailers Wal-Mart and the United States Department of Defence demanded their key suppliers to use the RFID tags to track pallets of goods from 1st January 2005 and other suppliers should follow in a year (Wu et al. 2006, Computerworld 2006). In the UK, the retail chain Marks & Spencer adopted RFID technology successfully in 2003 by attaching RFID tags to trays and containers of fresh food, produce and flowers which allowed data to be captured and processed 83% faster (Anon 2004). Both Procter & Gamble and Gillette are using RFID technology to track products from assembly line to the store shelves (Anon 2004).

The RFID market is expected to grow significantly over the next years with an estimated market value to 3 billion USD by 2007 (Anon 2004). According to the latest projections (IDTechEx 2008) the market value in 2008 is 5 billion USD which will expand to 17.5 billion USD by 2013.

Cumulative sales of RFID tags from 1944 to end of 2005 totals in 2.4 billion, with 0.6 billion tags being sold in 2005, 1.02 billion in 2006, 1.72 billion in 2007, and 2.16 billion in 2008 (IDTechEx 2005 & 2008).

2.7.13. Future challenges

RFID technology has developed very rapidly. A few years ago harmonised standardisation was seen as a significant issue (Wu et al. 2006) which is not the case anymore because of the development of standards by ISO and EPCglobal. Ranky (2006) has reported the following challenges for RFID research: 1) reliability of readers (desired 100%), 2) robustness of RFID infrastructure, 3) decision support tools to convert RFID data into usable information and 4) integration of active and passive RFID data and architecture. The improvements upon these issues in the development of RFID technology implies RFID has a potential to be successfully applied in agriculture where the operating conditions are rough and timeliness critical, the reliability and robustness are very important.

2.8. Application of RFID for agricultural traceability systems

2.8.1. Structure of potential applications

The objective of this section is to discuss potential applications of RFID in agriculture for traceability systems. The potential applications can be structured to as follows:

- Inputs :– such as agrochemicals and seeds.
- Outputs:
  - discrete items (pallets, boxes and bales),
  - bulk material.
- Inventory control.

The value of input and output products is also considered in relation to the cost of RFID transponders. The input product data both improves and guarantees the quality of the information on which the billing of costumers by agricultural contractors is based.

2.8.2. Agrochemicals and fertilisers

Currently the agrochemical manufacturers are not using RFID labels for identification of agrochemical containers. However, there is a great benefit in it for agrochemical traceability. The application of RFID tags for agrochemicals has been researched by Watts (2004) where the containers of agrochemicals were labelled with Infineon ISO 15693 10 kilobit smart labels and a sprayer equipped with RFID device (Figure 2-17). These results (reviewed herein in Section 2.9.2) have been developed further in this work.

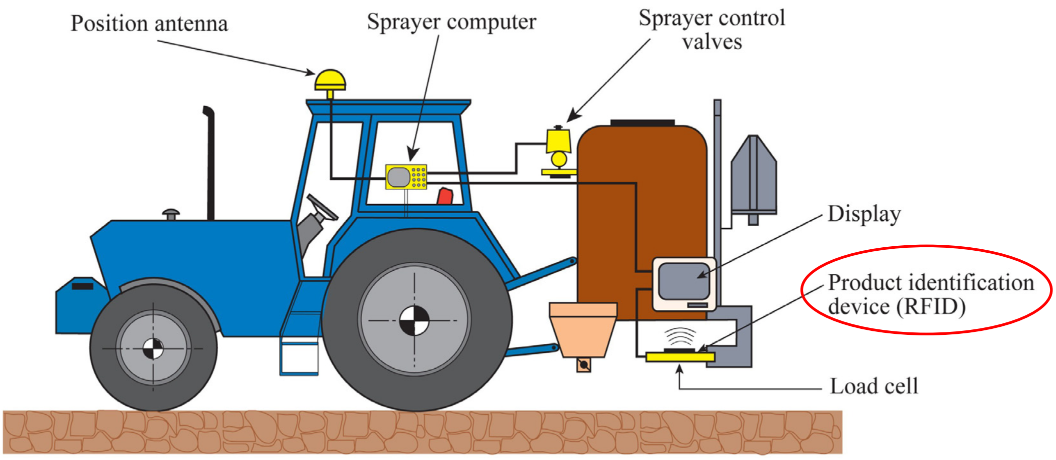


Figure 2-17 Schematic of a sprayer equipped with RFID device (Watts, 2004)

2.8.3. Seeds

With the increased share of genetically modified crops the traceability and correct identification of seeds is of particular interest. Bags of seeds can be labelled with RFID transponders.

The global agricultural company Monsanto initiated a trial to evaluate the use of RFID transponders on its seed packets (O'Connor, 2007). Packets of genetically modified seeds that are sent from research facility to test farms are tagged with passive HF and UHF RFID labels. The objective of the trial is to determine the reduction of labour time spent on scanning the packets. Currently barcode systems require 20 minutes or more to manually scan each small packet barcode in a tightly packed case of 235 packets.

2.8.4. Discrete items

Many vegetable growers have product tracking systems in place in order to provide traceability information. This requirement for gathering detailed data in-field creates interest in automation to reduce cost and increase accuracy of the data (Gasparin 2009).

Typical existing systems track the picking gang, field, plot, product and harvest date. However this manual tracking method is labour intensive and prone to errors. With RFID technology the process can be automated and improved. The trays or pallets of vegetables carrying an RFID label can be automatically identified at handling points, the unique identity of item can be linked with location (e.g. GPS), time stamps and other relevant information into a database and shared with other parties in the processing chain at later stages as suggested by Downey (2006). The definition of data processing logic to combine raw information robustly into a valuable product is a very considerable undertaking for each business case. However once configured, the information is produced with no manual intervention and minimal cost per unit. There may well be scope for cross-industry sharing of software components and combinational logic – e.g. GPS location and treatment data into "as applied maps".

A case study undertaken by Gasparin (2009) at a brassica grower in UK has indentified that currently the tractor driver is responsible for the visual identification of the pallets of products coming from the field. The driver collects cutting sheets from the gang and transports the sheets with the product to a weighbridge. Individual product traceability labels are generated at the weighbridge when the product is checked into store. These labels form a significant reference for later traceability, and any error may well not be detected later.

Currently, issues exist in that the cutting gang move frequently around the field and sometimes pallets from different plots can be mixed in the same rig. This leads to incorrect labelling at the weighbridge – a basic failure of traceability. In this study, each tray contains 12 plastic bags of fresh greens and each pallet holds 50 trays. Therefore, a misidentification of a single pallet source would result in 600 plastic bags mislabelled.

RFID tagging at the tray level would allow specific location of harvest to be recorded on the harvest rig (Figure 2-18). Records of tag identity and location could be transferred directly to the weighbridge for generation of labels. The addition of specific location reference and elimination of verbal and handwritten stages would greatly reduce the possibility for error. Secondly, any failure in data transfer would be immediately apparent to the system, so the opportunity to blindly generate incorrect product labels is eliminated. If records are transferred in an electronic format it is logical to retain on-farm the detailed location records of each tray, even for a limited period. This would allow any issues that did occur to be resolved properly and quickly.

Figure 2-18 Harvest process – fresh greens

Marks and Spencer have implemented RFID identification on 3.5 million returnable food trays and claim data capture reductions in terms of both cost and time of up to 83%, with much more data being collected and stored (Wyman, 2002).

Other potential applications for RFID are tagging agricultural materials such as bales of hay, straw, silage and cotton. The tags could contain not only the GPS location and manufacture time stamp but also criteria such as the bale weight (Maguire et al., 2007) and moisture content at manufacture, which may be important for the end user.

2.8.5. Bulk material

Bulk material such as grain goes through various handling operations in the food chain such as harvest, drying, transport and storage. Current process tends to treat the material as a commodity, and blending frequently occurs. This is not directly identifiable from the product. However, traceability issues are as significant as products currently individually packaged – e.g. identification of genetically modified products, food security issues, protection against theft.

There are principally two methods of tracing bulk materials by insertion of tracers:

- non-edible tracers,
- edible tracers.

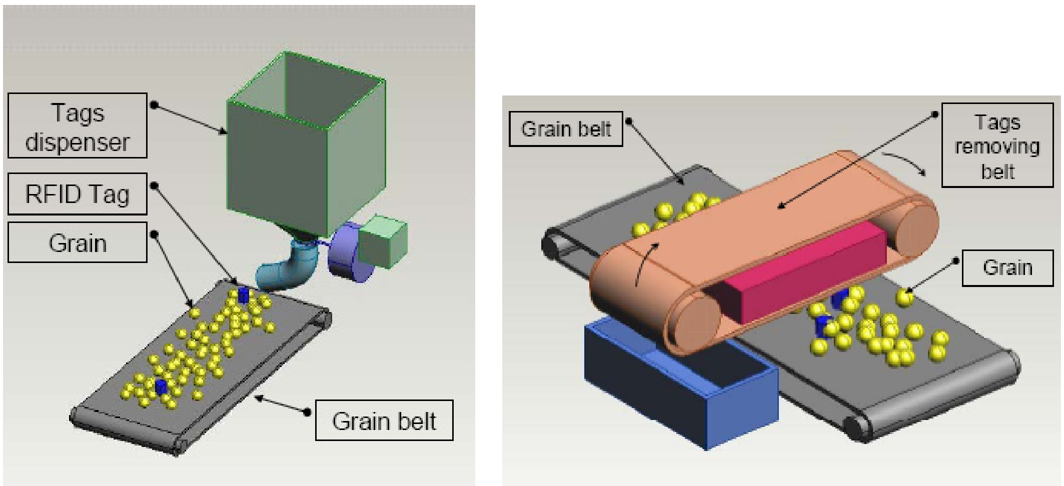
For the first case the tracers are electronic data carriers which store only a unique identifier or have an extended memory space for data logging. The unique identifier case requires infrastructure in place to manage the movements of tracers in the processing chain. Data logging type accumulates data in the memory provided at processing points. The size and shape of the tracers has to be as close as possible to the traceable material for uniform mixing. The tracers are introduced into the material at harvest but they must be removed from the material before used for food. The removing mechanism must be absolutely reliable or they represent a source of food contamination. RFID tags belong to this group.

The second method uses the same material as traceable product or similar substance for forming the tracers. These tracers are blended into the product in subsequent processing. Tablets with opto-electronically recognisable information, such as barcodes, belong here.

Hirari et al. (2006) have evaluated a grain tracking system based on bar coded caplets. Tracing caplets made of semolina with the following properties length 3–7 mm, diameter 4 mm, weight 87 mg and density 1.38 g/cm^3 were introduced into the grain with a seed dispenser as grains were transferred from combine to a lorry. Distribution uniformity of caplets in the wheat grains was assessed by sampling grain at the unloading auger discharge. The expected caplet concentration in the discharged grain was 7.3 caplets/*l*. The results showed uniform distribution of 7.2–8.2 caplets/*l* when the grain unloading rate was stable. However the concentration increased significantly as the grain flow dropped because of the constant dispensing rate of caplets. The barcode on the caplets would be scanned with appropriate scanners at grain handling points in the food chain. The size of the caplets was chosen such that they could be removed with a standard grain cleaner. However, due to the limitations the caplets without barcoded information were used and the performance of scanning was not evaluated in that study. In order to associate caplets with a location, they have to be scanned as they enter the grain or a set of caplets pre-allocated to a field.

Thomasson et al. (2008) have developed two types of tracers, starch-based and sugar-based, for insertion into grain for tracking it. The hardness of the starch-based tracers decreased significantly due to moisture in three week test. Sugar-based tracers were found to be suitably strong for handling and storing with grain. The barcodes printed on the starch-based tracers could not be read because of the surface properties.

A patented solution where RFID tags in magnetic casing are dispensed into the grain has been proposed by Hornbaker et al. (2004 & 2007). The RFID tags similar in size to grain are dispensed into the grain in a combine with a rate of one tag per 1.8 m^3 (Figure 2-19a), the tags travel in the grain and serve as electronic log books. At points of handling GPS time stamp and machine ID are stored into the memory space of the RFID tags.



(a) (b)

Figure 2-19 (a) Dispensing and (b) removal of RFID transponders in grain tracking after Hornbaker et al (2004, 2007)

The tracking tags are removed from the grain with a magnetic belt arrangement (Figure 2-19b). The reliability of this removal mechanism is clearly essential before the grain is milled. Although read/write tags are technically desirable, the recent market developments in cost noted earlier suggest a read-only serial number (e.g. 96 or 128 bit tag) linked to a database would be more economical.

Beplate-Haarstrich et al. (2008) used RFID tags encapsulated in epoxy resin as grain tracer. The experiment showed that tracers with density closest to the grain had lowest demixing ratio. However, the removal procedure of these tracers, which is essential, was not covered in the study.

2.8.6. Inventory control

RFID technology is widely used in industries other than agriculture for stock management. This applies equally well to all items of value in the farm business. These may be items such as agrochemicals or automatic identification of simpler machinery without ISOBUS connectors to tractor, but also workers. A tracking system of implements and drivers utilising RFID technology has been implemented by Pessl Instruments (2008). The controller of the system transfers the RFID, GPS, and other desired data such as weather information to the internet with certain time interval (e.g. 15 min) using the GSM-GPRS module. The main benefits from the system are claimed to be enhanced job management in terms of quality, precision of billing, logistics of machines, and responsiveness.

However, the main benefit is in tracking stock of the principal farm products, especially for a fresh produce grower/processor, where product cannot be stored for extended periods. Increasingly, food processing businesses have close ties with growers, where appropriate standard industrial stock control principles can link the requirements of the processing business to the harvest schedule of the grower. Tagging of product ensures the processing can identify the age and type of material before it leaves the business.

2.9. Review of Watts (2004)

2.9.1. Introduction

Particularly relevant work to investigate the monitoring and control of chemical inputs to arable farming systems was undertaken by Watts, as published in Watts (2004), and Watts et al., (2002, 2003 & 2004). The following aspects were examined: market perception, suitable automatic data transfer technologies, automatic identification, weighing and record creation of sprayer inputs, and architecture of a farm traceability system.

Market research in this 2004 study indicated that 95% of the poll respondents thought automatic record system would be useful addition to an agricultural sprayer. The integration of an electronic recording system into a contemporary sprayer with electronic control systems would represent a price increase of not more than 2% on a sprayer costing between £50,000–100,000. Watts (2004) concluded that a market does exist for such systems.

2.9.2. Suitability of barcodes and RFID

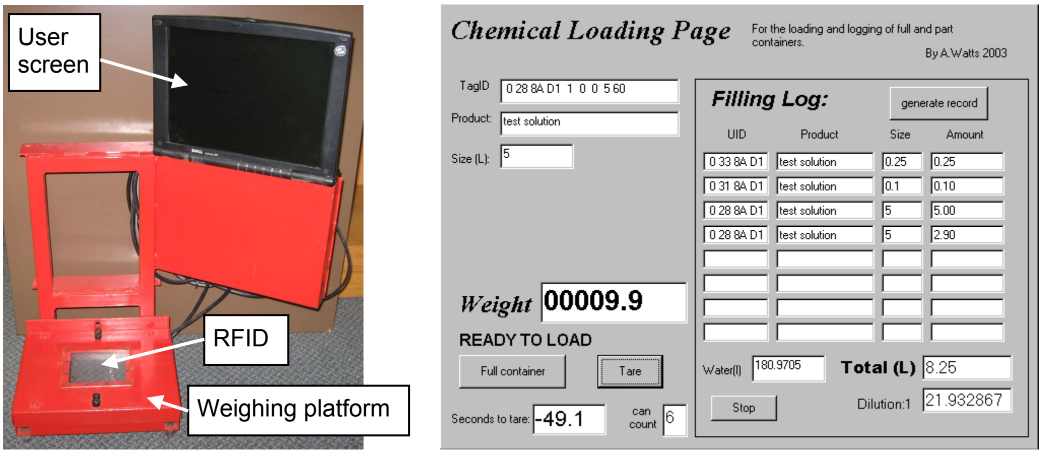
Barcodes were initially selected as a promising low cost method for automatic identification of products and transmitting data from product label to farm machinery. However, the trials proved that barcodes perform inadequately in the farm environment. Reliability trials with a barcode reader mounted on agricultural machinery indicated an average reduction of light transmission by 9% over a one year period due to surface contamination. That made reading barcodes almost impossible or, more important, erroneous.

RFID technology was found to be a robust solution for automatically transferring data in the agricultural environment. Passive RFID labels have sufficient storage capacity and their ability to transfer data is not affected by the surface contamination of the farming environment. Successful read rate during the reliability trials was over 99 %. Failures occurred normally because of grossly physically damaged labels.

2.9.3. Construction of the prototype automatic recording system

The Watts study designed and built a prototype automatic chemical input recording system which embodied a 13.56 MHz RFID reader, load cell weighing platform, and a portable computer to provide user interface, controller, and data storage functions (Figure 2-20a). This separate unit was mounted next to the induction hopper.

Based on the results of the questionnaire Watts (2004) developed a comprehensive user feedback display which includes current product details, tank filling log, water, dilution rate, remaining time to tare, and several keys (Figure 2-20b).



(a) (b)

Figure 2-20 (a) Weighing platform and (b) product loading screen (Watts, 2004)

The RFID hardware was located in the centre of the weighing platform. This had the consequence the RFID tag labels were located on the base of the agrochemical containers.

Because of the close proximity of RFID equipment and load cells, radio waves were found to interfere with the output of the load cell, affecting the achievable accuracy of weighing. That was overcome by programming the RFID and weighing to operate sequentially. However, switching the RFID reader took 3 seconds which caused a noticeable delay.

2.9.4. Performance of the prototype system

The analysis by Watts (2004) showed that load cells are suitable for determining the quantity of agrochemicals entered into the sprayer tank because of their versatility to measure both liquids and solids. This weighing platform was designed to take loads of 30 kg and the desired resolution was set to ±1 g. However, field trials of the weighing platform demonstrated that the desired resolution was not met. The best achieved resolution in working conditions after averaging was ±10 g. The limiting factors were the 12-bit resolution of the datalogger and vibration from the working machine. To overcome these problems Watts suggested the use of sampling frequency greater than 100 Hz and implement analogue signal filtering and software averaging.

A comparison of the automatic recording device with conventional manual methods showed that automatically measured values were more accurate than manually measured for the amounts larger than 1000 ml. The manual method was more accurate below 1000 ml. However, statistically there was no significant difference between the two methods (prescribed mean 1130.7 ml, automatic recorded mean 1140 ml, automatic dispensed mean 1134.4 ml, manual dispensed mean 1141.0 ml, SED 7.2 ml). The coefficient of determination of dispensed values versus recorded was marginally better for the automatic method with R^2 of 0.997 and 0.993 for the automatic and manual system respectively.

Investigating the loading cycle times, Watts (2004) found, the automatic recording system (68.5 s) was significantly (P=0.05) slower than conventional operation (53.2 s). However, when record creation time was also included the automatic device was faster by 4.3 seconds than conventional operation (72.8 s). The difference of 4.3 seconds was statistically significant at P=0.10.

2.9.5. Summary

The work of Watts is very significant in suggesting the suitability of RFID for the agricultural environment, and demonstrating the means to create automatic records of sprayer inputs with minimal operator intervention. However, several features are not present. These are discussed below.

The problem of RFID interfering with the load cell suggests the RFID hardware has to be relocated so that it does not cause interference with measuring system and will be able to read RFID labels placed on the sides of the containers where they are less likely to get physically damaged than on the base. The paper labels are normally attached to the side(s) of the chemical containers. Moulded tags would be more robust but they have to be inserted during the manufacturing of containers. If RFID labelling were implemented in a production context the tags would be applied as part of or underneath a paper label around the horizontal surfaces of the container. A covering paper label would also protect the RFID transponder.

The user interface should be simplified to meet the operational and environmental requirements. As standardised (ISO 11783) terminals become commonplace on tractors, the task management which requires a comprehensive interface for user communication can be carried out on the in-cab terminal and the specific loading functions extended to the user interface at the agrochemical induction/measuring device. This interface can then be designed a simple and robust task oriented device (following Figure 1-1).

The resolution of the weighing system of ±10 g achieved by Watts is not sufficient for the low end of application rates (Section 2.4.5). The main factor influencing the accuracy is the measuring noise induced by the operational tractor. In order to apply appropriate signal conditioning frequency spectrum analysis of the measuring signal has to be undertaken. Modern signal conditioning methods (Lyons 2004) suggest the use of digital filtering for noise suppression.

Because the platform was separate to the induction hopper, at least two measurements (the container has to be measured before and after dispensing) were required to detect the dispensed quantity. Such operation has no feedback in real time. Rather than being a separate weighing platform, the measuring system could be integrated into the induction system to improve the work rate and reduce the risk of operator and environment contamination due to minimised chemical handling. To take the full benefits of the demonstrated features of automatic recording, they have to be developed further to comply with the ISO 11783 communications standard for agricultural machinery which has gained acceptance in the industry.

2.10. Market requirement analysis

2.10.1. Workshop with stakeholders

A workshop on traceability study was organised by Gasparin (2009) and held at Cranfield University on the 30th of January 2007 with stakeholders. The objective of the workshop was to identify the stakeholders, i.e. market, requirements about traceability and to identify where further work needs to be carried out. The participants of the workshop were from the following organisations representing:

- AGCO — agricultural machinery manufacturers / sponsors.
- Patchwork — precision farming technology providers / sponsors.
- Cranfield University — academic research.
- Douglas Bomford Trust — academic research / sponsors.
- FarmWorks — farm software suppliers.
- Muddy Boots — farm software suppliers.
- Farmade — farm software suppliers.
- Cmi plc — food safety and assurance providers.
- Frontier — agronomy service providers, fertiliser handlers, grain marketers.

During the workshop, an insight into the principles of an automated agrochemical traceability system was given and an early prototype consisting of RFID agrochemical identification system and user interface was demonstrated.

2.10.2. Conclusions and recommendations from the workshop

1) Traceability system needs to comply with environmental protection schemes alongside with food safety and quality because it is a major concern of the market, particularly retailers. The purpose of various quality assurance schemes on the market is for the retailers to differentiate themselves from each other.

2) The traceability information has to be accessible by the customers in the food chain. However, it does not need to travel with the product. There should be one central

database, such as AFS (Assured Food Standard), to hold detailed traceability records, including agrochemical inputs. There is a need for a common data exchange standard. Traceability can provide an assurance that products are within certain quality category. Traceability has different value in different points in the food chain depending on the product and process.

3) Retailers perceive that they have strong traceability systems with their direct suppliers, however, they see issues with at the on-farm level. Therefore, farm traceability systems need to be sufficiently robust to satisfy their concerns. Retailers have the power to be driving force and demand extra traceability measures from the farmers.

4) For acceptance, the traceability system has to add value to the business. These values for the farmers and other bodies in the food chain have to be identified. Traceability is more than record keeping. Traceability data related to production system support the farmer in making managerial decisions, planning jobs, and running the business.

5) The traceability records may be allowed to be edited later to correct both technical and human mistakes. Raw field data may be misinterpreted when out of context. However, the authorisation, responsibility, extent, and procedure of edits have to be identified and well defined.

6) There should be a communication with agrochemicals manufacturers to see their opinion on RFID tagging of agrochemical products. There are difficulties with having an up to date and accurate pesticide database on the tractor to check products against legal proof. The best database in the UK is the PSD web database, although, it is not flawless.

7) Agronomist's crop recommendations are important. There should be no deviation from prescribed products. Specific products should be recommended not just active ingredients. As mixing of up to three-four products into a tank load is common, the compatibility of products is important and has to be followed. However, the operator may be confronted with different products containing the same active ingredient

when the parcel is delivered to the farm. Spraying has a seasonal nature, during the spraying time the demand for the products is high and the stocks of specific products may be exhausted, then the merchant may deliver a different product but with the same active ingredient which substitutes the original product.

8) Current practice is to recommend products by name. The storage of name on the automatic identifier, RFID, should be considered. However, agronomists could add registration number in the recommendations.

9) Rather than having a comprehensive database with all crop approval data on a tractor and a “mobile agronomist” system, the aim of the automatic recording should be to make sure that recommendations are followed and actions recorded.

10) Assurance does not give traceability, but traceability gives the tools to have assurance. Verification of agrochemicals, such as crop approval and expiry check, are more significant for assurance than traceability.

11) The user interface of an automatic recording system has to be as simple as possible. Visual aids, such as progress bars and pictograms, should be preferred instead of text. The units of measure have to follow the conventions: liquid chemicals to be handled in litres, dry products in grams.

12) Interface with existing hardware and software systems besides ISOBUS is of great interest. Connection to pocket PC’s is valuable for management systems.

13) An automatic recording system has to be useful as a practical management tool for a genuine honest farmer to improve the business, to identify errors, and to assure better use of pesticides. There are problems of dishonesty – the system will not work as policing tool or a totally foolproof traceability system if it relies too much on trust. The industry is not ready for full traceability and for a totally foolproof system. The automatic agrochemical recording system should increase the profitably for producers by improving the efficiency of the operation. It is recommended to construct the hardware, develop the software and go ahead with evaluation of the automatic recording system.

2.11. Conclusions

The following conclusions result from this review:

- Traceability is a regulatory requirement for the organisations in the food chain. Food safety and quality are of great public interest and related to traceability by consumers. Traceability is based on records collected about the history of a food product. Food safety alert systems use these records to trace the origin of the problem if required. Automated recording systems facilitate traceability.

- Current on-field application technology is capable of recording the spray applications and generating as applied maps. Farm software has the functionality to check the compliance of the spray application plan with the approved pesticide database. However, there is no subsequent automatic control or recording mechanism of the actual sprayer inputs. That remains a manual process.

- RFID has become a widely accepted technology for item level identification of products. RFID is proving to be an appropriate technology for the agricultural environment for agrochemical identification and other potential applications. However, currently the agrochemical manufacturers are not using the RFID labelling of agrochemical containers.

- There is an opportunity to view traceability as an integral part of management information gathering rather than a separate, costly process. An automated agrochemical traceability system would be a practical management tool for farmers. The raw traceability data from the farm has to be turned into a meaningful short summary for presentation to customers.

- Gravimetric measuring method and RFID technology are suitable for automatically recording the quantity and identity of agrochemicals as demonstrated by Watts. However, the automatic recording system by Watts requires improvements upon location of RFID device, user interface, resolution and accuracy of measuring, speed of operation, ergonomics and level of integration into the existing hardware and software. Analysis of the frequency spectrum of the measuring signal and digital signal conditioning is suggested for improving the measuring accuracy.

3. Automatic identification of agrochemicals

3.1. Introduction

Food traceability systems require identification of items involved in the food chain which can be achieved with automatic or manual data collection methods. The benefits of automatic methods are efficiency and reliability especially with larger amounts of data (Auernhammer 2002).

A traceable item, e.g. a container of agrochemical, should be appropriately labelled (Opara & Mazaud, 2001) so as to identify it to an automatic system (Chapter 4) and not require manual intervention. RFID has previously been demonstrated to be the best solution for agriculture (Watts et al., 2003 and Watts, 2004) – methods to use RFID for identifying and verifying agrochemicals are the focus of this chapter. The information originating from RFID labels would be used to verify the origin and validity of agrochemical product and facilitate traceability.

The automatic identifier complements the measuring systems by providing information about the physical characteristics such as the specific gravity of the product required for correct measurements of agrochemicals, which may be either liquid or dry form.

3.2. Product level and item level identification

Products can be identified at varying levels of precision, in this application, two levels are relevant, product level and item level. At product level the type of product is identified without differentiating individual instances within the type. That requires only information about the type of product to be stored in the associated database. The well established bar-coding technology is the best example of product level identification.

With the advent of RFID labelling, item level identification has become commonplace in the supply chain and stock management (Chapter 2). Item level identification adds the layer of item properties and requires details about each item to be stored in the database. Common practice in the supply chain is to keep a unique identifier on the RFID labels and associate it with an online data service (e.g. Object Naming Service). In that way relevant bodies can retrieve information from the data service about an item without the need to replicate and maintain a local database. However, every identification event requires access to that online service to retrieve meaningful information about the item. Otherwise, a comprehensive database has to be kept locally, introducing issues of distributing updates, version control and managing a large database in the case of mass-produced products.

Concerning agrochemicals, chemical manufacturers have requested information such as lot number, date of production and batch number to be included on the RFID label for logistics and quality management purposes (Döhnert, 2007). Logistics information such as article number is particularly relevant in supply chain management, where online access to comprehensive databases is guaranteed and the focus has been to deploy a solution which can resolve to a fine level and cover all likely future traceability needs. The unique serial number of RFID label provides item level identification and management in conjunction with these online database services.

3.3. Agrochemical data

3.3.1. Agrochemical paper label

A product label is a comprehensive stand alone set of data communicating to the user details of the requirements for safe, humane and efficacious use of the product (Figure 3-1). In the UK a product label has to abide by rules set in the Pesticide Labelling Handbook (PSD 2004) according to the Control of Pesticides Regulations (COPR) and Plant Protection Products Regulations (PPPR).

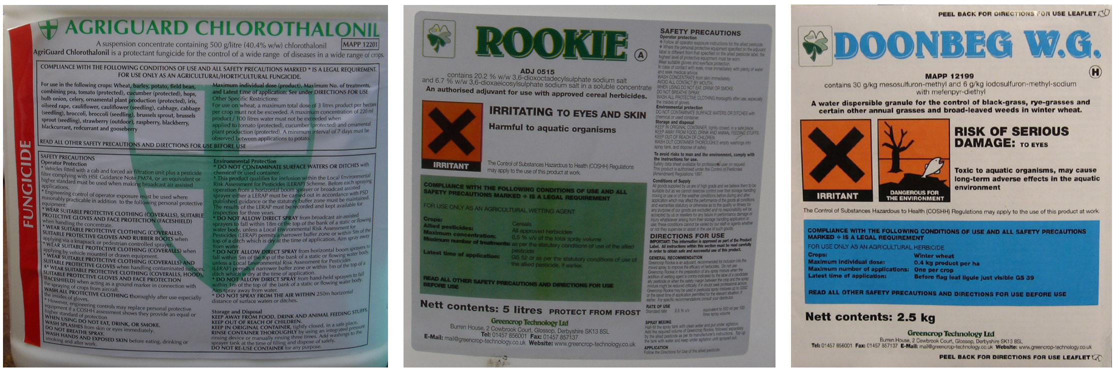


Figure 3-1 Examples of agrochemical labels

3.3.2. Registration of agrochemicals

In most countries, there are several publicly available pesticides product databases. In the European and Mediterranean region, a list of these databases (EPPO, 2006) is gathered by EPPO (European and Mediterranean Plant Protection Organization) an organisation with 50 (as of 19 September 2008) member countries responsible for European co-operation in plant protection. In the EU, active substances are harmonised in accordance with Directive 91/414/EEC (EC, 1991). Nevertheless, approval of individual pesticide products is decided by each member state. Individual countries have their own pesticide registration system.

The registration of products, management of the database, and the format of registration number of a selection of countries is reviewed below. The countries are selected based on the share of the world production of cereals, fruit and vegetables. China, USA and India are the largest producers according to FAOStat (http://faostat.fao.org/site/339/default.aspx, 3 Oct 2008). Europe produces high value crops with more technical, mechanised agriculture which increases the relative market interest for technology suppliers such as AGCO.

3.3.3. National agrochemical databases

PSD pesticides register of UK approved products

In the United Kingdom, the approval and use of agricultural chemicals, also named as plant protection products, is regulated by the Food and Environment Protection Act (FEPA), the Control of Pesticides Regulations (SI 1986/1510) and the Plant Protection Products Regulations which implements the EU directive 91/414/EEC regarding the placing of the plant protection products on the market. These regulations ensure that a pesticide product, when applied correctly, should not harm people, non-target species or the environment. The Pesticides Safety Directorate (PSD), an Agency of the Health and Safety Executive, is responsible for the approval and withdrawal of approval for pesticide products.

In the UK, every approved product carries a unique product registration number, a five digit MAPP number which stands for Ministerially Approved Pesticide Product number (PSD 2006b), and is allocated upon issue of the first commercial approval for a product or where approval is given for a significant change in identity for an existing product. Registration number can be used as a unique identification number of pesticide products.

PSD publishes the database of approved and registered pesticides on their website (PSD 2006a) where the products can be searched by their unique registration number. The database contains currently 3091 plant protection products.

EPA pesticides register of USA approved products

In the United States of America, pesticides must be registered both by the Environmental Protection Agency (EPA) and the individual states authorities before distribution and use (EPA 2006a). Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and state laws regulate the pesticides. Pesticides must be registered both by EPA and state before distribution.

EPA assigns a unique registration number (11 decimal digits) to registered pesticide products where the first part is the company number and the second part after a dash is the product number. The EPA registration number must appear on the product label.

The Pesticide Product Information System (PPIS) (EPA 2006b http://www.epa.gov/ opppmsd1/PPISdata/index.html) contains information concerning all pesticide products registered in the USA. The database files are presented in ASCII text to enable access with a variety of software. The basic registration information file is currently (19 September 2008) 9.2 megabytes and contains data about 69,039 agrochemical products.

BVL database of pesticides certified in Germany

Office of Consumer Protection and Food Safety, *Bundesamt für Verbraucherschutz und Lebensmittelsicherheit* (BVL), organises pesticide certification and application in Germany where a legal obligation to register pesticides has been in force since 1968 (BVL 2006a). BVL assigns a unique registration number with format nnnn-nn, where n is a decimal number in the range of 0 to 9, for every approved agrochemical. The approval is limited to a maximum of 10 years, after which a re-evaluation of product is required. BVL with support from Central Office of Rural Documents and Information, *Zentralstelle für Agrardokumentation und –information* (ZADI), runs an online database containing currently 1058 registered pesticide products (BVL 2008).

e-PHY database of pesticides approved in France

Ministry of Agriculture and Fishery, *Le ministère de l'Agriculture et de la Pêche* (MAP), co-ordinates pesticide registration and holds an online database, e-PHY (MAP 2006), of approved pesticide products. Every pesticide product has a seven digit authorisation number.

AGROFIT database of pesticides approved in Brazil

Ministry of Agriculture, Cattle and Supply, *Ministério da Agricultura, Pecuária e Abastecimento* (MAPA), assigns unique seven digit registration numbers to approved pesticide products. The online database AGROFIT (MAPA 2006, http://extranet.agricultura.gov.br/agrofit_cons/principal_agrofit_cons) contains currently 1303 products and is available via the internet.

China

Institute for the Control of Agrochemicals, Ministry of Agriculture (http://www.china pesticide.gov.cn/en/en.asp, 30 April 2009) controls the pesticide registration in China. The product information is available through Pesticide Information Network published by the Institute for the Control of Agrochemicals, Ministry of Agriculture (http://www.chinapesticide.gov.cn, 30 April 2009).

India

In India the registration of agrochemicals is regulated by the Insecticides Act 1968 (http://www.cibrc.nic.in/insecticides_act.htm, 30 April 2009) and Insecticides Rules 1971 (http://www.cibrc.nic.in/insecticides_rules.htm, 30 April 2009). All of the agrochemical products are reviewed by the Central Insecticides Board & Registration Committee (http://www.cibrc.nic.in/, 30 April 2009). The database of registered products is published by the Central Insecticides Board & Registration Committee (http://www.cibrc.nic.in/product.asp, 30 April 2009). Although registration numbers are allotted, they are not shown in this database.

Summary

This review has found that all pesticide products approved for use in major agricultural regions are assigned a unique registration number which must appear on the product label and which can be used as an identifier. Pesticide information is made publicly available through regularly updated databases. Some of the databases are very thorough containing a wide selection of data (Table 3-1).

Table 3-1 Summary of data fields of available pesticides databases

PSD UK	EPA USA	BVL De	e-PHY Fr	AGROFIT Br	China	India
Product name	Product name	Product name	Product name	Product name	Name	Product name
MAPP number	EPA reg. number	BVL reg. number	e-PHY reg. number	MAPA reg. number	Reg No	Validity status
Approval holder	Registrant name	Approval holder	Approval holder	Registrant name	Manufacturer	Type
Marketing company	Registrant address	Distributors	Holder's address	Pesticide type	Toxicity	Shelf life
Active ingredient	Distributor brand names	Product expiry date	Product type	Classification of toxicity	Active ingredient	Toxicity
Formulation type	Active ingredient	Pesticide type	Active ingredient	Environmental classific.	Validity status	Srop
Field of use	Formulation code	Active ingredient	Formulation	Action and application	Formulation	Pest
Crops	Site/pest uses	Formulation	Similar products	Hazards	Crop	Dosage
Amateur/profess. use	Pesticide type	Hazard data	Hazard data	Packing	Pest	Period from last spray to harvest
LERAP category	Toxicity category	Direction to use	Prudence	Formulation	Dosage	
Aquatic use	Registration status	Field of use	Toxicity	Active ingredient	Application method	
Aerial use	PC code	Crops	Comments for AI	Concentration of AI		
Approval level		Pest	Crop and reason for treatment	Crop and reason for treatment		
First approval date		Application rate	Directions for treatment	Application rate		
Product expiry date		Application directions	Application rate	Directions for treatment		
Available notices			Approval state			

However, they all include essential data fields such as:

- Product name
- Registration number
- Approval holder
- Active ingredient
- Formulation type
- Crops
- Date of expiry

The following example, Table 3-2, illustrates the registration number of the same product (fungicide Amistar from Syngenta) in reviewed national databases.

Table 3-2 Format of the registration numbers

Country	**Format**	**No of bits in binary**	**Example**
UK	nnnnn	17	10443
USA	nnnnnn-nnnnn	37	100-1164
Germany	nnnn-nn	20	5090-00
France	nnnnnnn	24	9600093
Brazil	nnnnnnn	24	10199
China	nnnnnnnn	27	20092501

3.4. Methods of handling data on RFID tags

Although the RFID technology standards are well established, a key issue remains of what information to write on the tag in order to have an effective and reliable system appropriate for the identification of agrochemicals. There are three logical ways to handle data:

1) Store all information currently on paper labels on the RFID label – local system.
2) Store only an identifier on the RFID label and require a database for all real data – item or product level identification, as defined by design.
3) Store minimal essential information on the RFID label and employ a secondary database to supply additional data – product level identification with optional item level resolution.

The first option requires a significant memory size as indicated by typical product labels (see Figure 3-1). The amount of text on selected labels ranges from 6576 to 11,140 characters with spaces. That is equivalent to 9.5 kilobytes of ASCII or 21.8 kilobytes of Unicode encoded plain text.

ASCII character encoding is based on the English alphabet (Haralambous, 2007). Each character is presented as a 7-bit code in computers or other electronic devices that work with text. However, because 8 bit systems are common on computers, ASCII is commonly embedded in an 8-bit field. Unicode, such as 16-bit UTF (Unicode transformation format), is the standard for digital representation of the characters used in all of the worlds written languages (http://www.unicode.org, 23 Oct 2008).

Considering the industry trend and, hence, low cost label availability, using RFID labels with this memory capacity would not be an economic proposition.

The second option is commonly implemented in other industries, and would be technically simple to implement – using only an identifier, name or registration number, and request all additional data from a database. That option makes the RFID label entirely dependent on continuous availability of a comprehensive and frequently updated database. Conceptually, this could be delivered easily over the internet, however, practical access in-field on a sprayer is a real problem at present time (Walker 2006). With the advance and increasing acceptance of wireless data transmission technologies on tractors such as Wi-Fi, GPRS, 3G the problem may be solved in many cases, but this is not yet the case, especially covering all worldwide markets.

The third option appears to offer a number of advantages, the RFID label can be read independently, to some extent, but need to reference a database for additional detail (especially at the item level) and verification when required. The reference between tag and database can be based on the national registration numbers and data which are already made available for such purposes. There are virtually no costs related to these databases because they have already been established and are offered freely to the public.

Using such a combined system also covers the issue of recording every individual container of spray product. If the label identifies the type of product this may be sufficient in many circumstances and the detail of the particular can or bottle (i.e. item) number in the read-only portion of the tag does not have to be verified at every stage. This greatly reduces the size of the databases required on-farm and frequency and size of database updates.

3.5. Agrochemical label RFID

3.5.1. Concept

The existing national agrochemical registration numbers and freely available agrochemical databases provide up to date information about approved agrochemical products. The discussion showed the need for independently usable electronic label which mainly identifies the type of product. This suggested that combining these enable the storage of a minimal amount of essential information on RFID labels and use existing registration numbers to reference national pesticide database.

3.5.2. Information on the label

The automatic recording system on the sprayer must be able to associate the registration number to a database, identify name, container size and specific gravity of the product to enable correct measuring.

As the registration number structure and format vary by country, a registration system identifier (country of registration) is required. The ISO 3166-1:2006 3 digit numeric code for the representation of names of countries is suggested to be implemented here.

Encoding container size allows the system to increase speed by loading whole-packs directly where appropriate. The range is from 50 g or 100 ml to 25 *l* (see Chapter 2). Recording a specific gravity gives the ability to transfer from volume to mass and vice versa in order to manage with application rates in *l*/ha (liquids) and g/ha (granules). It is approximately in the range of 0.28–1.28 g/ml being smaller for granules and larger for liquids (see Chapter 2). Specific gravity is affected by temperature, especially in countries like Brazil or the USA with a large temperature range. Inclusion of unit of measure gives flexibility in using units at both manufacturer and farm.

Product name is the primary means for humans to identify the product. However, product names are often long and ambiguous. The EPA pesticide database allows a width of 70 characters for product name. The longest name in PSD database is 73 characters. 70 characters requires 490 bit in 7-bit ASCII encoding, and 1120 bits in international character set such as UTF-16 (Unicode) for worldwide use. This occupies most of the memory capacity of commonly available RFID tags (2048 b). Thus, the economic method is not to store the name on the RFID tags but retrieve it from the database. The necessity to include full text product name depends on the availability of the database in a manageable form.

Logistics data such as article number or 96 bit EPC number may be required for traceability in the supply chain. The importance of the verification mark is explained below in section 3.6.

From this analysis, the minimum essential information to store on RFID tag is as follows:

- country of registration,
- chemical type (e.g. herbicides, fungicides, and adjuvants),
- registration number (main identifier),
- container size,
- unit of measure (g, kg, ml, *l*),
- specific gravity,
- verification mark,
- name (optional),
- logistics data (optional).

Figure 3-2 shows a diagram of a proposal layout of the data within the memory space on a label.

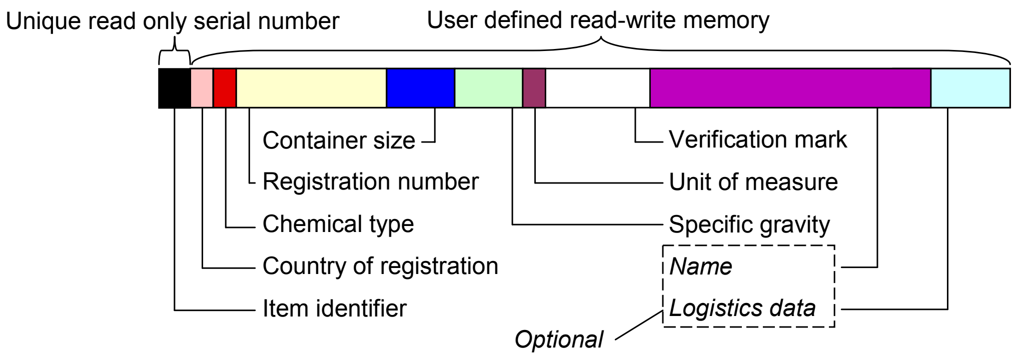


Figure 3-2 Proposal for the information on agrochemical RFID label

3.6. Verification of data integrity and security

3.6.1. Introduction

Analysis of market requirements indicates that the agrochemical industry is concerned about brand protection and traceability of chemical product origin. The recent report by the European Crop Protection Association points out the increasingly alarming problems with counterfeit pesticide products on the European market (ECPA, 2008). The spray application market has concerns with responsibility and data traceability. Currently the legal and practical responsibility for correct application is entirely on the spray operator, who is also responsible for making accurate records. However, in practice, an operator is often following directions of an agronomist, who has specified a particular application to a particular area. The use of automatic recording systems can provide an audit trail of actions for an operator, so that they can prove they have followed the application plan from the agronomist or other qualified person. If this audit trail is sufficiently robust, it helps to take some of the burden of responsibility from the operator in the field. This both more accurately describes the true source of the instructions and may prove a market advantage in selling automatic recording systems to operators.

RFID labels and other types of electronic product label are widely available on the open market, and can be written and rewritten. In order to use the technology for audit processes, features must be included to verify the source of the product referenced in the label.

3.6.2. Data verification methods

Widespread approach of data verification involves calculation of a check value from the recorded data and comparing it to a previously calculated check value in some way stored on the tag. Any differences between the original and derived check value indicates a communications error or alteration of data.

Cryptographic checksums are a good example of error detection and data verification techniques (Ralston et al., 2000). Cyclic redundancy check, a form of checksum, is used for detection of transmission errors in RFID (Finkenzeller, 2003). Hash functions compile a stream of data to produce a small digest (hash), via a non reversible function. Message digests are commonly used to verify file integrity, store passwords, and digitally sign documents. Even one bit changed in the original content changes the message digest.

Encryption is a two way operation to transform clear text to cipher text and back with an encryption key (Ralston et al., 2000). It is used to authenticate the source of information and make the content unintelligible to all but the intended receiver of the message. Asymmetric key cryptography involves a pair of cryptographic keys: distributed public key and secretly kept private key. “Digital signatures establish the origin of a message in order to settle disputes of what message was sent” (Ralston et al., 2000). In digital signature technology, a user operates a message with the private signing key to generate a signature (encrypted hash value) which depends on all the bits in the message and the private key. The signature is created in such a way that it cannot be economically forged by a user who does not have the original signing key, but it can be verified (decrypted) by anyone with the valid public verification key.

3.6.3. Data protection on RFID labels

Agrochemicals are high value products and subject to counterfeit (ECPA, 2008). Illegal pesticide products are untested and potential risk to farmers, environment, and consumers. Therefore, ways to protect data on RFID labels must be considered.

There are several ways to protect data on RFID labels from being tampered with. The majority of the methods use hash functions and public key cryptography in different forms (Sarma et al., 2002). These functions can be processed in an external reader or using on-chip processing. However, if cryptographic functions are set to be executed in tag with embedded crypto circuit, e.g. for encryption of data transmission, significant mathematic processing power is required. A promising method is suggested by Wong et al. (2006) for authenticating high value products where a valid EPC code is hidden in a pseudo-EPC code. However, it requires the reader to be authorised to unlock tags. In this system the readers are individually authorised and contain one half of the registration key. This constraint restricts the free applicability of the system due to the administration overhead of authorising and recording reader issue.

3.6.4. Digital signature scheme for agrochemical RFID labels

Pesticide databases in combination with digital signature technology provide a good opportunity to verify labels. A scheme is suggested whereby the manufacturer compiles data on an RFID label, compiles a message digest of the data and encrypts the data with a private key. Finally, they append the digital signature to the label as shown in Figure 3-3. A database, containing product info and public keys, is supplied to the farmer or contractor from a secure certified source, in a similar manner to trusted root certificates used for conventional internet transactions.

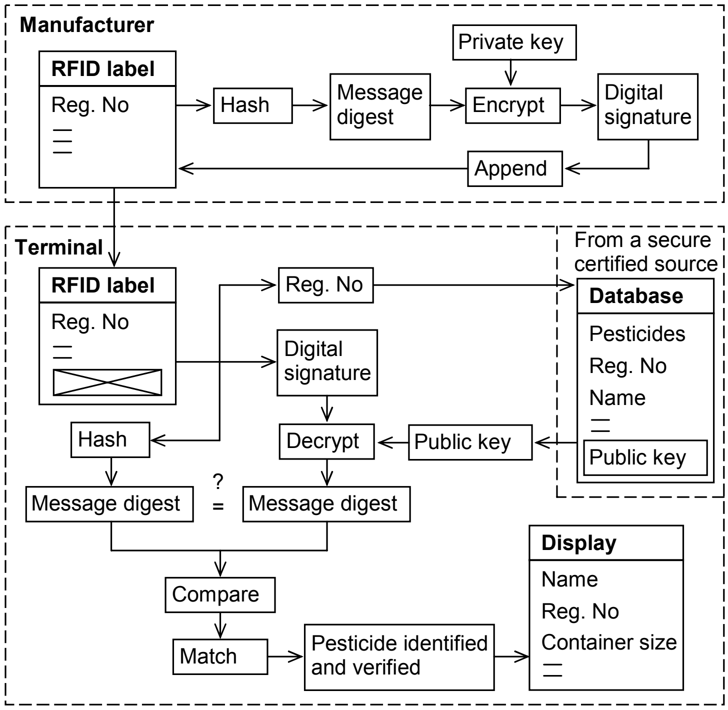


Figure 3-3 Digitally signed RFID product label

Software on the terminal at the induction hopper reads the data on the RFID label and calculates a message digest. Then it retrieves the public key from the database and uses it to decrypt the digital signature from the label. If these two message digests match then data found on label is intact and product verified. If the calculated hash value does not match the deciphered signature, either data stored on RFID label has been tampered, or not signed with the appropriate authorative key.

The solution presented above confirms data integrity and prevents falsified container sizes and signatures. In order to add more security against tag cloning, the unique serial number of each RFID label can be embedded into the hash. It would be more complicated to manufacture as the tags would have to be encrypted and written individually on the production line, but tamper resistance would be significantly higher as tags could not be cloned. On-line creation of tags also reduces the opportunity for accidental or deliberate release to the black/grey market of encoded, signed tags before they are attached to physical containers of product.

3.7. Encoding agrochemical data

3.7.1. Schemes

Resulting from the discussion above, all proposed data to be stored on a RFID label are decimal numbers except the product name. It is necessary to consider how these values will be encoded into the binary memory space on the label in an efficient and easy to read layout. There are three common ways to encode decimal numbers:

- ASCII characters
- Binary-coded decimals (BCD)
- Raw binary numbers

Resulting from the designed encoding schemes, Table 3-3, data can be recorded in 73 bits plus digital signature, logistics information, and product name. Whereas binary coded values are often presented in hexadecimal numbers (4 bit) then it is reasonable to round up to 4 bits as well.

Table 3-3 Memory allocation in bits in different encodings

Data	7-bit ASCII	4-bit BCD	**Binary**	Rounded to 4bit
Country of reg.	21	12	**10**	12
Registration No	77	44	**37**	40
Container size	21	12	**10**	12
Specific gravity	28	16	**11**	12
Type & Unit	14	8	**5**	8
Total	**161**	**92**	**73**	**84**

The preferred option is to use HF tags which can typically carry up to 2 kilobits of data. That allows enhancing the basic set of data with verification mark (up to 512 bits), and logistics information (e.g. 96 bit article number). There would be space for product name if required.

Theoretically, the basic set of data could be encoded on a UHF EPC 96 bit labels. These are currently the lowest cost RFID tags on the market and most commonly used for item tagging in retail (RFIDJournal, http://www.rfidjournal.com/). However, there would be then no room for security elements or logistics data. Also, the reliable operation of UHF frequency tags in proximity of metals and with items containing water, i.e. liquid agrochemicals, is challenging.

In practical use, agrochemicals are mostly prescribed by their name. If the market does not accept shifting to registration numbers in addition to names then name has to be included on the RFID label.

With the further progress of wireless data transmission technologies (WiFi, GPRS, 3G) they may become commonplace on agricultural machines and thus reliable access to a comprehensive online database may not be a problem. Then a low cost RFID transponder carrying just the identifying number may be sufficient.

3.7.2. Allocation in RFID transponder memory

The memory of RFID transponders is often structured in blocks (e.g. 32 bits) as indicated in the review (Chapter 2). Data can either be written by individual hexadecimal digits (rounded to 4 bits) or organised into one binary word depending on the availability of memory. The procedure of encoding data into labels memory is following:

- Conversion to binary.
- Conversion to hexadecimal.
- Creation of verification mark.
- Writing the data and verification mark into transponders memory.

The allocation of agrochemical data presented in Table 3-3 into memory space of a typical 256 bit ISO 15693 label is shown on Figure 3-4.

<table>
<tr><th rowspan="2">Block No</th><th colspan="2">Byte 1</th><th colspan="2">Byte 2</th><th colspan="2">Byte 3</th><th colspan="2">Byte 4</th></tr>
<tr><th>4 bit</th><th>8 bit</th><th>12 bit</th><th>16 bit</th><th>20 bit</th><th>24 bit</th><th>28 bit</th><th>32 bit</th></tr>
<tr><td>Block 0</td><td colspan="3">Country code</td><td colspan="5">Reg No</td></tr>
<tr><td>Block 1</td><td colspan="5">Reg No</td><td colspan="3">Container size</td></tr>
<tr><td>Block 2</td><td colspan="3">Specific gravity</td><td colspan="2">Type & Unit</td><td colspan="3">Checksum</td></tr>
<tr><td>Block 3</td><td colspan="5">Checksum</td><td colspan="3"></td></tr>
<tr><td>Block 4</td><td colspan="8"></td></tr>
<tr><td>Block 5</td><td colspan="8"></td></tr>
<tr><td>Block 6</td><td colspan="8"></td></tr>
<tr><td>Block 7</td><td colspan="8"></td></tr>
</table>

Figure 3-4 Memory allocation of agrochemical RFID label

3.8. Implementation of the proposed solution

Based on the above, the RFID controller on the sprayer is required to have the following functionality: read only one label per time, decode the data on the label, verify the data, and check the products validity in the pesticide database. The logical structure of the program to implement the required functions is described on the flowchart on Figure 3-5. Software to implement this functionality has been developed as part of this work as described in Chapter 4 and evaluated as described in Chapter 6.

3.9. Discussion

The proposed role of RFID tags is to assist in the reliable and robust creation of the traceable records of farm operations concerning agrochemicals. This solution focuses on "up" traceability – demonstrating the history of a farm product. It is also desirable that a system can deliver "down" traceability, so that, for example, a manufacturer can identify the current location of items of agrochemical product.

This could be incorporated, but would require additional infrastructure steps beyond the proposal, such as the voluntary submission of a list of currently held RFID unique ID values to a central list by farms. Such data could also be generated by the agrochemical distribution chain, submitted at point of sale when access to data networks may be easier. There are potential costs, however these could be offset by traceability benefits to manufacturers, and potentially to applicators, the prevention of theft or unauthorised use if it is widely known that chemicals are individually traced.

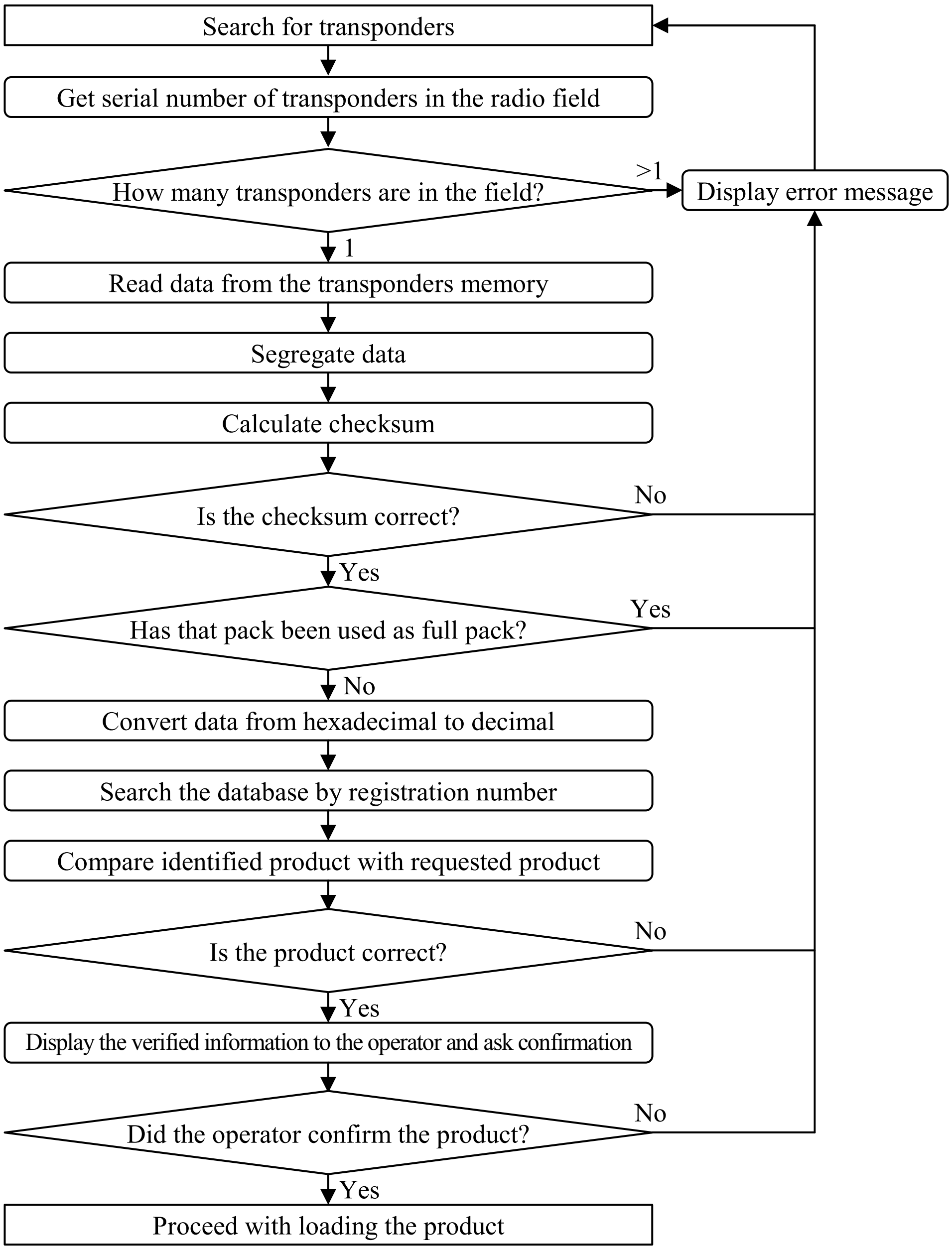


Figure 3-5 Flowchart of the automatic agrochemical identification

To adopt the RFID scheme the following issues have to be considered:

- the unconstrained availability of the national pesticide database of registered products in a form suitable for implementation on sprayers,
- the agreement as to which RFID tag type and data standard will be used,

- the labelling of agrochemicals with RFID tags,
- the implementation of RFID readers on sprayers,
- the accommodation of RFID tag data into ISO 11783-10 field records.

3.10. Conclusions

- Food traceability systems require identification of agrochemicals as inputs to food production. Automatic data recording methods provide efficient traceability information. A method to use RFID tags, appropriate medium for agricultural environment, to identify and verify agrochemicals in traceability systems has been proposed in this chapter.
- The review showed that all pesticide products approved for use in major agricultural regions are assigned a unique registration number which must appear on the product label and which can be used as an identifier. Pesticide information is made publicly available through regularly updated databases. That information can be applied with RFID tags to identify and verify agrochemical products as they are inserted into application system.
- The investigation showed that the most appropriate route is to store a minimal amount of essential information on RFID labels and employ a database for the storage of detailed data which makes the RFID label capable to identify the product type and other key parameters independently at any location with an RFID reader and greatly reduces the size of the database held on-farm because item level data is not held for all instances.
- From the analysis, the essential information to store on an RFID tag is as follows: country of registration, chemical type, registration number (main identifier), container size, unit of measure, specific gravity, and verification mark; optionally product name and logistics data.

- Digitally signed product label provides verified information about authenticity of the origin of the product which is an increasing concern. Sufficiently robust verified traceability records of spraying actions prove the compliance with prescribed application plan and help to reduce the burden of responsibility of spray operators.
- Encoding schemes have been designed which can record all of the above in 73 bits plus digital signature and optional items. Preferred option is to store the enhanced set of information on a HF RFID tag with a memory of 2 kilobits.

4. Design and construction of the automated agrochemical traceability system

4.1. Introduction

4.1.1. Objective

An automated agrochemical traceability system (AACTS) is an integral part of a robust on-farm traceability system. The current practice of handling records is chiefly based on log sheets of paper filled in by the operator following the visual identification of products and manual quantity measurement (Miller, 1999). A comprehensive automatic recording system capable of improving upon the manual practice must be able to communicate to and take commands from the operator, detect the agrochemical products to be applied, quantify the dispensed amount, and interface with the existing hardware and software. The objective of this chapter is to describe the design and construction of an automated agrochemical traceability system with such features.

4.1.2. Methodology

The engineering design of the automated traceability system, particularly the measuring system, follows the methodology of Pahl et al. (2007):

1) formulation of the task,
2) clarification and generation of the requirement list,
3) conceptual design leading to the working principle,
4) embodiment design determining the layout and form.

Construction of a prototype follows the design. The objective is to generate the pointers of detail design for subsequent development of a commercial prototype.

4.2. Current practice of dispensing

Conventionally, agronomists give to the sprayer operator a crop management recommendation sheet, which contains field name, crop area, reasons for treatment, product rate per hectare, water volume, comments, and other relevant information. The operator works out the total volume of solution, number of tank loads, total amount of chemical products and a detailed plan of chemicals per tank load based on the recommendation, legal requirements and responsibility. Chemicals are usually dispensed volumetrically from the manufacturer's packs using jugs or measuring cylinders. It is common practice (Appendix B) to assume the pack size of a container is accurate, and load a whole container where appropriate to the recommendation. Some operators extend the practice by visually judging a half container increment.

To increase the work rate a field may be treated simultaneously with multiple chemicals rather than a single product providing there are no issues of compatibility (O'Mahony 2003). This judgement is made by the agronomist and sprayer operator based on product label. Mixing chemicals in this way further complicates the process and introduces a greater potential for error in calculation. Any application errors have greater consequences as they apply to all products in the tank mix.

The main rule from operator's point of view is not to go over the maximum rate set by the chemical manufacturer. It is legally acceptable to use less than the maximum rate, however this may lead to ineffective treatment, with potential loss of crop performance through delayed application, or costs of later reapplication at the correct rate.

4.3. Structural design of the system

The facilities to pre plan the field activities and prepare an electronic task file describing a job plan are already in place. After planning, functionality exists to receive and manage an electronic task file and record field application of chemicals using in-cab terminals. These terminals are increasingly available as part of original equipment or added to provide convenience features in the aftermarket. Thus the rational way to design an automated traceability system is to complement the existing hardware and software by developing and integrating the functions which are currently missing.

The functional requirements of the automated traceability system are:

- identification of products to be inserted into the application machinery,
- metering of prescribed quantities of products,
- automatic generation of electronic traceability records,
- input and output of information, i.e. task file and records,
- interaction with the operator.

With such structure (see also Figure 1.1 Chapter 1) the activities are logically divided between the farm computer, tractor terminal, and the prototype system. The prototype system is focussed to direct and record the procedure of loading the products into the sprayer efficiently.

The overall functionality required leads to the following specific points:

- product identification system,
- measuring system,
- user interface,
- real time software,
- data interface with the existing tractor information system (ISOBUS).

4.4. Chemical quantity measurement

4.4.1. Task

The function should quantify a dispensed amount of agrochemical in a form suitable for automatic recording by other parts of the system.

An electronic measuring system capable of measuring prescribed forms and amounts of agrochemicals and delivering records of measured quantities provides a solution.

The task is to design a measuring system with the following properties:

- Input agricultural plant protection products sold to the farms.
- Capable of measuring both liquids and granules.
- Compatible with the packaging of the chemical products.
- Capable of handling available range of application rates with adequate resolution, accuracy and speed.
- Performance as good as or better than conventional manual method.
- Integration with existing sprayer hardware and software.

4.4.2. Design factors

Before conceptual design, the task has to be clarified by identifying and looking at the significant design factors.

A key requirement is a high speed method of transferring products into the sprayer. The number of available spraying days per year is small because of constraints on weather conditions and plant growing requirements. Thus, spraying is a very time pressured job which has to be done as swiftly as possible when the window of opportunity is there. To be desirable to operators, loading speed has to be equal or better than for manual loading. The market is expecting improvements in speed (Spackman, 2008).

Packs of chemical delivered to the operator have already been dispensed into the pack for sale with a high degree of accuracy. Therefore when a particular tank mix requires a quantity of chemical equal or greater than a pack size it is logical to allow whole packs to be identified and placed in the induction system (including pack rinsing) without repeating the quantity measurement. The RFID system described in Chapter 3 describes the elements required to enable this functionality. Quantities smaller than one pack require a measurement function.

Safety through minimising the operator and environmental exposure to toxic chemicals, thus minimising the handling of chemicals is also very important. The best method in terms of minimal risk of contamination is the closed transfer system. However, there are still issues with commercial uptake, standardised interface with the chemical containers as indicated in the review in Chapter 2. Induction hoppers are a widely used aid

(Section 2.5.1), hence, the preferred solution is to integrate the measuring system into the induction hopper to exclude the need for a separate metering vessel, so that the operator could pour the product directly into the hopper.

Agrochemical products are delivered to the farm as liquids or dry material. There are two ways of measuring materials – gravimetric and volumetric. The manual volumetric metering method is based on pouring the material into a graduated jug where the graduation marks are usually printed or moulded on the side of the jug. Automatic volumetric metering is based on flowmeters. Gravimetric measuring involves weighing forces from gravity acting on the mass of material. Liquid chemicals are traditionally measured volumetrically with a jug with appropriate size and resolution (Miller, 2003a). Granules are also normally measured volumetrically with an appropriately graduated jug. Generally balances for gravimetric measurement are not to be found in farm chemical stores. The best resolution achieved by conventional manual dispensing methods is typically stated to be 5 g or 5 ml (Miller 2006).

The task requires a measurement system compatible with both forms of material. The review by Hughes & Frost (1985) demonstrates that common flowmeters do not have sufficient accuracy with highly viscous fluids such as some agrochemicals and cannot be used with granules. Therefore, a gravimetric technique is proposed as more suitable. Then the specific gravity of volume based chemicals has to be provided in the product identifier as discussed in Chapter 3.

The sources of uncertainties in the whole process of transferring product from the original packaging to the sprayer and applying to the field are summarised in Figure 4-1.

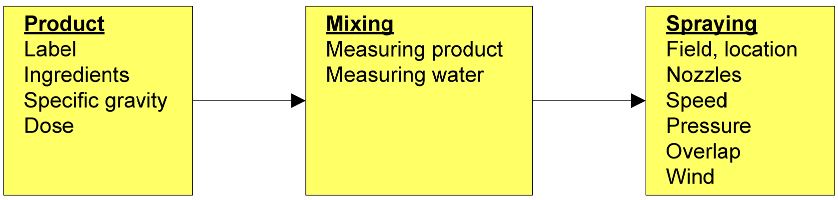


Figure 4-1 Sources of uncertainties in applying chemicals

The application rate of agrochemicals ranges from 12 ml/ha to 5 *l*/ha as reported in Chapter 2. Sprayer nozzles shall have a discharge rate within ±5% (i.e., range of 10%) of the nominal value according to the standard (BSI 1989). Miller et al. (2008) suggest the quantity of material loaded into the sprayer should be resolved to this 10% level, i.e. 1.2 g. Thus, the ideal measuring system should have a resolution of 1.2 g when a minimum area of 1 ha requires spraying. Commonly, the sprayers are capable of treating 10 ha per full tank load based on the report by Garthwaite (2004). Hence, the required resolution per tank is 12 grams.

The measuring system is required to be compatible with all commonly available chemical packaging and specified application rates. The largest available containers subject to manual lifting are 25 *l*, as the maximum allowed package weight of 25 kg is set by the manual lifting guidelines (HSE, 2004). However, it was found in the review in Chapter 2 that the most common size range is 1–10 litres. Watts (2004) designed a weighing platform for the maximum available container size. With the resolution achieved in that study (±10 g), the platform was capable of measuring in the range of 200 g to 30 kg with an error less than ±5% (Table 4-1). However, the investigation in this work suggests designing a refined specification of 12 g to 13 kg.

The measuring system is required to deliver a work rate equal to or ideally greater than the manual loading method. In trials of their proposed system, Watts (2004) found that time per container for one agrochemical was 53.2 s without record creation and 72.8 s with record creation time for the manual loading and 68.5 s for the weighing platform.

Table 4-1 Performance of the existing weighing system vs. recommended

Feature	Existing (Watts, 2004)	Recommended specification
Range	200 g – 30 kg	12 g – 13 kg
Resolution	20 g	1.2 g
Resolution of full scale	0.067 %	0.0092 %
Time per container	68.5 s (68.5 s)*	53.2 s (72.8 s)*

* – Time in brackets is with record creation. Statistically different at P=0.10

Agrochemical products contain substances harmful to humans and environment. The induction equipment is required to have a rinsing system to clean equipment and containers after the task has been completed. The requirement of rinsing applies also to the measuring system because it is in direct contact with chemical products.

The materials in contact with the chemicals are required to resist the aggressive effect (corrosion) of these chemicals. Therefore the chosen construction materials have to be corrosion resistant. The induction hoppers are made of stainless steel or hard plastics. These materials are recommended for the measuring system.

The operating conditions require the metering system to work in a rough environment, i.e. mechanical and electrical noise, dust, and water. The system has to be capable of working on a fully operational sprayer and withstand temporary immersion to water (protection level IP67) as the induction hopper may become completely full during loading and rinsing. The external parts outside induction hopper have to be protected against water jets and dust (protection level IP66).

4.4.3. Design specifications

Task clarification and analysis of requirements, quantities, and qualities results in the following specification of the measuring system:

- Content – available forms of agrochemicals, i.e. viscous liquids and dry matter.
- Compatibility with a range of standardised containers – 1.0, 3.0, 5.0 and 10.0 litres. Closure 45–50 mm on 1.0 litre size and 63 mm on other sizes.
- Measuring method – gravimetric.
- Measuring range 12–13,000 g / 12–10,000 ml.
- Resolution 1.2 g.
- Resolution of the full range 0.0092%.
- Speed of operation – whole cycle time less than on manual (72.8 s).
- Minimise operation effort as far as possible within cost constraint.

- Safe operation – no spillage or contamination to the operator. Compliance with requirements for induction hoppers.
- Tank mixing – effectively load multiple agrochemicals per tank.
- Dimensions – has to fit in a standard induction hopper (BSI 1996a)
- Rinsing included with pressurised or free flowing water. Compliance with requirements for induction hoppers (BSI 1996a).
- Operating conditions – mounted to a fully operational sprayer. Affected by mechanical vibration of the working machine and electrical noise.
- Chemical resistance according to requirements for induction hoppers (BSI 1996a).
- Dust and waterproof to IP66 (powerful water jets) or IP67 (temporary immersion in water if the hopper is completely filled).

4.4.4. Conceptual design

The objective of the conceptual design is to produce the specification of a principle solution (concept). The first step in conceptual design is to abstract and generalise the requirements to identify the essential problems (Pahl et al. 2007). In this case, the task is to measure out prescribed quantities of agrochemicals both in liquid or dry form from their original packaging, indicate and record the quantity, and deliver the chemical into the induction system of a sprayer.

Function structure

The function structure can be established by breaking it down into subfunctions based on the flow of energy, material and signals (Figure 4-2). The flow of measurable material – agrochemical – is the process of transferring the required quantity of it from the original packaging into the induction system of the sprayer. Whilst hold, the signal of dispensed quantity is generated and measured.

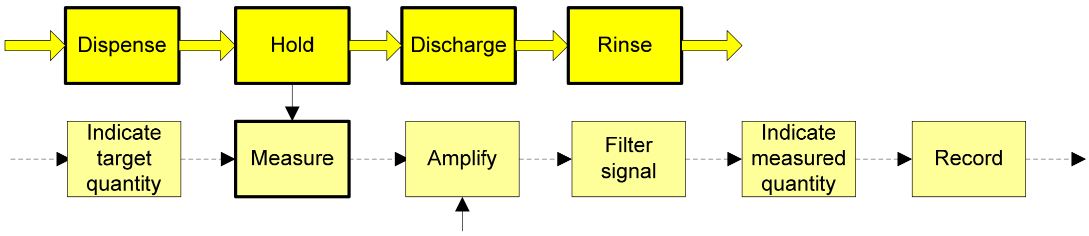


Figure 4-2 Function structure of an agrochemical measuring system

Indication of target and measured quantity are accomplished through the user interface screen and appropriate functions in the controller software. Amplification can be easily achieved by the choice of an appropriate device. The filtering task will be analysed once the embodiment has been realised and the level of problem identified (see Chapter 5). The important solution-determining functions here are the actual measuring function and the functions related to the flow of agrochemical product: dispense, hold, discharge, and rinse.

Working principles

A number of possible solutions for subfunctions are presented on Figure 4-3 with the most suitable solutions highlighted. The arguments for the selection are discussed below.

Subfunction	Solution		
Dispense	**Pouring**	Suction probe	Closed transfer
Measure	Continuous flow	**Static quantity**	–
Contain	Induction hopper	**Special weighing container**	–
Discharge	Automatic	Semiautomatic	**Manual**
Rinse	**Free flowing water**	Pressure jets	–

Figure 4-3 Classification scheme with possible solutions for the subfunctions

The agrochemical product has to be dispensed into the measuring system. Pouring is the most common method of transferring agrochemicals from their original packaging into the induction system of the sprayer (Miller 2003a). It is compatible with induction hopper and all of the commercially available container types (see Chapter 2).

A suction probe is a semi closed transfer method where the end of the probe is dipped into the product (through the neck of the container) and material is transferred to the sprayer. It can be used successfully only for liquids because granular materials may adhere to themselves, forming a lump and may be very difficult if not impossible to transfer through the probe. Practical tests suggest a suction probe arrangement is cumbersome and slow to use Miller (2003a). Fully closed transfer systems require a standardised container design to match with the coupling on the induction system. Most of the existing systems are only for liquids.

There are methods to measure the flow of mass continuously. One of these used in combine harvesters is deflection plate mass flow meter. The principle of working is to measure the mechanical deflection caused by continuous stream of material as it strikes the flow meter's sensing plate. Saunders (1997) has developed a double inclined plane transducer system based upon the principles of force reaction, to measure the true mass of reasonably free flowing granular materials. The system was built for combines to use at flow rates from 1 kg/s to 10 kg/s and performed with accuracy better than 0.9%. However, viscous liquids may stick to the sensing plate, introducing forces not related to mass flow, which makes deflection plate inappropriate for the case.

To measure mass of a discrete quantity, the material has to be held in the metering device. In the discussion above the requirement of operation within the induction hopper was set. The first option is to instrument the whole induction hopper in a way that the weight of hopper is measured. In that case the product can be transferred directly into the hopper. However, the exacting resolution of 1.2 grams suggests the following problems achieving it. The induction hopper has a relatively high mass compared to the smallest measurable quantity. The dynamic flow of water/dilution through the hydraulic connections and hopper is a significant source of measurement noise. The solution is therefore a smaller container on a weighing system which holds the products for the time of measurement. This container can logically be placed within the induction hopper as stipulated in the design requirements above. That arrangement allows the operator to transfer the product directly into the induction system which is both safe and practical. It benefits from the reduced risk of spilling the chemical by reducing the handling operation to minimum. Minimised handling also means less time is consumed for the operations. A system without external parts is compact and protected from mechanical damage that may occur while the tractor is driving to and on the field. An integrated container may also be rinsed directly within the induction hopper; an externally mounted container would need a catchment system.

The product has to be transferred to the induction system after weighing. To discharge the weighing container, it can be tipped over or equipped with an outlet valve. These operations in turn may be manual or automated. Manual action is the simplest where the operator has a lever or a handle to operate the valve or tip the container. Automated action requires a suitable actuator synchronised with the rinsing system. Simple electrically driven solenoid valves are available but small clearances suggest problems with rinsing and large diameter valves have dimensions difficult to fit in the confines of the induction hopper.

The surfaces that are in contact with agrochemical products have to be cleaned after the completion of the job. Induction hoppers are equipped with a rinsing system where a perforated channel or a pipe is fitted on the top part of the hopper around the perimeter. Logically that can be extended to rinse the weighing container as well.

Solutions to achieve the specified resolution

The capacity of the weighing container has to be carefully considered in order to achieve the specified resolution and accuracy. The desired resolution of 1.2 grams in a range of 13,000 grams sets a very high requirement (0.0092% of full scale) to the measuring system. In practice, there are sources of error such as the mechanical vibration from the diesel engine, wind, electrical noise and computational which influence the accuracy of the measuring system. Possible solutions to achieve the specified resolution are listed below and the concepts investigated in more detail:

- Very high precision data logging
- Multi range weighing system
- Summation of small quantities, i.e. multiple sequential measurements

Theoretically to date 16-bit dataloggers can achieve the required resolution in a single range: 1 part in 2^{16} is 0.0015 %. However, the practical accuracy of 16-bit dataloggers is one order of magnitude lower than that (Table 4-2). Hereto, including sensor and measurement noise, it means the desired accuracy is not achievable in practice in that way.

Table 4-2 Practical performance of 16-bit dataloggers based on product data sheets

Datalogger	Resolution	Accuracy	Linearity
Iotech LogBook £2725	0.00153%	± 0.01% FS	± 1 bit
Iotech Personal Daq £1021	0.00153%	± 0.031% reading + 0.009% FS	± 1 bit
Campbell CR3000	0.00167%	± 0.04% reading + offset	n/a

It would be possible to design a mechanically dual range weighing system with two weighing containers (larger and smaller) with a resolution in the same order as Watts (2004) then the resolutions would be as listed in Table 4-3. However, these containers have to be accommodated into the restricted space of the induction hopper. A dual range system adds complexity and duplicates the cost because effectively two weighing systems are required.

Table 4-3 Possible ranges and resolutions for weighing platform in grams

Range	Resolution
5000–12,000	8.0
1000–6000	4.0
12–1200	0.8

The concept of multiple measurements is to design a measuring system with relatively limited range which splits the requested quantity and measures it in small amounts sequentially. If the range is limited to 1000 g for instance, then it is practically possible to achieve the required resolution of 1.2 grams. Error adds up if weighing in small amounts consecutively but error multiplies if increasing the range. With this method, the mechanics of the system can be relatively simple and most of the engineering can be carried out in the software. However, extra time is taken to make many repeated measurements.

4.4.5. Weighing container solution

As a result of the investigation above, the principle solution is a weighing container inside the induction hopper. There are several conceptual implementations to consider, these are discussed below:

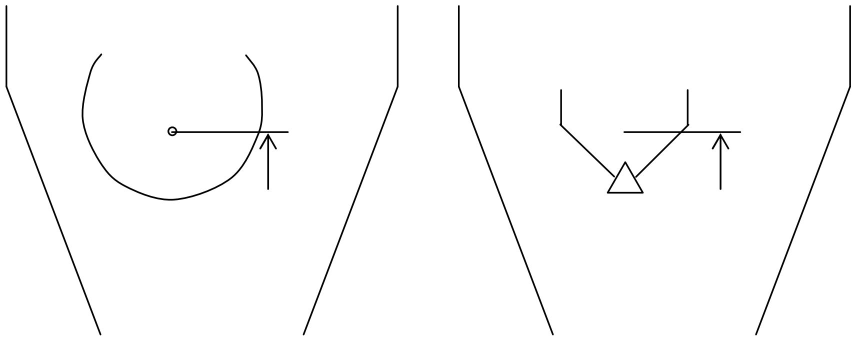
- Weighing arm with a detachable jug
- Fixed weighing container
- Pipe with a motor driven valve on top of a container

Weighing arm with a detachable jug

This variant involves a weighing arm placed inside the induction hopper which holds a detachable jug. To discharge and rinse this the operator has to unhook the jug from the weighing arm. Although, the construction of the weighing arm is relatively simple, the discharge and rinse operation requires extra effort from the operator. There a risk of contamination when touching and moving the jug. The advantages are ease of replacement and use of different size jugs.

Fixed weighing container

Alternatively, a suitable shaped weighing container can be fixed on a weighing arm. In order to discharge, the container can be pivoted (Figure 4-4a) or equipped with a valve on the outlet (Figure 4-4b). The discharge function can be actuated by the operator directly by tipping the container or through a mechanical linkage to remove the operator from the contaminated areas. The rinsing mechanism has to be a water jet directed into the sphere when it is in inverted position. An upright fixed container can be rinsed with free flowing water similarly to the main induction hopper. The advantages are the ability to see the surfaces whilst rinsing. The handle for the valve can be located into uncontaminated area outside the induction hopper in a convenient place for the operator to minimise the effort.



(a) (b)

Figure 4-4 Induction hopper equipped with (a) a tripping sphere shaped container or (b) a funnel with outlet valve

Pipe with a motor driven valve on top of a container

As a combination of a closed transfer system with an induction hopper, the agrochemical container with a pipe-valve plugged on it, is placed on the induction hopper and the valve slotted in a socket (Figure 4-5). The socket has a motor which drives the valve. The external motor can be a simple stepper motor or an electric solenoid actuator. Chemical is dispensed through the valve to a weighing container. The diameter of the valve can be chosen according to the viscosity of the chemical in order to speed up the loading of viscous liquids or increase the dispensing precision of low viscosity liquids. The valve can be chosen a cheap plastic disposable type. Each time when the container is filled to a requested amount it trips. Eventually the weighing container is rinsed automatically with a water jet. The rinsing cycle may be programmed to occur after each trip. The safety of the operator is maintained because the operator does not have to pour out the chemicals, and the measuring system dispenses chemicals without operator intervention.

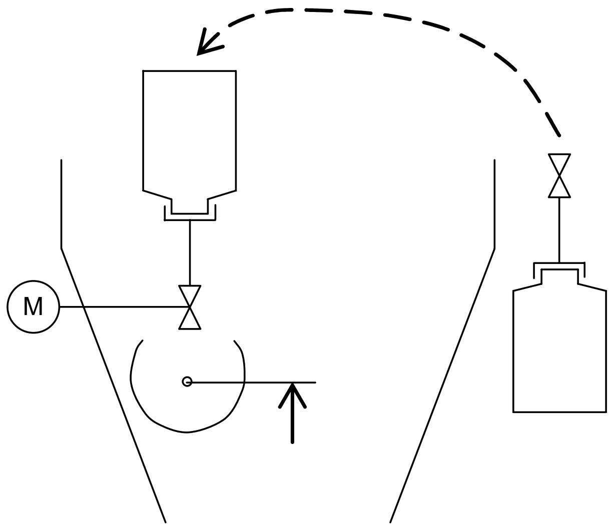


Figure 4-5 A design with a motor driven valve plugged to a container

4.4.6. Selection of the conceptual solution

After carefully considering all of the variants, it was decided to continue with the embodiment design of a conical/pyramidal shaped weighing container built inside an induction hopper and equipped with a manually controlled outlet valve.

The investigation above indicated required resolution is achievable with a weighing container with a capacity of about 1000 ml/1000 g. A basic feature, the selected solution is compatible with all of the container types as specified for standard induction hoppers. The chosen variant has a relatively simple construction and is compatible with many more advanced concepts such as a closed transfer system with an interface on the lid of the induction hopper (e.g. Chemlock, see Figure 2-4).

The shape of a cone/pyramid fits into the similarly shaped induction hopper and simplifies the cleaning of the surfaces with free flowing rinsing. The sprayer operator is able to monitor the surfaces during the rinsing cycle and ensure they are cleaned. Only one moving part, the outlet valve, is required.

The discussion in the following sections describes both the embodiment design of an initial prototype to illustrate the key issues, and then covers the improvements made to the initial prototype after construction and first trials.

4.4.7. Embodiment design

During the embodiment design the overall layout, geometry, shapes and materials are determined. The basic rules of embodiment design according to Pahl et al. (2007) are clarity, simplicity and safety. These rules are the leads to meet the general design objectives: fulfilment of the technical function, economic feasibility, individual and environmental safety.

Geometry

The problem to be solved is how to accommodate the main components of the weighing system – a funnel shaped container, a load cell, and the outlet valve with its supporting and driving mechanism – into the induction hopper in a technically sound way.

In order to achieve good resolution, the load carrying capability of the load cell has to be matched with the required range of the weighing system (ca 1000 g). The load cell has to carry the measured product and additional weight of the components of the system. Thus, the aim is to use lightweight materials where possible to reduce the extra weight. The materials and equipment placed into the overall induction hopper have to be corrosion resistant and tolerate immersion into water.

The starting point of the embodiment design is a standard stainless steel induction hopper manufactured by Watson & Brookman (Engineers) UK and used worldwide. Induction hopper market is very specialised and that type of hopper is representative. The opening of the hopper has dimensions of 258×384 mm (Figure 4-6a).

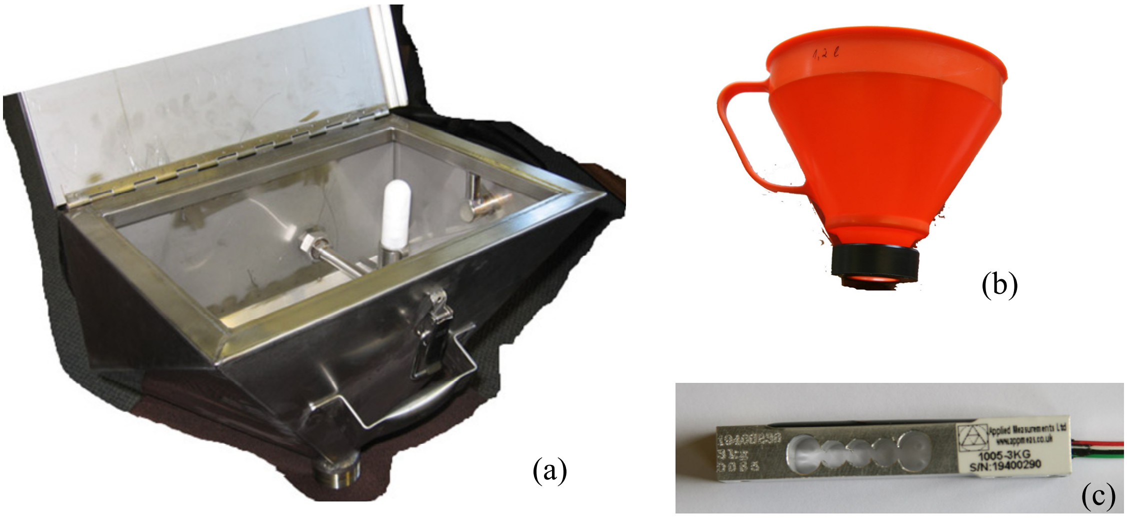


Figure 4-6 (a) Induction hopper, (b) funnel, (c) load cell

A suitable funnel was found from a commercial supplier’s catalogue (RS Components). A standard funnel with opening diameter of 155 mm and neck diameter of 30 mm and resistant to chemicals is suitable (Figure 4-6b).

Due to the space constraints, the load cell has to be compact size. Load cell OBUG-1005 (Applied Measurements, UK) was selected for this application (Figure 4-6c). The load cell is a bending beam “binocular” design dual cantilever (Anon 1982) with four strain gauges wired into a Wheatstone bridge. It is moment insensitive and has single point load attachment, compact dimensions, nominal range of 3 kg, and sensitivity of 1.46 mV/V at rated load (Appendix C).

The load cell has to be placed into the induction hopper so that is protected from overloading and lateral stability is provided.

Valve mechanism

The important part of that solution is to design a reliable valve mechanism. The required functionality is as follows:

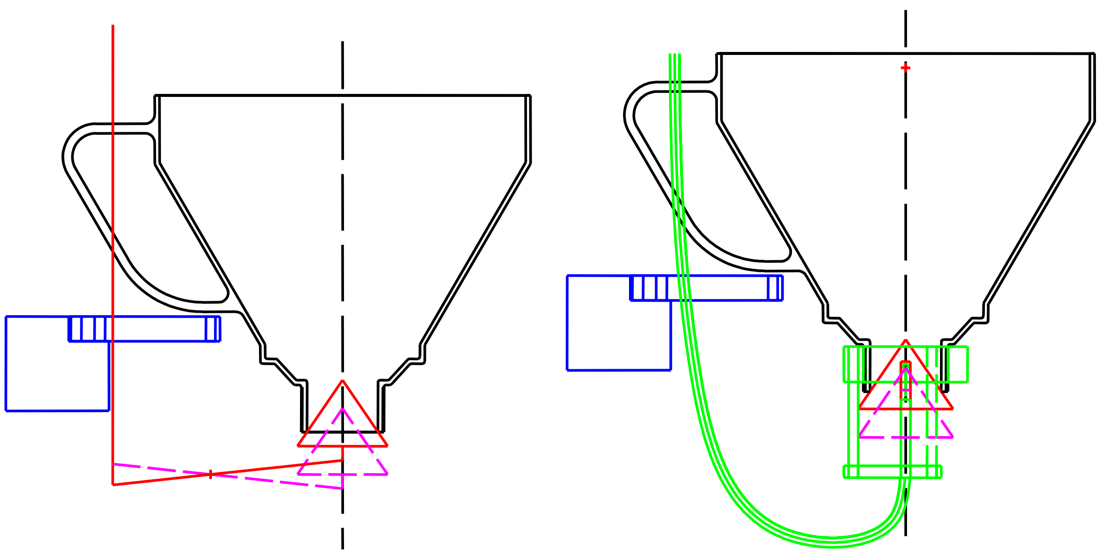
- Secure seal (no leaks during the time of measurement).
- Easy cleaning.
- Opening movement in the output direction of the funnel.
- Minimum effect of the valve actuating mechanism on the load cell.

The preferred location of the valve actuating mechanism is outside the funnel. So that it does not disturb filling and that the mechanism is outside of the directly contaminated area. A reasonable place for the operating handle is outside the induction hopper, as it is less likely to become contaminated and is a safe and convenient place for operator use.

Options for the valve control mechanism are as follows:

- Rod-arm mechanism (Figure 4-7a)
- Flexible mechanical wire
    - Centre attachment (Figure 4-7b)
    - Pivoting arm (Figure 4-8)

The flexible mechanical wire acting on the pivoting arm is the best option in terms of simplicity, flexibility, protection of the spring, separation of vertical and horizontal forces (interference with load cell). A similar mechanical wire mechanism is used on the Berthoud sprayer to operate the valves of the induction hopper (see Figure 2-1 Chapter 2). A coil spring was chosen to keep the valve shut based on the calculations of hydrostatic pressure and clamp force to seal the valve (Appendix D).



(a) (b)

Figure 4-7 Valve control mechanisms: (a) rod-arm, (b) wire attached to the centre

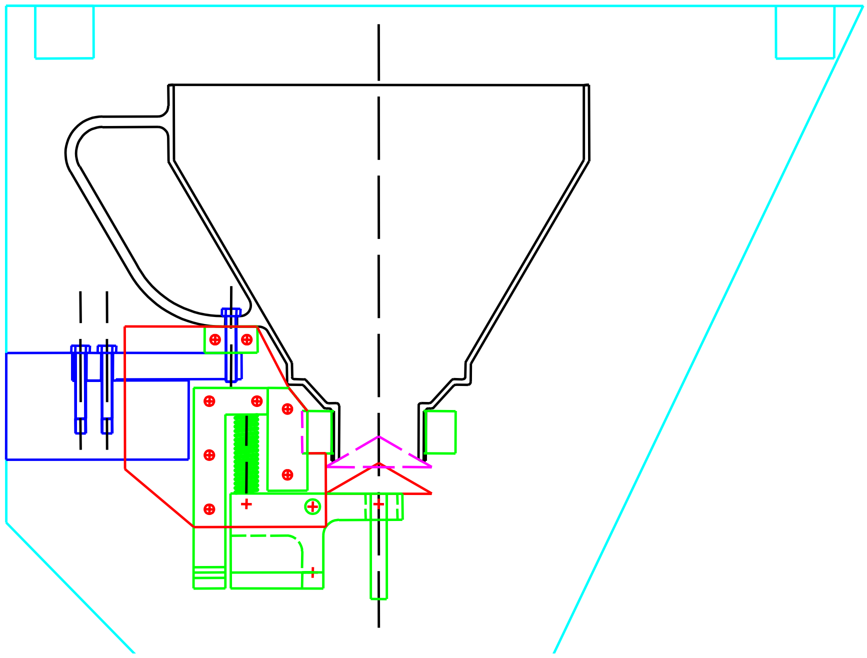


Figure 4-8 Pivoting arm valve drive

4.4.8. Construction of the weighing system

The container of the first type weighing system is a standard plastic funnel with a volume of ~1.2 litre and an inlet diameter of 155 mm. The valve mechanism and load cell are packed between two plastic plates which provide lateral stability (Figure 4-9). The plastic plates are 5 mm thick; the gap between plates is 12 mm. The load cell is attached to the induction hopper through a solid brass block which protects the load cell from over load by limiting the available deflection range. The handle of the funnel is used to connect the funnel and the valve drive to the load cell. The valve mechanism is attached to the funnel through a plastic ring where the funnel fits in with outlet pipe. The pivoting arm is hollow and covers the mechanical wire to protect it from chemicals. The spring is packed in between the side plates and distance blocks and located above the arm. A hemispherical rubber valve is attached on the valve stem which is fixed on the arm with a pin and engineering silicone. The pivoting arm has equal length arms, the valve lift is 10 mm, arm length 24 mm.

Technical drawings of the weighing system are shown in Appendix F.

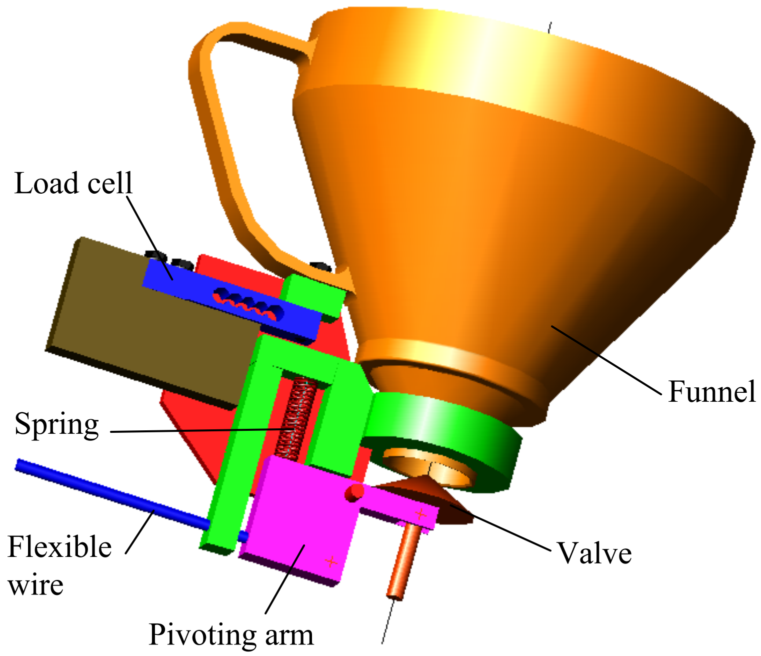


Figure 4-9 3D CAD outline of the construction of the weighing system

4.4.9. Selection of materials

Following the design requirements, the main construction material for the valve actuator mechanism (weight taken by the load cell) was chosen synthetic polymer Nylon 6-6 which is commonly used for mechanical parts. Details which had to be made of steel such as the coil spring and some of the screws were chosen grade A4 stainless steel. The funnel was chosen a heavy duty polypropylene resistant to chemicals with a mouth diameter 155 mm, stem diameter of 30 mm and a capacity of 1.2 *l*.

4.4.10. Modifications of the induction hopper

The existing induction hopper was modified by adding a vertical bracket inside it to give an adjustable attachment point for the weighing system (Figure 4-10).

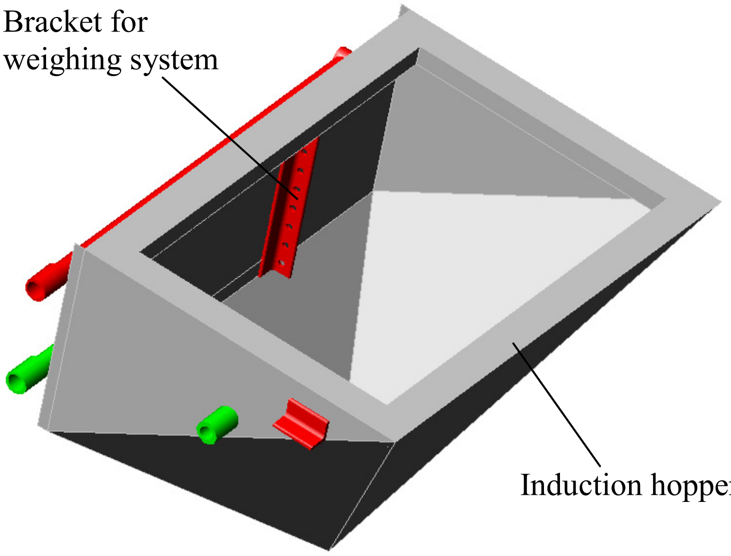


Figure 4-10 Modifications of the induction hopper

4.4.11. Complete assembly

The weighing system was assembled and mounted inside the induction hopper as shown on Figures Figure 4-11, Figure 4-12 and Figure 4-13. The electrical wiring of the load cell is shown in the diagram Appendix E.

The rinsing system was made of laboratory plastic hose connections and silicone and rubber hoses (Figure 4-13). 9 holes with diameter of 2 mm were made on the perimeter of the rinsing loop. T-junction with a drain pipe down to the hopper drains the rinsing loop quickly and avoids dropping to the funnel.

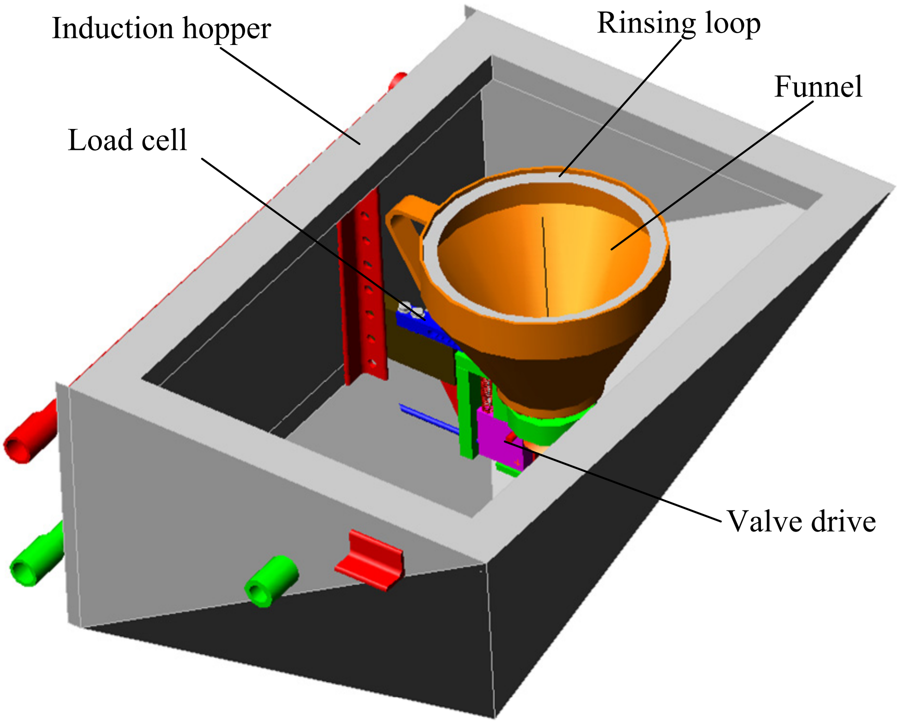
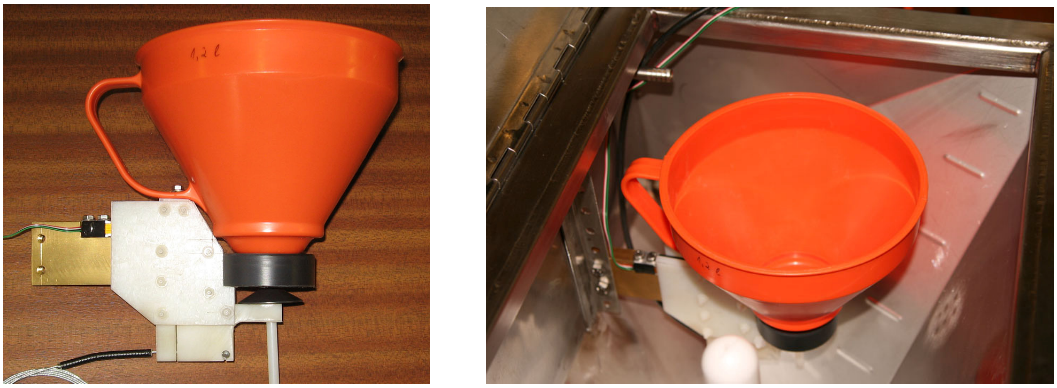


Figure 4-11 Complete assembly of the weighing system



(a) (b)

Figure 4-12 Weighing system: (a) funnel with mechanism; (b) mounted in the hopper

A standard lockable cycle hand grip was chosen as the handle for the valve. It was mounted on the outside of the hopper on the right hand side. In such arrangement the operator uses the left hand for operating the rinsing valves and right for operating the weighing system discharge valve (Figure 4-13).

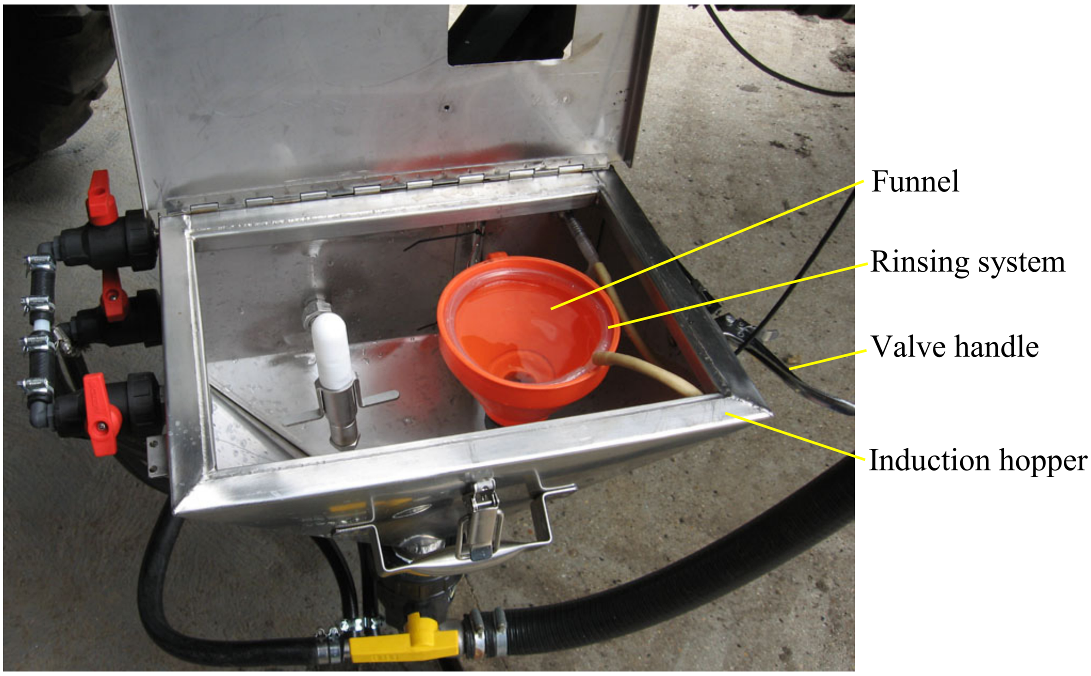


Figure 4-13 Hopper weighing system

4.4.12. Improved version

The weighing system was calibrated as described in Appendix G. Based on the initial trials the first type funnel design was successful, but there were following issues:

1) The surface of the plastic funnel was too rough and resulted in measured substances sticking to the surface.
2) Extended rinsing time caused by the first problem.
3) Tendency to extensive resonance at some mechanical excitation frequencies (see Chapter 5).

The first version was improved by replacing the plastic funnel with an inverted pyramidal shaped stainless steel funnel with mouth dimensions of 180×220 mm and a capacity of 1.4 *l* (Figure 4-14). The mass of the funnel increased by 451 grams (from 104 grams plastic to 555 grams stainless steel) which remained within the capacity of the load cell.

The new funnel required a modification of the rinsing system: a new rinse bar above the funnel without contact to it (Figure 4-15). That arrangement also protects from the overload from externally applied load on the weighing funnel (e.g. the product container slips). It is connected to the main rinsing system of the induction hopper which simplifies the operation. Both the funnel and hopper are rinsed concurrently.

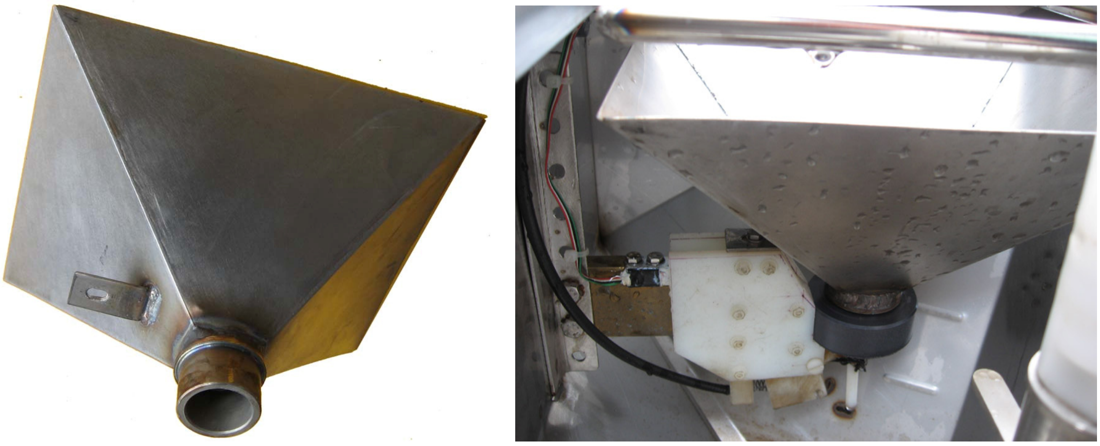


Figure 4-14 Stainless steel funnel

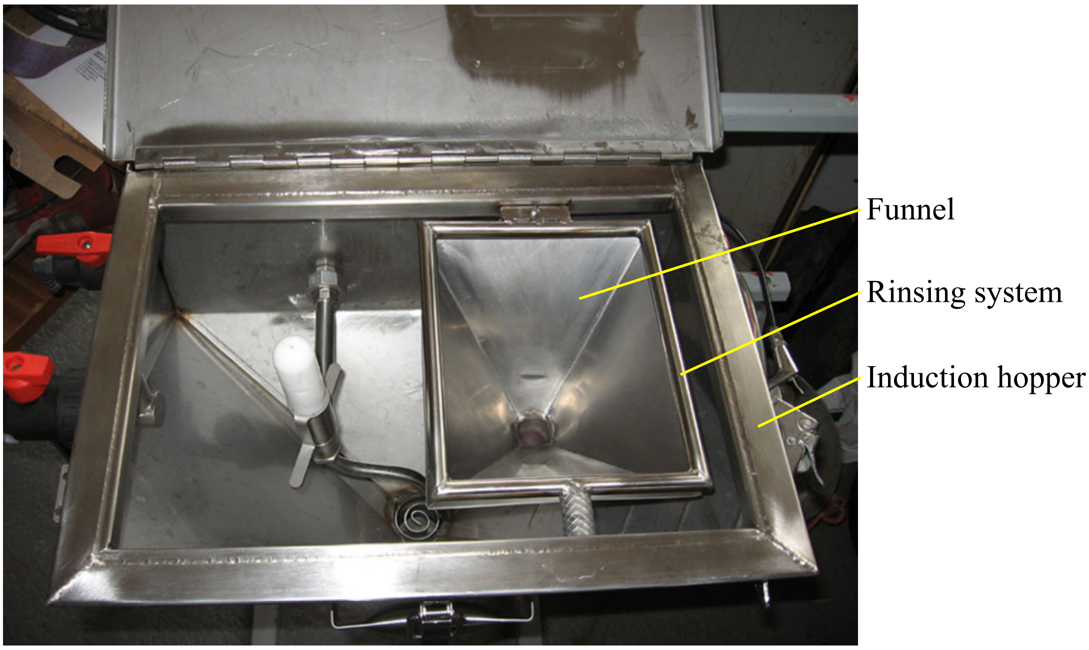


Figure 4-15 Modified weighing funnel

Inclination and position of the load

The spraying machine may be loaded with agrochemicals on a ground which is not level. The measuring system is affected by the cosine effect: for an inclination of 10° the error is 1.5%.

With a single point load cell the significance of any moment induced by off-centre loading which occurs if the granular load is distributed asymmetrically in the funnel has to be analysed. This situation does not happen with liquids. In order to determine the measuring error caused by the off-centre load an experiment was conducted. The weight of a laboratory mass was measured by placing it in the centre and then moving into the corners of the weighing funnel. Based on the results, the measuring error was plotted against bending moment of the load cell (Figure 4-16). E.g. a load of 0.42 kg (granules filling half of the funnel) with a centre of gravity 50 mm off the centre line produces a bending moment of 0.21 N·m. The data demonstrates an error of 5 g (1.2%).

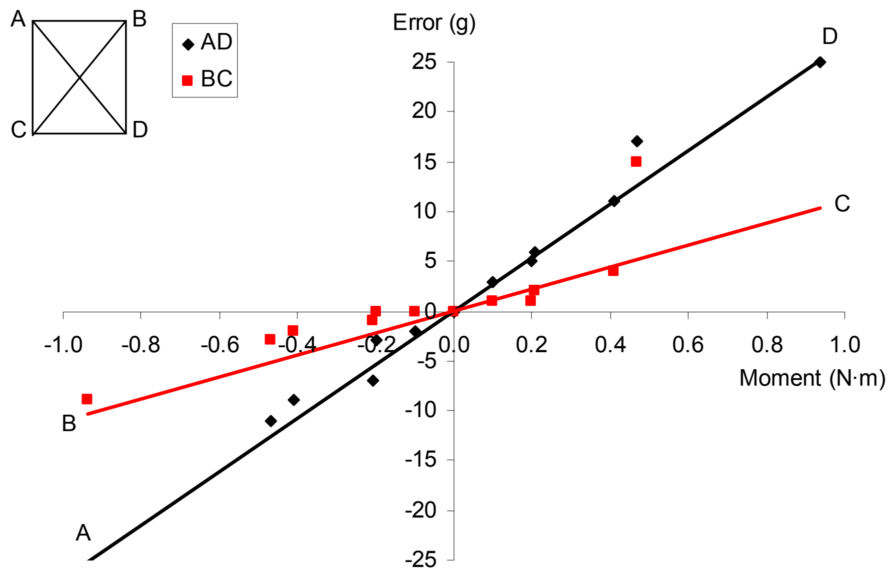


Figure 4-16 Error of the bending moment of the load cell

4.4.13. Embodiments of the induction hopper's attachment to the sprayer

The initial trials of the weighing system indicated issues with mechanical vibration from the sprayer's chassis imparted to the induction hopper and thus variation in weighing system output. These vibrations were seen to influence the performance of the weighing system. The most direct method to remove this factor is to mechanically isolate the hopper from the vibration. In increasing order of separation, the following options are available:

1) Attached directly on the sprayer (normal arrangement)
2) Connected through mechanical dampers
3) Isolated mechanically

The first approach is most desirable because it has no additional cost associated, the hopper is securely fixed and can easily be toggled between transport and working positions. However, this arrangement admits the highest levels of vibration to the weighing system. Stability of the output signal relies entirely upon post-measurement signal processing to remove the unwanted variation.

Mechanical dampers such as rubber mounts are widely used solution to absorb shock and vibration and isolate machine components to minimise the propagation of disturbances. The function of rubber mounts is to filter vibration. Filtering characteristics depend on the properties of the rubber and attached mass. The construction of the mounting plate of the induction hopper is most suited to transverse mounts (see Figure 5-24 Chapter 5).

The third approach is to mechanically detach the induction hopper from the chassis for the time of measurement. This can be achieved in a form of a supporting leg which resting on the ground unhooks the induction hopper. However, the additional construction adds cost and complexity; there is a risk of damage to the equipment if the machine drives off with the hopper in the demounted position.

The effect of these approaches on the performance of the weighing system was investigated in Chapter 5.

4.5. User interface

4.5.1. Design principles

The user interface is a critical component in delivering overall system performance in speed, accuracy, and user acceptance. Usability is defined through the following user-oriented characteristics by Shneiderman (1992): ease of learning, high speed of user task performance, low user error rate, subjective user satisfaction, and user retention over time. Human factors describe the response in terms of human behaviour to an engineering system. Four important human factors to consider in designing user interfaces are listed by Sommerville (2007):

- Limited short term memory – people can instantaneously remember about seven basic units (entities) of information +/– two (Miller, 1956).
- Mistakes – people make mistakes, especially under external stress (e.g. time).
- Physical capabilities – people have different seeing, hearing, and physical manipulation abilities, e.g. about 10% of men are colour-blind (Sommerville 2007).
- Interaction preferences – some people prefer to work with text, others with pictures. Icons eliminate the language issues.

These human factors form the basis of the design principles of user interface designs. The design guidelines (Hix & Hartson, 1993, Sommerville 2007) to be followed can be summarised in the following:

- User familiarity and experience levels
- Consistency
- Simplicity
- Informative feedback
- Minimal surprise
- Recoverability
- Reversibility of actions
- User guidance
- User diversity

The first stage in the development of user interface is paper prototyping as recommended by Sommerville (2007). The objective of the design of the user interface is to achieve good sprayer operator performance including error reduction, increased throughput, user satisfaction, and user comfort.

4.5.2. Design requirements and operating conditions

According to the market requirements analysis the main agricultural industry requirements are as follows:

- Simple and easy to use
- Low cost
- Integrated technology
- The ability to be retrofitted to existing systems

The user interface has to operate in harsh environmental conditions and operator environment. The user interface has to comply with the following conditions and influences:

- Environmental conditions
  - Electrical noise
  - Acoustic noise
  - Vibration
  - Water
  - Dust / dirt / soil
  - Sunlight
  - Corrosive chemicals
- Operator environment
  - Protective clothes
  - Rubber gloves
  - Face shield
  - Ear plugs

- Climatic and crop induced time pressure
- Fatigue
- Stress

4.5.3. Communication to operator

The loading task is interactive, communicating feedback information to the operator. User communication options are as follows in increasing order of cost/complexity:

- Audio signal
- Visual signal
  - Indicator lights
  - Single line LCD
  - Two line LCD
  - Black-and-white full matrix LCD
  - Colour screen
  - Full colour touch screen

Audio communication signals cannot be used easily because of the environmental conditions (engine and pump noise etc). The precise requirements of the chemical loading process requires the system to communicate back to the user the identifier (name) of the product and wait for a user confirmation or decision. A full matrix screen is the most appropriate method for that task. ISO 11783-6 recommends a minimum screen area of 200×200 pixels for virtual terminals. Black-and-white full matrix LCD screens deliver high contrast image in direct sunlight and are lower cost than colour screens. A touch screen is a comprehensive data presentation-input user interaction device. However, they are higher priced than ordinary screens, e.g. £379 for a 12.1'' open frame screen (http://www.protouch.co.uk/touch/items.asp?&CatMoveby=0&Cc= Open&iTpStatus=0&Tp=&Bc= (26 January 2009)) or £880 for a 17'' industrial robust screen (http://www.amplicon.co.uk/IPC/ product/Industrial-Senses-353.cfm (26 January 2009)). For economic reasons the size of the screen needs to be kept as small as possible within the information requirements.

4.5.4. User input

In order to confirm the steps in the process and set the responsibility, a user input device is required. Considering the operating conditions, the main requirement is a robust and straightforward manipulation of the objects on the screen. The input device has to be with fast and intuitive interaction and easy to learn. The options are following:

- Voice recognition
- Keyboard
- Touch screen keys
- Industrial buttons

Voice recognition cannot be used because of the acoustic noise in the operating environment. This leaves buttons or keys. Keys can have dedicated functions, be used in conjunction with screen prompts ("softkeys") or a full keyboard can be used.

Although a full keyboard can be implemented they can be difficult to operate with gloves and are relatively complex. A large number of individual buttons would be required to access all functionality. Softkeys (a small number of physical buttons with the function displayed on an adjacent part of the screen) are a commonly used solution, for example tractor in-cab console ISO 11783 virtual terminal specifications (BSI, 2004g). This method is recommended for the prototype.

The number of physical buttons must be carefully matched with the on-screen user interface. Too few results in a very large number of screen prompts, too many increases cost and complexity. After considerable review the prototype system proposes three buttons are required, being used consistently throughout the system for:

- "Yes, OK, continue"
- "No, do not but continue in the process"
- "Go back up a level or change the process"

Buttons such as "OK", "cancel", "exit" are very commonly used throughout many user interfaces (Sommerville 2007). These can also be appropriately coloured to help identification.

4.5.5. Graphical interface

The analysis above suggests a black and white full matrix LCD screen and three distinguished rugged buttons associated with soft keys for user interaction. The general type of device described in the ISO 11783 standard for virtual terminals (BSI 2004g) seems entirely suited to this application. The minimum data mask area is specified of 200×200 pixels and the minimum soft key designator field 60×32 pixels. The embodiment of the design is shown on the Figure 4-17.

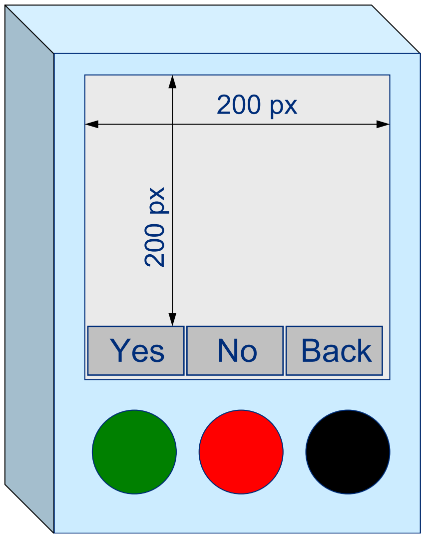


Figure 4-17 Graphical interface

4.5.6. User pages

The interaction between the user and the system occurs through a screen. More than one page is necessary to present individual tasks in the process. The results of a paper prototyping demonstrated that the following pages are required:

- Tank summary
- Identification
- Confirmation
- Loading of full pack
- Weighing
- Messages

The user pages shaped with paper prototyping were refined and designed in programming environment (discussed below in section 4.7) as presented in Figure 4-18 in logically structured way.

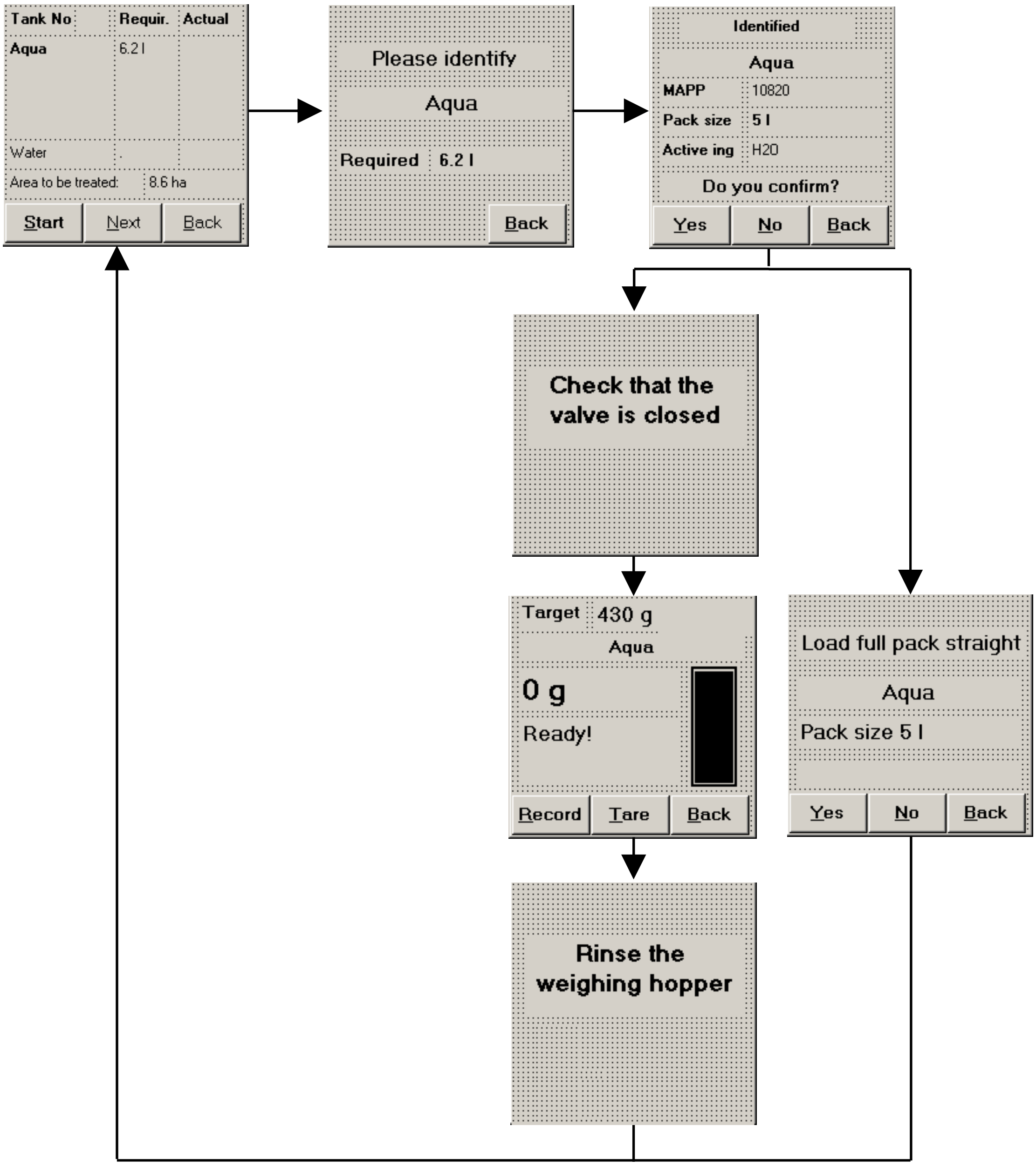


Figure 4-18 User pages and their logical relations

4.5.7. Embodiment and construction

Hardware selection for the prototype is discussed in section 4.7. In summary, a notebook PC was chosen, however a restricted part of the screen was the only item visible to the operator. The remainder of the electronic equipment was housed within the sealed enclosure where the PC was housed (Figure 4-19). Three appropriately coloured industrial push buttons were installed below the screen next to the associated soft keys.

Figure 4-19 Construction of the user interface

4.5.8. Improvements to visual feedback

Based on the initial operator performance evaluation (see Chapter 6), the following additions were made to the visual interface:

- Shade for the screen to improve the readability in bright daylight, Figure 4-20.
- 8 segment multicolour LED-bar.

Figure 4-20 Screen shade

A custom made multi colour LED-bar (Figure 4-21) was designed and constructed to satisfy the operating conditions. The LEDs were totally encapsulated in a block of Nylon 6-6 for protection against the environment of the hopper. The LED-bar provides a simple progressive visual indication of quantity against requirement ranging from green through amber to red, directly in the line of sight of the operator during filling. Extra care is required from the operator as the target level is approached. Thus, higher resolution is provided in this range. Completely linear action through full scale would not satisfy that condition. The following operating mode was designed for the LED-bar.

The first of the 6 green LEDs lights at 30% of the target, the rest will light proportionally with 10% steps as the actual weight increases. Amber LED lights at 90% and signals careful approaching the desired value, and red signals the target has been reached within ±5%. The whole LED-bar flashes if overfilling occurs. The LED-bar is controlled by the software, which means the operating mode can be reprogrammed without changing the hardware.

For the production prototype it is recommended to enable left-right repositioning of the LED-bar to overcome possible handedness problems.

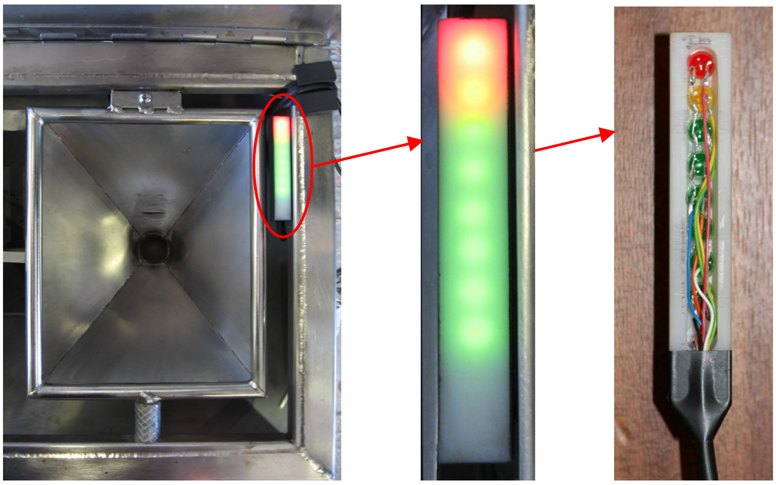


Figure 4-21 LED-bar

4.6. Identification system – RFID

4.6.1. Suitable frequency for identification of agrochemicals

The RFID system for identification of agrochemicals has to meet a range of requirements:

- Sufficient range (~100 mm) to read the label of a treated container in the area of weighing device. Too long range may result in reading all possible containers near the weighing device, leading to manual removal of duplicates.
- Penetration into water and insensitivity to surrounding metal objects is required.
- The containers have to be identified uniquely, thus item level identification is required.
- Memory size of the tag has to be sufficient for saving the required information as proposed in Chapter 3.
- Well standardised and widespread system to ensure interoperability of readers and tags, and availability of low cost tags.

Based on the requirements and properties of different frequency systems currently on the market the adequate RFID system for identifying agrochemicals is ISO 15693 compatible HF 13.56 MHz. The RFID reader FEIG MR100 and FEIG ANT100/100 aerial were chosen for the prototype as typical of currently available products after consultation with a leading UK supplier (RFID Components Ltd).

4.6.2. Construction

The location of the RFID antenna has to satisfy two requirements: ergonomic height for the operator to introduce the products, and minimum interference from proximity of metallic objects. The analysis of the situation and possible mounting options has lead to design where the RFID antenna is located in front of the hopper (Figure 4-22). The casing protects from environmental influences and provides sufficient distance from metal bracket. As the hopper is by design at a suitable height, the location of RFID antenna will also satisfy the criteria.

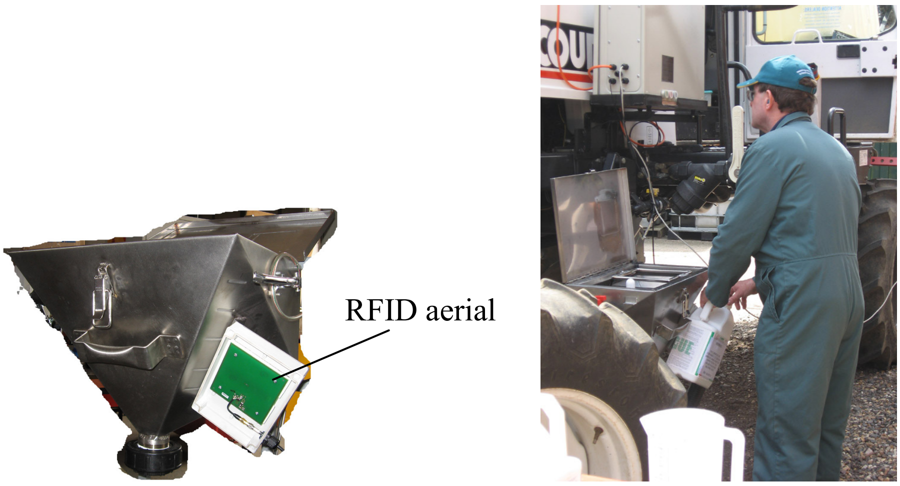


Figure 4-22 Location of the RFID aerial

4.7. Hardware and software implementation

The hardware and software implementation of the development prototype has to be considered in order to have a universal development platform but as close as possible to a production prototype.

The hardware platform has to meet the following requirements:

- User display Black and white LCD
- User input 3 rugged buttons
- Ports RS232, 2×USB, PCMCIA, CAN
- Programmability Visual Basic 6 & C++
- Data storage (chemical database) 500 MB

The logical options are as follows:

- Dedicated rugged hardware and Windows CE/Linux
- PDA device and Windows CE/Mobile/Linux
- PC desktop and Windows/Linux
- PC notebook and Windows/Linux

The desired embodiment for the user interface is a compact and rugged unit with an integrated screen and user input device that can be mounted next to the induction hopper in the line of sight of the operator. A dedicated rugged hardware or PDA would be very suitable here. However, the software development for the RFID reader under Windows CE/Mobile or Linux would be very difficult (e.g. lack of drivers).

A notebook PC is optimal because of the easy software development and hardware compatibility which is important on experimental prototype system to minimise time spent on secondary tasks such as driver development. They have an integrated screen and are also relatively compact compared to desktop PCs. To satisfy the design requirements, the screen of the notebook PC is restricted to 200×200 pixels black and white, it is equipped with three industrial buttons for all user input, and housed in a suitable enclosure to allow field trials (see Section 4.5).

4.8. Software development

In contemporary engineering the software development constitutes a significant intellectual part of mechatronical systems. With relatively simple and robust mechanics sophisticated software allows flexibility in configuration and updates. However, with greater share of software in systems it has to be reliable especially in agriculture where time window to complete jobs may be very narrow. Dependability of software has been defined by Sommerville (2007) through the following main criteria:

- Availability – up and running.
- Reliability – delivers services as expected by the user.
- Safety – damage to people and environment.
- Security – resist accidental intrusion, includes integrity.

Additionally, reparability, maintainability, survivability and error tolerance are mentioned. Software development consists of the following stages: specification, design and implementation, validation, and evolution.

The automatic recording system acquires real time measuring data and processes user inputs. Sommerville (2007) defines a real-time system as “a software system where the correct functioning of the system depends on the results produced by the system and the time at which these results are produced”. Real-time software must react to events generated by the hardware and issue control signals in response to these events. In the automatic recording system very fast response at the appropriate time is not required – response within human reaction time is adequate. Thus, a near real-time software is required.

The user input occurs at irregular time intervals. The signal from the weighing is acquired with predictable time intervals for subsequent processing and analysis to provide real time user feedback within human reaction time. Thus both periodic and aperiodic stimulis are represented. A mix of sequential program and concurrent processes is required. The main components of the software are presented in Figure 4-23.

The software program (Appendix H) has been developed according to the structure presented in Figure 4-24 and evaluated as part of the prototype system (Chapter 6).

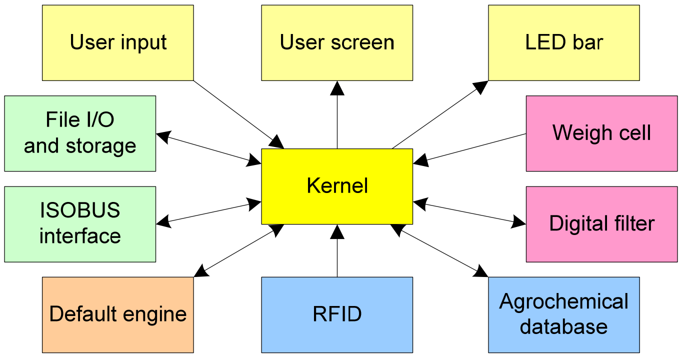


Figure 4-23 Main components of the software

The initial flow of the program was designed to be a blend of automatic actions and operators manually evoking actions by pressing the buttons. However, the preliminary trials indicated high level of automation is required. The manual part requires decisions from operators which require confidence and proficiency otherwise the work is slowed down. To overcome the problem a default engine was implemented which evokes the next logical action and displays appropriate user page.

Following the structural design of the system (Section 4.3) the task file input, record file output and file storage functions are provided and mastered by the tractor's in-cab terminal. The AACTS receives the job information completely in a form of an electronic task file. The structure of task file designed for the development prototype is given in Appendix I. The task file includes field name, crop, water rate, tank number, total amount of water per tank, chemical name, chemical registration number, total required amount per tank, and unit of measure. To satisfy the traceability requirements (see Section 2.3.3 Chapter 2) the record file contains date, time, tank number, field name, crop, total amount of water, agrochemical name, registration number, dispensed amount, and unit of measure (Appendix I). The record of used agrochemical containers contains date, time, tank number, unique identifier of agrochemical container (RFID label), product name, registration number, active ingredient, full pack size, and unit of measure (Appendix I).

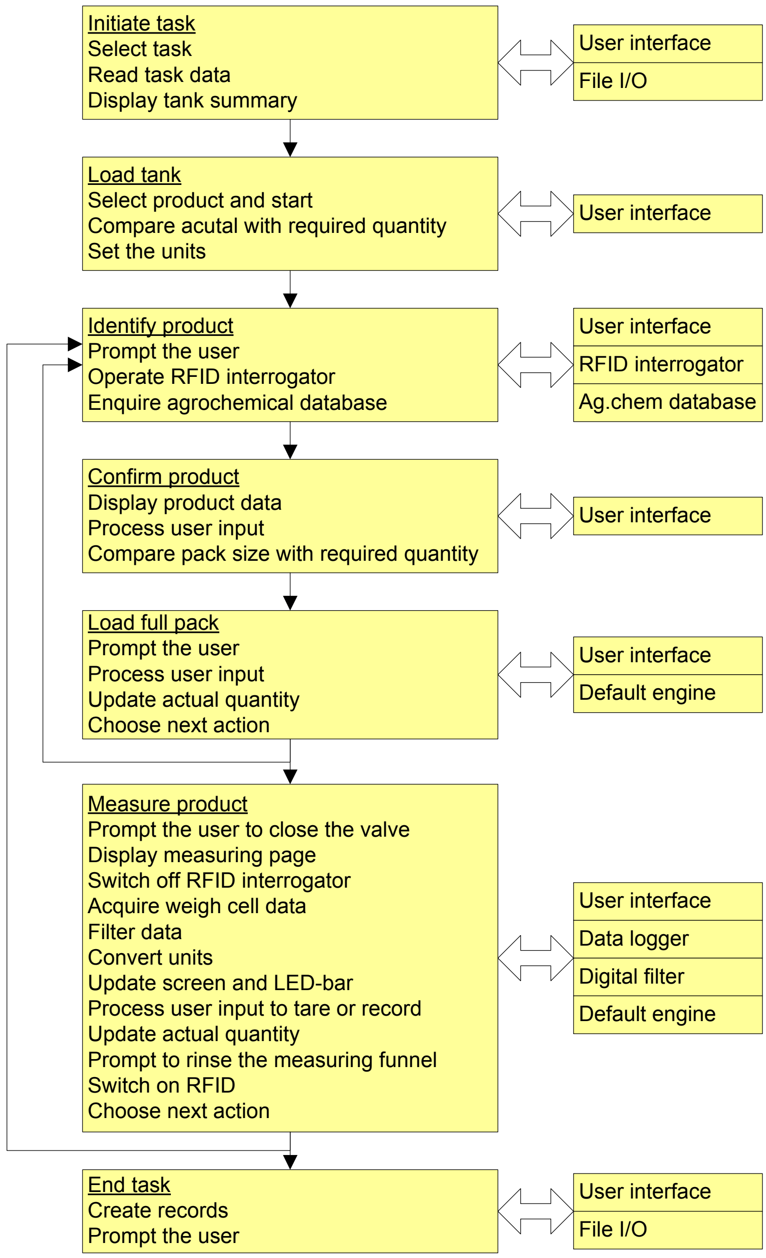


Figure 4-24 Structure of the software

4.9. Data exchange interface ISO 11783-10

The AACTS is required to exchange data with tractor terminal and farm computer. Current data communication standard for tractors and machinery in agriculture is ISO 11783 which is rather well established and has gained market acceptance and has been adopted by many agricultural machinery manufacturers. Compatibility with ISO 11783-10 data transfer standard allows achieving full benefits of the recording system.

In the ISO 11783-10 task data file the activities are classified as planned and effective. The investigation of options of integrating the filling instructions and records generated by the AACTS into the task file delivered the following solution as shown in Figure 4-25 on an example with four products. Loading task (TSK1) is planned in the farm management information system (FMIS) and agrochemical products (PDT1–PDT4) allocated to it (PAN) including the total amount of product to be used. The effective loading of first tank is stored as TSK2. Product allocations contain the actual loaded amounts. The unique identifiers (UID) of agrochemical containers – the unique number of the RFID tag associated with the product container – are stored into Data Log Values as DDI (data dictionary items). There can be several RFID UID per product depending how many containers are used to dispense the required amount.

After loading is completed the spraying task (TSK3) is generated from TSK1 and TSK2 on task controller in-cab. The product to be sprayed is tank mix PDT5 yielding from effective loading task TSK2.

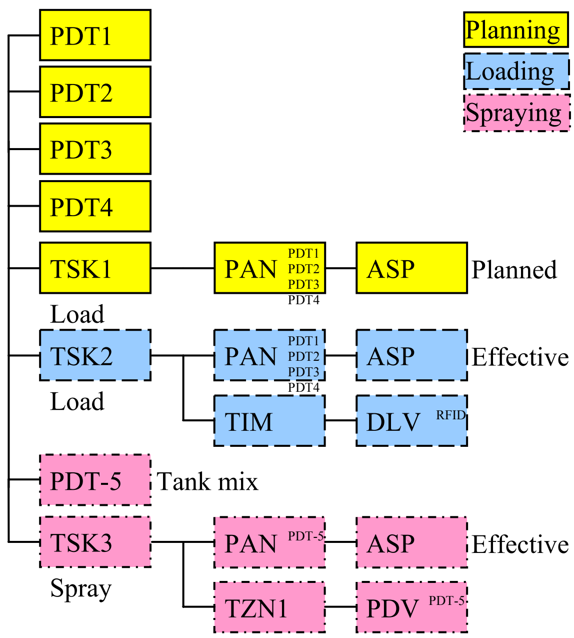


Figure 4-25 Structure of loading and spraying tasks

After completion of application of the first tank load on the field, the next tank is loaded under TSK4. The required amount of chemicals is the difference between TSK1 and TSK2. The next spraying task is TSK5 with a product PDT6 which is the tank load of loading task TSK4. Thus, the proposal is to handle the tank mixes as products and generate a new tank mix product after each tank load which is true reflection because each tank mix is unique.

Suggested new attributes in XML elements are for the product:

- Registration number 8 bytes.
- Country code 1 byte.
- Notes (product specific information such as mixing instruction, special precautions) String (32 characters).

The registration number and notes support a similar proposal by a leading agricultural machinery manufacturer AGCO Corp. (Tevis et al., 2007). A new data dictionary identifier is required (8 bytes) to log the UID of RFID labels (agrochemical containers).

4.10. Cost analysis

The functionality of AACTS requires additional components on the sprayer. The cost of the prototype system and the predicted cost of a volume production unit were analysed. Table 4-4 summarises the main components of the prototype system with their original cost without VAT.

The total cost of the prototype hardware is £2081 disregarding the labour cost of manufacture and software development which are difficult to quantify based on methods used for a research and development prototype. The construction of the production unit will be optimised by using manufacturer's unified parts. The cost of a volume production unit has been investigated by Gasparin (2009) who found the total predicted cost of a unit manufactured for production volume of 1001–2000 is £1582. The retail list price is with 100% extra above production price. Thus, for a volume of 1001–2000 the retail price is £3164. For full economic and market analysis see Gasparin (2009).

Table 4-4 Cost of components

Component	**Sub-component**	**Cost (GBP)**
RFID	Interrogator	216
	Antenna	44
	Cables	25
	Antenna casing	13
Weighing system	Data logger	550
	Load cell	108
	Amplifier	75
	Weighing funnel (stainless steel)	212
Controller & screen	IBM Thinkpad T23 notebook	250
	Casing & mounts	84
User interface	Push buttons	25
	LED bar	15
	Data logger digital I/O	74
ISOBUS interface	CAN-USB adaptor	315
Accessories	Materials	45
	Electronic parts	30
Total hardware		**2081**

A contemporary self propelled crop sprayer, such as Challenger Spra-Coupe 4455 with 24.4 m boom and 1575 litre tank costs £90,000 (AGCO Corp.). Thus, the additional cost of AACTS would be 3.5% of the sprayer's retail price.

4.11. Conclusions

The following conclusions can be made:

- A gravimetric measuring system is required to measure liquid and granular agrochemical products in quantities smaller than one pack with a resolution (1.2 g, 0.0092% of full scale) and speed (72.8 s per container) equal or better than on manual loading.

- A weighing system has been designed and constructed based on a smaller (capacity of 1.4 litres) funnel shaped weighing container built inside an induction hopper on a load cell featuring a manually controlled outlet valve, a rinsing system and compatibility with all of the agrochemical product container types specified for induction hoppers, type of closed transfer systems with an interface on the lid of the induction hopper.
- A simple user interface satisfying the demanding operator and environmental conditions has been built. It features a 200×200 pixel black and white screen, three appropriately coloured rugged buttons and an indicator bar made from 8 coloured LED (green–amber–red).
- Graphical screen pages and their logical structure have been developed to communicate to the operator, assist the operator and indicate user input command.
- An RFID system with operating frequency of 13.56 MHz and a read range of 100 mm has been integrated in the induction hopper in a suitable location.
- Near real-time software that acquires real time measuring data and processes user inputs has been developed.
- The cost of the prototype system is £2081 which could be £1582 as an assembly price in volume manufacture.

5. Signal conditioning analysis

5.1. Introduction

5.1.1. Objective

The weighing system has to deliver high resolution of 1.2 g (Section 4.4.3 Chapter 4) whilst operating in an environment with high levels of mechanical vibration. These vibrations had previously been found to be a major limitation in the work of Watts (2004). Preliminary experiments with the weighing funnel design presented in the previous chapter have shown vibration induced variation to be a significant source of error, influencing amount of chemical dispensed, recorded values and the performance of human working with the system. In order to remove the unwanted elements from the signal, the characterisation of these elements and the development of appropriate filtering application is required. In this chapter, the developments in signal analysis, filtering and processing are presented.

5.1.2. Anticipated sources of noise

In the weighing system there are many sources of vibration and several coupling paths to the induction hopper. The initial inspection revealed the following sources of energy are expected to have an effect on the performance of the weighing system:

- Diesel engine combustion (4 cylinder at 1000–2500 r/min)
- Rotating components (engine, driveline, pumps)
- Fluctuating liquid in the flexible hydraulic drives
- Oscillating liquid in the weighing funnel
- Electromagnetic interference by RFID, alternator
- Operator knocking the hopper
- Wind

The main source of mechanical noise is the diesel engine – reciprocating-piston engine with internal combustion – operating at nominal speeds of 1000–2500 r/min. The sprayer used in the trials (Spra-Coupe 4440) had a typical in-line 4-cylinder 4-stroke tractor engine. Diesel engines have a very powerful combustion stroke. By design 4-cylinder in-line engines have substantial free inertial forces of 2nd order oscillating at a rate twice of the crankshaft rotational frequency (33–83 Hz) in vertical direction (Dietsche & Klingebiel 2007). Free forces impart movement to the engine. This is transmitted in the form of vibration to the weighing system through engine supports, chassis and linkage arm which is used to connect the induction hopper to the chassis and to toggle between transport and work positions. The weigh cell is sensitive in the vertical direction, therefore it is affected by the vertical free inertial forces of the engine. A 6-cylinder in-line engine as used in larger tractors and sprayers would run more smoothly because it is without free inertial forces and moments (Dietsche & Klingebiel 2007).

Being part of the sprayer's hydraulic system, the hopper is coupled with it by flexible rubber hoses. The movement of the hoses caused by the liquid pulsating in them is transmitted to the hopper and weigh cell in the form of relatively low frequency (<33 Hz) mechanical vibration.

Based on visual and analytical observation, the liquid content of the weighing funnel is forced to oscillate by the mechanical vibrations. These oscillations are seen to have an effect on the load cell output. There is a range of resonant frequencies for the load cell because the stiffness of the load cell is constant and the mass in the funnel changes (see Figure 5-12).

The induction hopper transmits accidental impacts by the operator to the weighing system which are likely to have an impulse effect on the output of the load cell. Wind was observed to cause slight movements of the induction hopper.

The measurement system includes amplification of very small voltage signals generated by the strain gauges. Electromagnetically induced voltages from external fields are also amplified and presented as noise. Here, there is a significant radio transmitter in the RFID system, and additional radiation from the alternator of the sprayer engine.

The above sources have differing levels of significance in determining the undesired variation of the load cell output signal. Based on observation with the prototype system, it was decided to investigate closer the influence of the diesel engine, fluctuating liquid in the flexible hydraulic hoses, oscillating liquid in the weighing funnel and electromagnetic interference of the RFID system. The results are discussed in the following sections below.

5.2. Methodology of signal analysis

In order to characterise the signal of the weighing system and effectively apply signal conditioning, it is necessary to analyse the whole signal to identify constituent parts. With current technology the prevalent method is the digital signal processing (Lyons 2004). Standard commercial software (Matlab R14 & signal processing toolbox, Mathworks Inc, 2008) provided rapid and easy to use analysis tools; the script files written for signal analysis in this work are given in Appendix J.

Power spectral density (PSD) estimates how the average power of a signal (discrete-time sequence) is distributed over the frequency (Stoica & Moses, 2005). In the current context, PSD is an indication of the level of noise and its ratio to the useful signal component (in this case weight in the funnel) – an estimation of error.

The methodology applied in the present chapter can be summarised as follows:

- Perform fast Fourier' transform (FFT) of the time domain sequence.
- Calculate and scale the magnitude of the complex output $|X(m)|$ (grams).
- Calculate the mean square power $|X_{pwr}(m)|^2$ (grams squared).
- Find the noise ratio X_{Δ} (dB).

The output of the strain gauges of the weighing system is a continuous time varying signal. Using an analogue to digital converter, the signal is periodically sampled to represent it with a sequence of discrete values. In order to represent a signal with a frequency band of B, the sampling frequency f_s must satisfy the Nyquist criterion $f_s \geq 2B$ (Lyons 2004, Nyquist 2002) to prevent frequency domain aliasing.

To characterise the frequency content of discrete-time domain signal, the discrete Fourier transform (DFT) is the most dominant and powerful procedure. It originates from continuous Fourier transform and is expressed, according to Lyons (2004), as a discrete frequency domain sequence $X(m)$ where

$$X(m) = \sum_{n=0}^{N-1} x(n) \left[\cos\left(\frac{2\pi nm}{N}\right) - j \sin\left(\frac{2\pi nm}{N}\right) \right] \tag{5-1}$$

where $x(n)$ is a discrete sequence of time domain sampled values,

m – the index of the DFT output in frequency domain,

n – the time domain index of the input samples,

N – the number of samples of the input sequence and the number of frequency points in the DFT output.

With high number of points in the DFT the amount of processing time becomes significant. To perform DFT efficiently, an algorithm called fast Fourier transform (FFT) is used (Cochran et al., 1967). The most popular of it radix-2 FFT algorithm utilises the principle of dividing complex mathematical computation into simpler operations until reaching the length of 2 (radix-2) as explained by Lyons (2004). This reduces the number of calculations significantly compared to the DFT. The number of points N is determined by the sampling frequency F_s and desired spectral resolution F_{res}:

$$N = \frac{F_s}{F_{res}} \tag{5-2}$$

The resulting N is rounded up to the next number of power of 2.

The output magnitude of the DFT for a real input signal containing a sinewave component of peak amplitude *A* with and integral number of cycles over *N* input samples is *M*, where

$$M = \frac{A\ N}{2} \tag{5-3}$$

The output magnitude of the DFT for a DC input with a magnitude of D_0 is equal to

$$M_0 = D_0 N \tag{5-4}$$

The frequency of the *m*th DFT output component is, yielding from Eq. (5–2),

$$F_{analysis}(m) = \frac{mF_s}{N} \tag{5-5}$$

For real inputs, an *N*-point DFT's output provides N/2+1 independent terms.

The power of a signal is proportional to its amplitude (or magnitude) squared. The power of a signal in time domain can be expressed as

$$x_{pwr}(n) = x(n)^2 = |x(n)|^2 \tag{5-6}$$

And in frequency domain

$$X_{pwr}(m) = X(m)^2 = |X(m)|^2 \tag{5-7}$$

By Parseval's theorem (Davenport & Root, 1958), the power of a time domain sequence, i.e. the time average of its energy, is equal to the sum of the average energies in each frequency component:

$$\frac{1}{N}\sum_{n=0}^{N-1}|x(n)|^2 = \sum_{m=0}^{N-1}|X(m)|^2 \tag{5-8}$$

Because their squared nature, plots of power values often show both very large and very small values on the same graph. To make these plots easier to evaluate, decibel scale is usually employed. Power difference of two signals is defined as

$$x_{\Delta} = 10\log_{10}\left(\frac{P_1}{P_2}\right) \tag{5-9}$$

Normalised power difference of a frequency domain sequence

$$X_{\Delta}(m) = 10\log_{10}\left(\frac{|X(m)|^2}{|X(0)|^2}\right) = 20\log_{10}\left(\frac{|X(m)|}{|X(0)|}\right) \tag{5-10}$$

where $X(0)$ is the DC component.

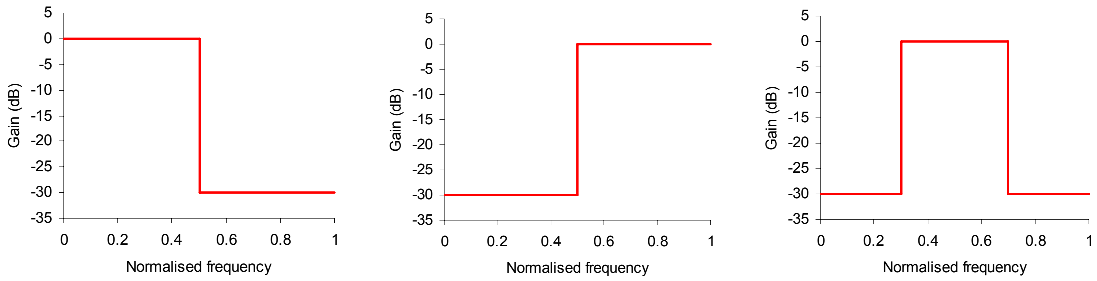
Equation (5–10) takes the following form to express the noise to signal ratio of the weighing system, where the numerator is the sum of noise components and the denominator is the weight in the weighing funnel (DC component):

$$X_{\Delta} = 10\log_{10}\left(\frac{\sum_{m=1}^{N-1}\frac{|X(m)|^2}{2}}{|X(0)|^2}\right) \tag{5-11}$$

5.3. Signal filtering

5.3.1. Classification

Filtering is defined by Lyons (2004) as the processing of a time-domain signal resulting in reduction of some unwanted input spectral components. Meaning, the filter attenuates some frequencies whilst allowing other frequencies to pass according to the design of the filter (Figure 5-1). For example, a low pass filter reduces the magnitudes of signal components with frequencies higher than specified cut off frequency. A high pass filter is the opposite of low pass filter. A band pass filter allows (Figure 5-1c) components within certain frequency band whilst attenuating outside the pass band.



(a) (b) (c)

Figure 5-1 Classification of filters according to pass band: (a) low pass, (b) high pass, and (c) band pass

Most of the anticipated significant noise is expected to have frequencies higher than the effective change rate of the useful signal. Therefore a low pass filter is principally very suitable for this application. The cut off frequency has to be selected carefully to guarantee adequate response of the system for operator feedback.

Filters may operate on the signal in the mechanical, electrical or numerical parts of the system. In this case, the following are particularly relevant:

- Mechanical isolation/damping
- Electronic filtering
    - Analogue (continuous prior to digitisation)
    - Digital (discrete, after the signal has been converted to numerical values)

Mechanical isolation reduces the vibration input to the system by isolating it from the source of noise. Analogue electronic filters are electrical circuits constructed from a combination of passive or active components. Digital filters can be a software program, a programmable hardware processor, or a dedicated integrated circuit (Lyons 2004).

Digital software filtering techniques provide great power with ease of reconfiguration. They provide tools to experiment flexibly with different designs of filters without changing the actual hardware. For these reasons, digital software filters are of particular interest in application of processing the signal of the weighing system. The primary limitation is in aliasing, where noise frequencies above half the sampling frequency cause variation in the measured values. Digital filters alone are ineffective above the Nyquist limit, and for this reason practical systems often contain analogue anti-alias filters to remove very high frequency components. This issue will be discussed in more detail below in section 5.4.2.

5.3.2. Digital filters

Traditional digital filters are classified into two categories: finite impulse response (FIR) filters and infinite impulse response (IIR) filters. A comparison of characteristics of FIR and IIR filters is given by Lyons (2004).

FIR digital filters use only current and past input samples, i.e. its previous output samples are not fed back. Given a finite duration of nonzero input values, the FIR filter will have a finite duration of nonzero output values. Likewise, if the input level drops to zero, the output will eventually also be zero.

The output samples of IIR filter, on the contrary, depend on the previous input samples and previous filter output samples. Because of the feedback, there is a possibility of having infinite duration of nonzero output values, even if the input becomes zero.

IIR filters are more efficient than FIR filters and can simulate a prototype analogue filter. However, FIR filters are simple to design and their stability is guaranteed. FIR filters were used in this work.

5.3.3. Requirements and implementation

A very common smoothing filter, easy to understand and implement, often a standard built in feature of data acquisition hardware (also in the project data logger Dataq-CF2), is a rolling average, also known as moving average (Lyons 2004, Smith 2003). A moving average filter calculates the mean of a window of samples each time it moves the averaging window by one sample forward in the signal. Moving average is a very good filter for reducing random noise in time domain but very poor frequency domain filter because of its small ability to separate frequency bands from each other (Figure 5-2). The components with an integer number of period inside the averaging window have a sum of zero and are cut off. The frequencies which do not fit exactly in the averaging window are leaking through the filter. So, the window can be tuned only for a particular set of frequencies.

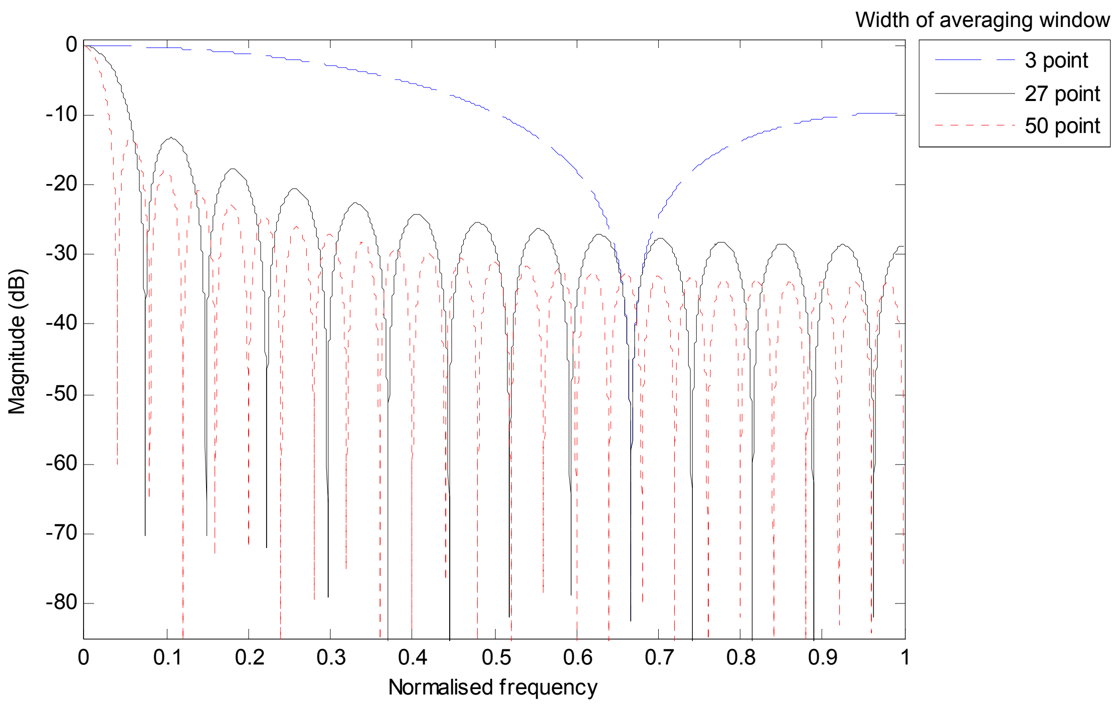


Figure 5-2 Frequency response of a rolling average filter on logarithmic scale (dB)

As the metering system has to report back to the operator in real time, the dynamic response of the system has to be such that there are no delays noticeable to the human operator. As an initial target value, the approach was taken to match a typical human stimulus-reaction time of 0.3 seconds (Dietsche & Klingebiel 2007), therefore the screen refresh rate was initially set at 3 Hz.

To generate a stable reading on the screen, a maximally flat ripple free frequency response in the pass band is desired (Figure 5-3). Ripple would make the system sensitive to small changes in noise frequency, with apparently sudden changes in the variation seen in indicated values from small changes in operating environment. A ripple free filter has a very smooth roll off allowing some levels of noise pass near the cut off frequency. Sharp roll off is gained with the cost of some ripple in the pass band and less attenuation in stop band (Figure 5-4). At the cut off frequency the gain is approximately –3 dB (a factor of 0.5).

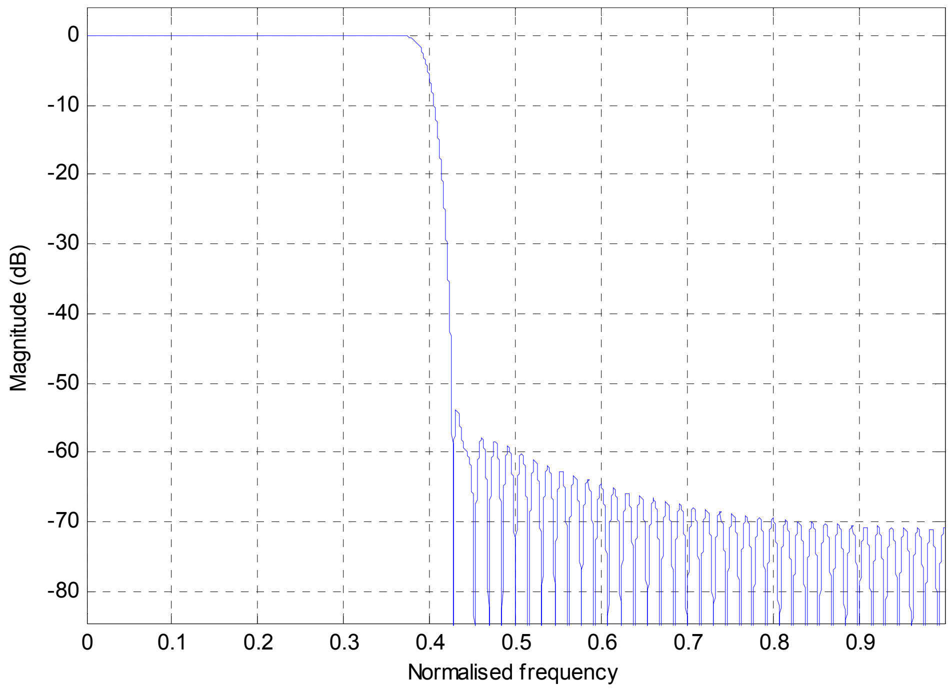


Figure 5-3 Frequency response of a 128th order FIR filter using Hamming window

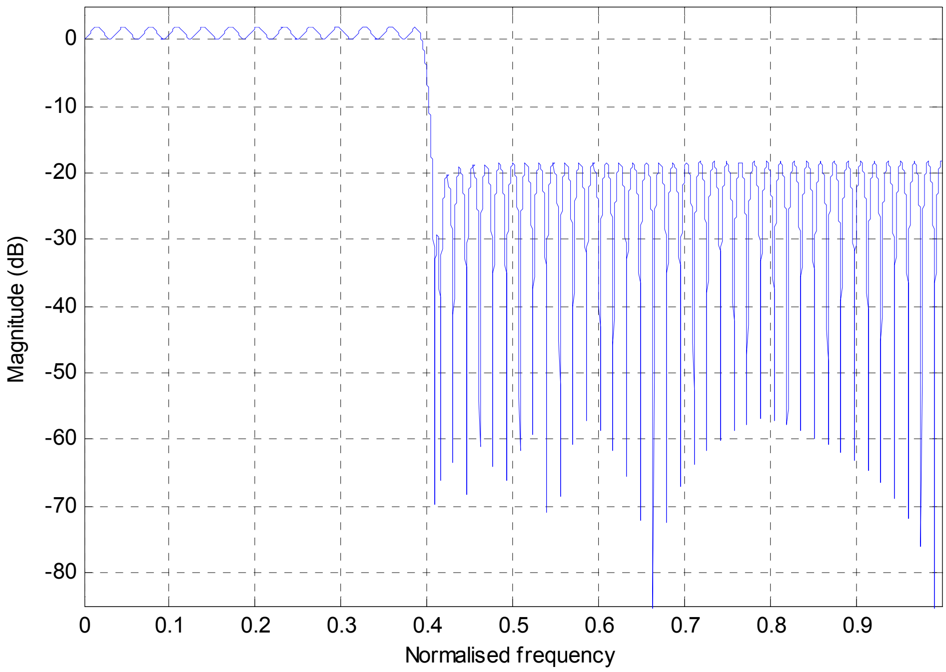


Figure 5-4 Frequency response of a 128th order FIR filter using Chebyshev window

5.4. Preliminary investigation of performance of the weighing system

5.4.1. Background

The performance investigation started as soon as the first version based on the plastic weighing funnel was completed, and was conducted in parallel with the mechanical improvements. Therefore, the preliminary investigation was carried out with the plastic funnel. Some of the frequency patterns are specific to the plastic funnel; some are common for both the plastic and stainless steel design. The principle difference between the two designs, concerning resonance properties of the system, is mass and stiffness.

5.4.2. Experimental design

The following experiment was conducted to characterise the output signal of the weighing system and confirm the hypothesis about expected sources of noise. A series of tests were conducted with the plastic funnel at various combinations of the following:

- engine rotational frequencies 1000, 1500, 2000 and 2500 r/min,
- weighing funnel empty (0 g) and fully loaded with water (1000 g),
- sprayer pump engaged and disengaged.

On each run, once the system had initially stabilised, a regular number of samples (18431) was acquired at a fixed sampling rate of 3000 Hz. From the Nyquist criterion, this includes frequency information up to 1500 Hz. The amplifier of the load cell has an internal bandwidth of 1000 Hz (–3 dB) therefore frequencies above 1500 Hz are suppressed by design and there should not be significant aliasing.

The sprayer engine can operate at any speed in the specified operating range (1000–2500 r/min). Higher engine operational speeds yield higher pump flow rate, thus higher fill rate of the tank and more efficient rinsing of the hopper.

Four engine speeds were chosen arbitrarily from the full operating range. A 4-cylinder 4-stroke engine has the significant vibration causing force oscillating at a rate twice of the crankshaft rotational frequency (Table 5-1). The engine speed was read from the cabin tachometer.

Table 5-1 Rotational frequency of the crankshaft and corresponding frequency of the vibration causing force

Crankshaft (r/min)	Crankshaft (Hz)	Principal exciting force (Hz)
1000	16.7	33.4
1500	25.0	50.0
2000	33.3	66.6
2500	41.7	83.4

The effect of hydraulic noise from the Venturi injector at the base of the induction hopper and other flows was investigated at an engine operating speed of 2000 r/min by using the hopper circulation valve and hopper outlet valve to allow or prevent flow in these circuits.

5.4.3. Characterisation of noise

The results of the trials identify the key sources of noise are at frequencies of sources identified above. From the frequency spectrum (Figure 5-5 and Figure 5-6) the following can be stated:

- significant noise is found in the range of 0–250 Hz,
- there is a predominant peak at the frequency which relates to frequency twice of the rotational speed of the engine recorded by the cabin gauge,
- liquid oscillating in the weighing funnel increases the magnitude of the peak and at low frequencies of 10–30 Hz.

The results of FFT (Appendix K) confirm the dominant peak is found at the frequency twice of the engine rotational speed as recorded by the cabin tachometer. However, this particular design showed tendency to resonate at 150 Hz when funnel unloaded and engine operating at 1500 and 2000 r/min (Figure K.5, K.6, K.9, and K.10 Appendix K). Significant peaks at 25 Hz with loaded funnel were found at engine operating 1500 r/min (Figure K.7 and K.8 Appendix K).

According to Dietsche & Klingebiel (2007) the magnitude of the free inertial force of a 4-cylinder in-line engine is proportional to the rotating frequency of the crankshaft. Therefore, the magnitude of noise is also proportional to the rotating frequency of crankshaft. That force increases the oscillation of the liquid in the funnel as well. The effect of running the sprayer pump (belt driven centrifugal type) has no significant effect on the ratio of noise in the output signal. The noise from the liquid fluctuating in the flexible hydraulic drives has a slight effect on the full funnel at typical engine operating speed of 2000 r/min on filling. Results are summarised in Figure 5-7.

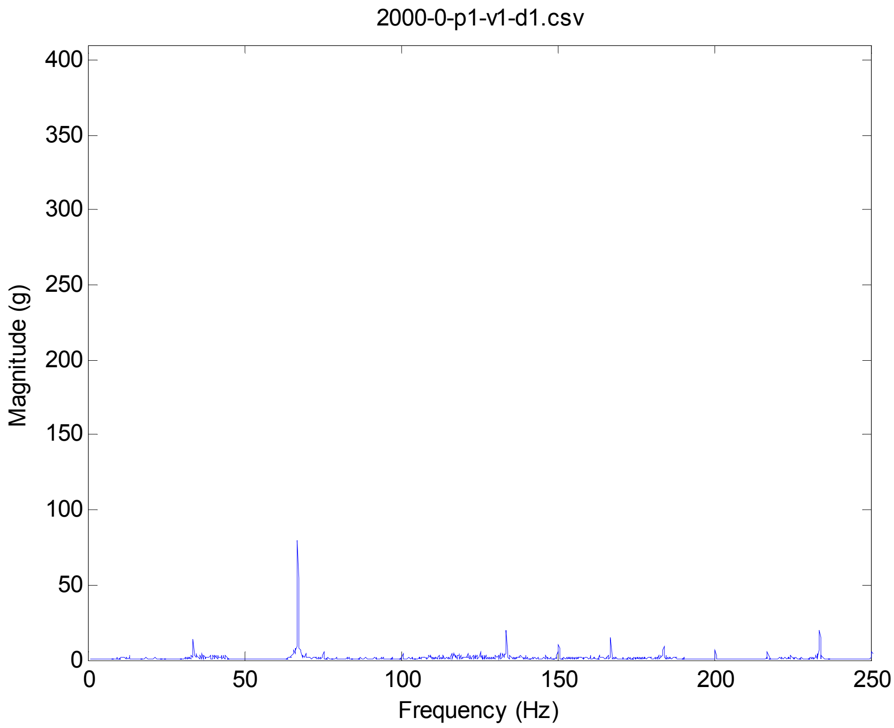


Figure 5-5 Frequency spectrum of the output signal at engine 2000 r/min, 0 g of weight in the funnel, pump on, circulation and outlet valves open

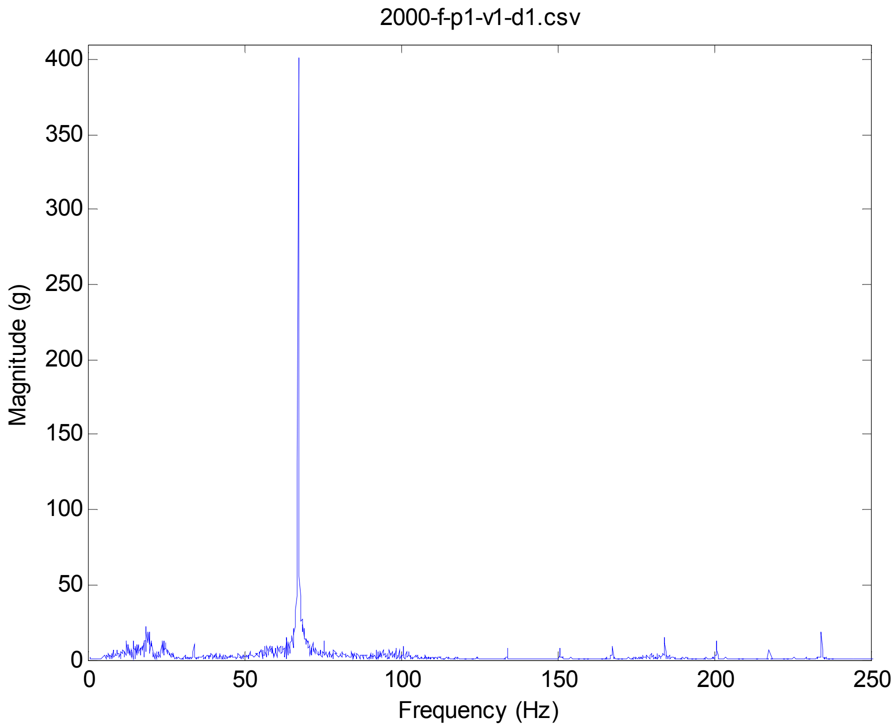


Figure 5-6 Frequency spectrum of the output signal at engine 2000 r/min, 1000 g of weight in the funnel, pump on, circulation and outlet valves open

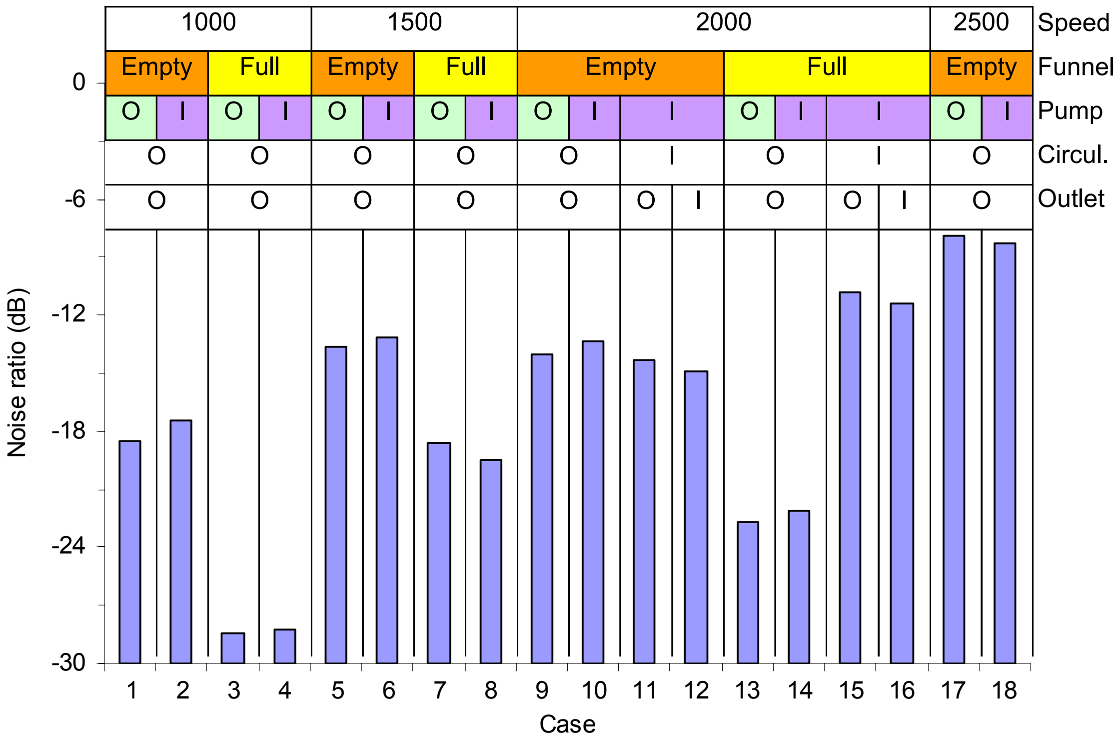


Figure 5-7 Ratio of noise in the output signal of the weighing system

The allocation of noise in the frequency band was investigated by dividing the spectrum into five analytical bands and finding the maximum ratio of noise across the cases:

- 0.33–29 Hz
- 30–90 Hz
- 91–250 Hz
- 251–500 Hz
- 501–1500 Hz.

The frequency band influenced by the engine (30–90 Hz) induces the highest level of noise to the signal (Figure 5-8).

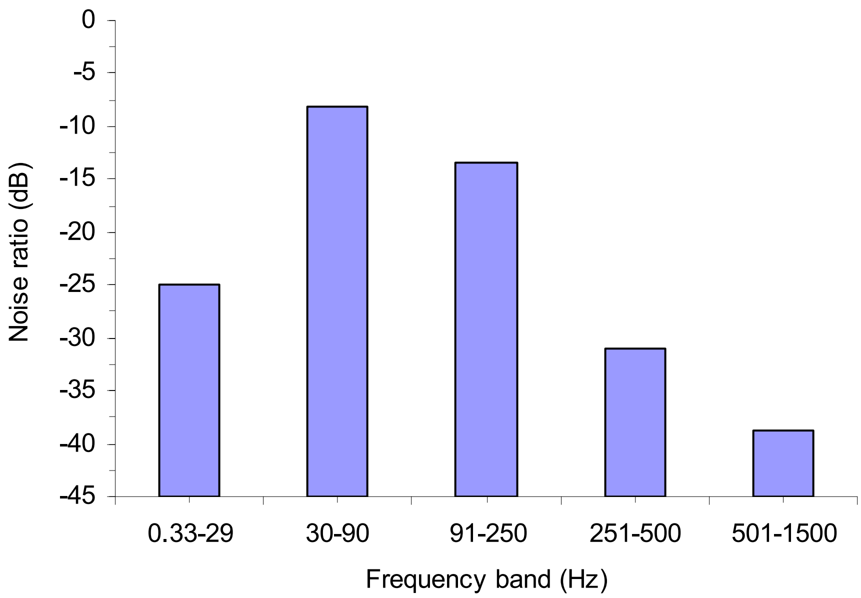


Figure 5-8 Noise ratio of the output signal by analysed frequency bands

Apart from the FFT analysis, sensitivity of weighing apparatus to electromagnetic interference produced by the RFID transmitter was observed. It was found this could easily be removed by switching off the RFID system when weighing without any effect on identification. This functionality was therefore included as an automatic function of the prototype hardware and software (Appendix E).

5.4.4. Noise suppression

The investigation has demonstrated that a very significant level of noise is present in the output signal of the weighing system. To remove this effect, and approach the specified required performance of the system, filters are required. Following the discussion above, they have been implemented with digital signal processing.

The potential for the simplest filter, a rolling average, is shown in Figure 5-9. As expected, it does not deliver adequate performance throughout the operating range due to the weak ability to separate frequency bands and the varying frequency components in the weighing system signal. Significant smoothing is possible. However, the size of the window (number of averaged points) has to be precisely matched for every operating condition. This is completely impractical for a system where the driving frequencies (e.g. engine speed) are freely adjusted by the operator.

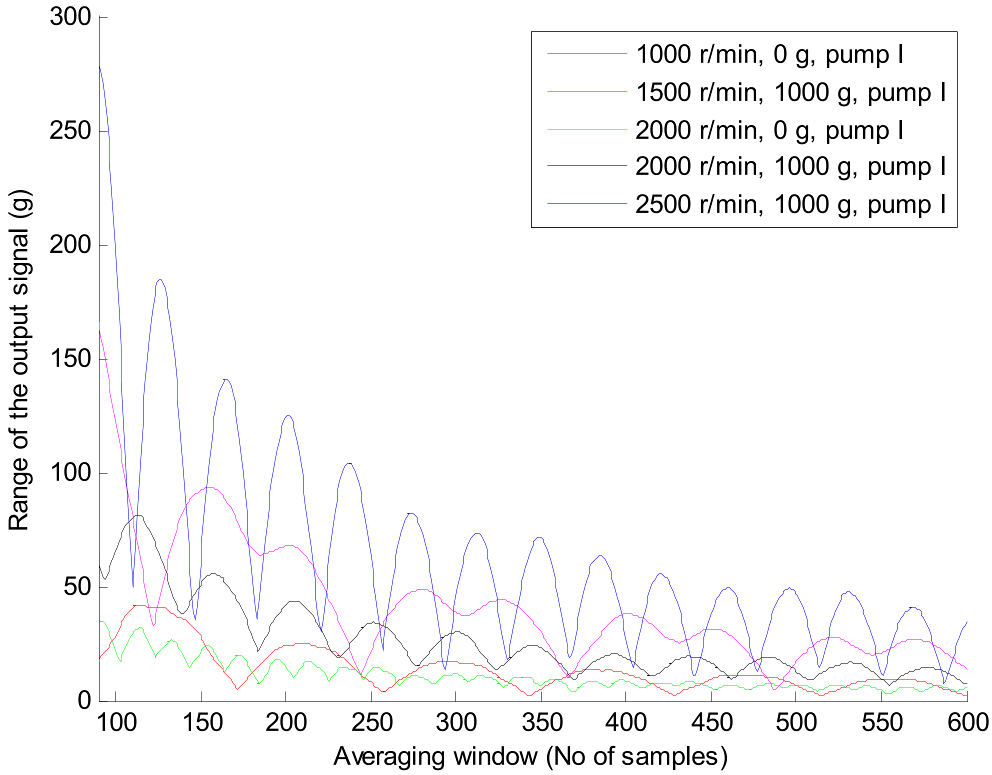


Figure 5-9 Results of applying rolling average filter at various engine rotational frequencies and static mass in the weighing funnel

The effect of a 3 Hz ripple free low pass filter was investigated. The results in Figure 5-10 confirm the noise was reduced considerably (12–37 dB) on all of the examined working cases. In practice it means the range of the output signal was reduced by 172–2103 grams (Figure 5-11).

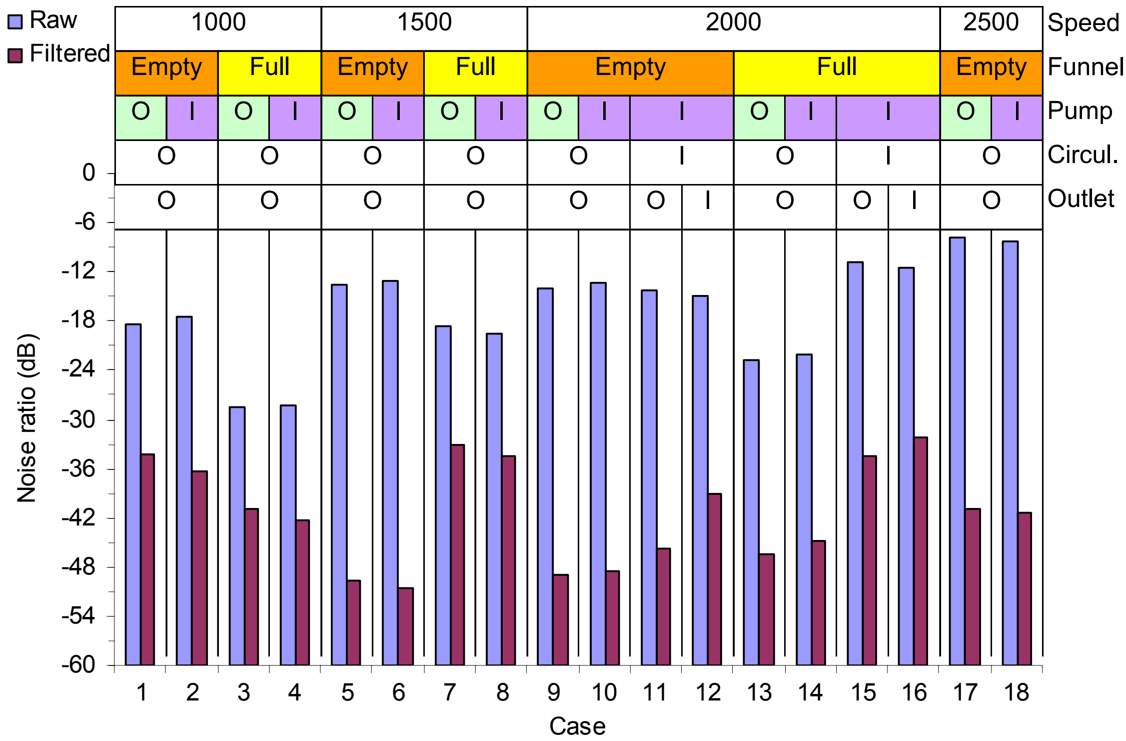


Figure 5-10 Effect of 3 Hz cut-off low pass filter on the ratio of noise in the output signal of the weighing system

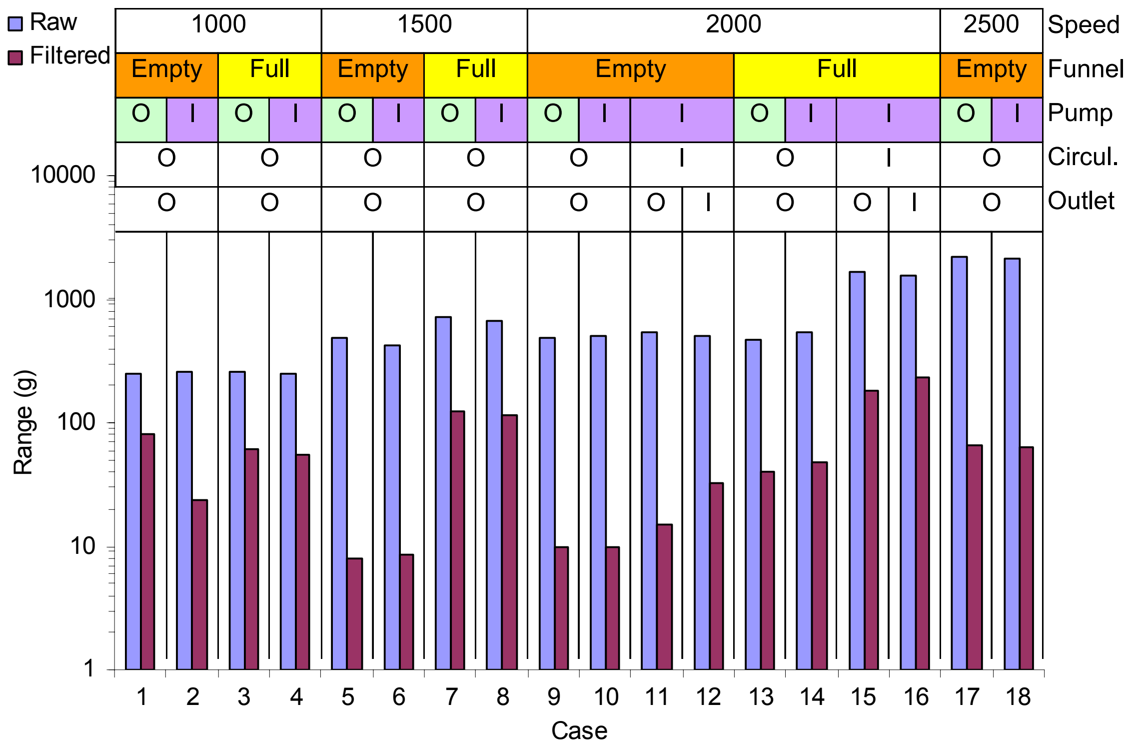


Figure 5-11 Effect of 3 Hz cut-off low pass filter on the range of the output signal of the weighing system

5.4.5. Difference between plastic and stainless steel weighing funnel

The fundamental difference between the plastic and stainless steel weighing funnel regarding resonance frequencies is mass (104 vs 555 grams, funnel empty), stiffness of the material and volumetric capacity. The stainless steel funnel produced here is capable of holding a larger amount of liquid which has larger oscillation energy at similar frequencies when excited by the engine.

The natural frequency f_n of a system is equal to $\frac{1}{2\pi}\sqrt{\frac{k}{m}}$ where k is the stiffness and m mass. The stiffness (k = 196,078 N/m) was calculated by measuring the deflection of the load cell element under a range of loads and plotting the results in N/mm and taking a regression to identify the slope (Appendix L). By inserting the mass range of each funnel system, from empty mass to total mass full of liquid of the maximum specified density, the following operating ranges were obtained as shown in Figure 5-12. A stiffness of at least k = 648,824 N/m would give the required characteristic to avoid engine frequency.

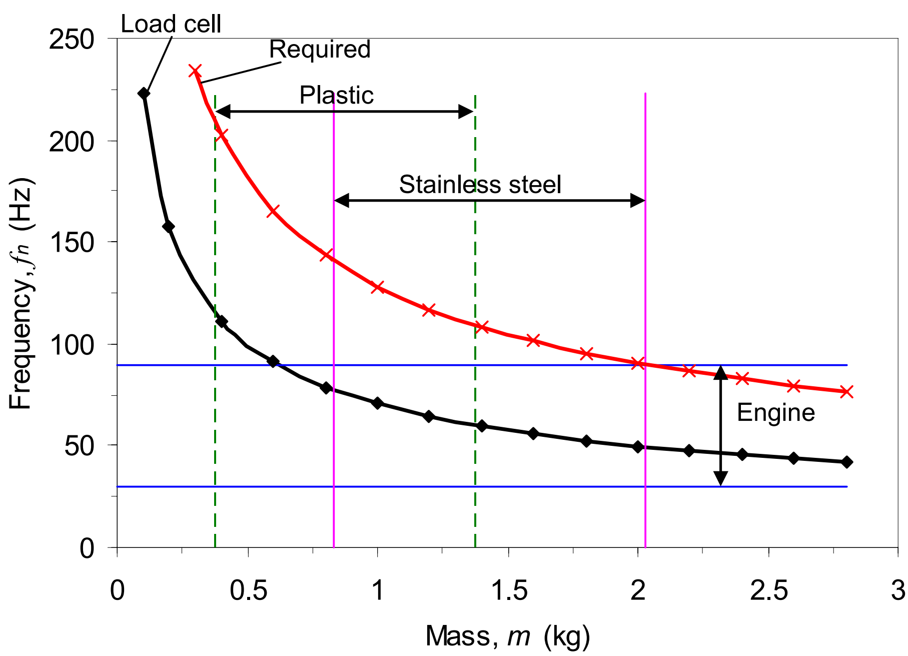


Figure 5-12 The effect of mass on the natural frequency of the load cell

5.5. Detailed performance review – stainless steel implementation

5.5.1. Rationale

The preliminary investigation confirmed the belief that the engine induced vibration is the most significant source of mechanical noise on the load cell output signal. Low pass filtering has been demonstrated to be useful in improving the system performance. To improve the understanding in relation to interactions of engine rotating frequency, mass in the weighing funnel and oscillations of liquid in the funnel, more complete investigation with the stainless steel weighing funnel was conducted.

5.5.2. Experimental design

Previous trials demonstrated engine rotational speed as indicated by the manufacturer's instrument, is related to the single clearly identifiable peak on an FFT plot. Therefore to allow engine speed to be measured more accurately and simultaneously with data from the load cell, an accelerometer was mounted to the chassis of the sprayer. This measured vibration in a vertical axis, which could be processed via an FFT to determine the instantaneous speed of the engine.

The engine was operated across the operational speed range of 1000–2500 r/min, in combination with a range of weights of fluid in the measuring funnel (0–1200 g). The weight was incremented by 100 grams and at each weight the rotational speed of the engine was gradually increased from 1000 r/min to 2500 r/min in steps of 125 r/min. Previous analysis demonstrated no significant signal above 250 Hz, therefore a sampling rate of 500 Hz was used. The sprayer pump was engaged and circulation and outlet valves were fully open which was previously observed the worst case in terms of measuring noise.

5.5.3. Results

From the acquired data a three dimensional noise map was constructed (Figure 5-13 and Figure 5-14). The results indicate the highest rate of noise (dB) is found with 100–200 grams of liquid in the weighing funnel and the engine running at 2200–2300 r/min. The noise curve at zero weight correlates with the resonance frequency of the load cell (see Figure 5-12).

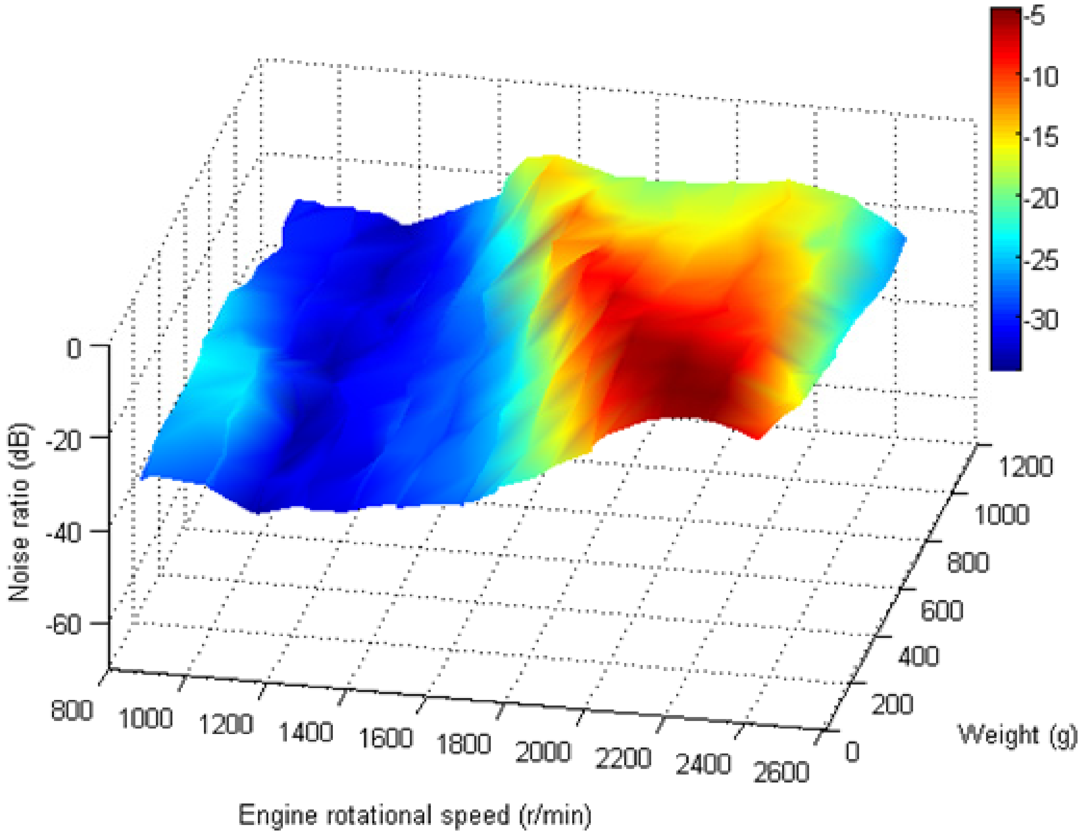


Figure 5-13 Noise ratio in relation to engine rotational speed and weight in the funnel

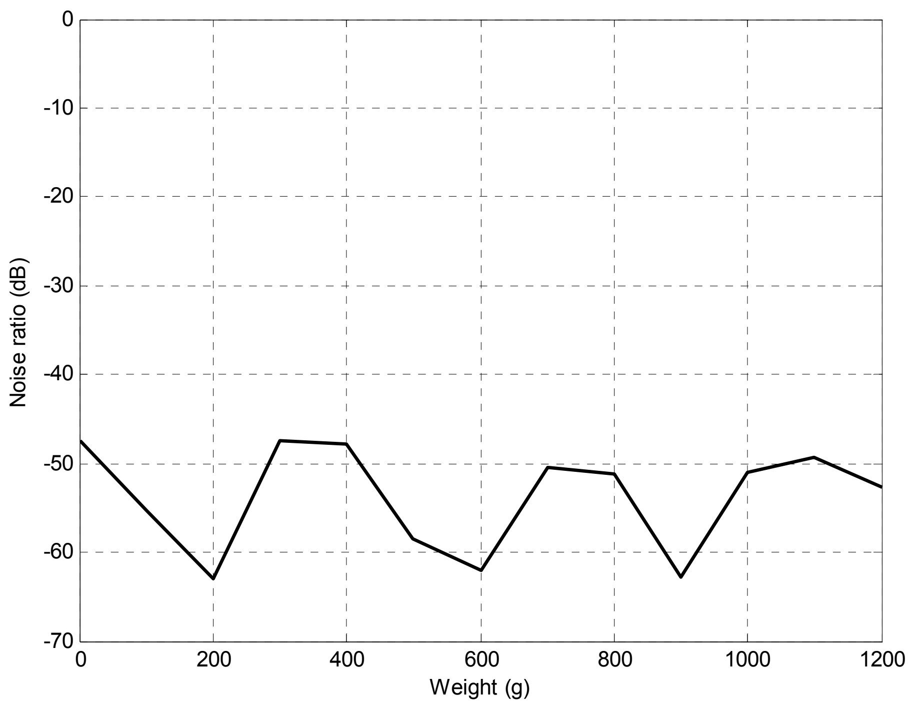


Figure 5-14 Noise ratio in relation to weight in the funnel with engine switched off

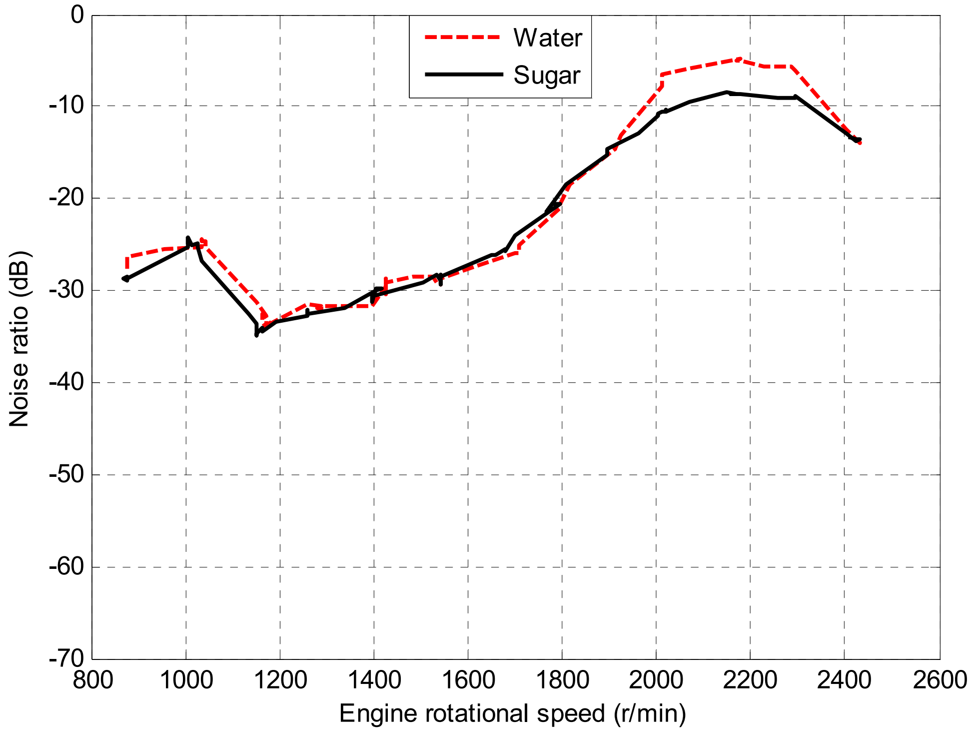


Figure 5-15 Comparison of noise ratios of liquid and granular material at 200 grams of static mass in the funnel

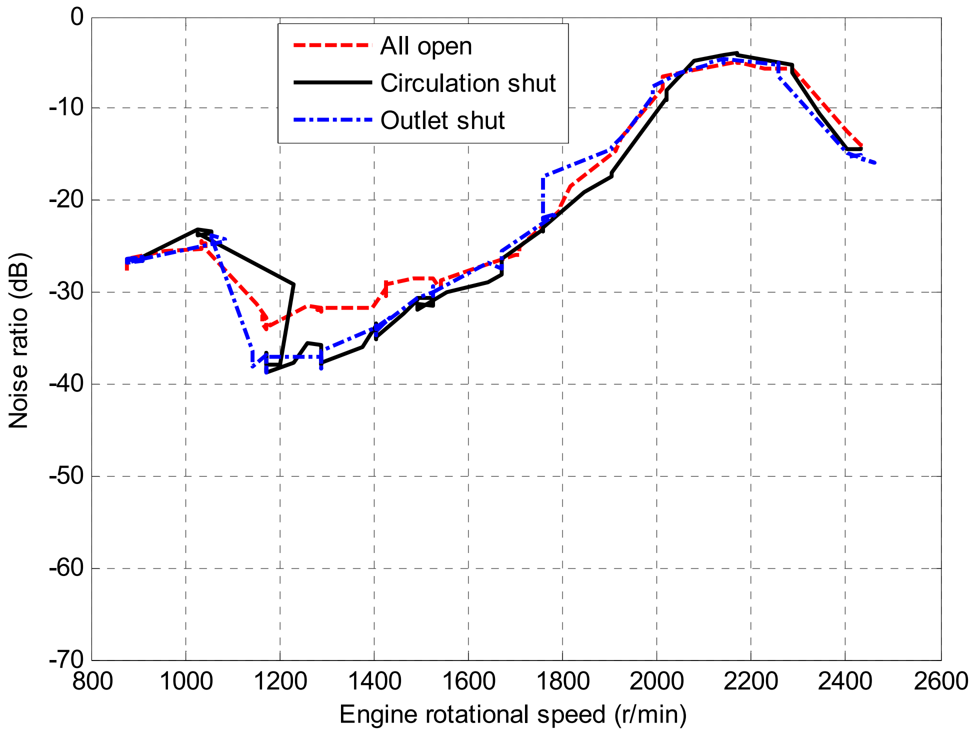


Figure 5-16 Comparison of noise ratios at different valve configurations at 200 grams of liquid in the funnel

It was confirmed that a liquid in the weighing funnel has a higher noise ratio (increased by 3.7 dB) than a granular material because of oscillations of the material (Figure 5-15).

The investigation of the effect of flowing and pulsating liquid in the hydraulic hoses passing the induction hopper indicated no difference in noise level (Figure 5-16).

5.5.4. Implementation of digital filter

Based on the above investigation, a specific low-pass FIR filter was designed and implemented to block unwanted high-frequency signals while retaining adequate display response for real time monitoring of the quantity by the operator during filling. The filter implemented has the magnitude response as shown on Figure 5-17 and the following characteristics:

Type	low pass 128th order FIR filter
Cut off frequency	3 Hz
Nyquist frequency	500 Hz
Roll off	smooth, ripple free

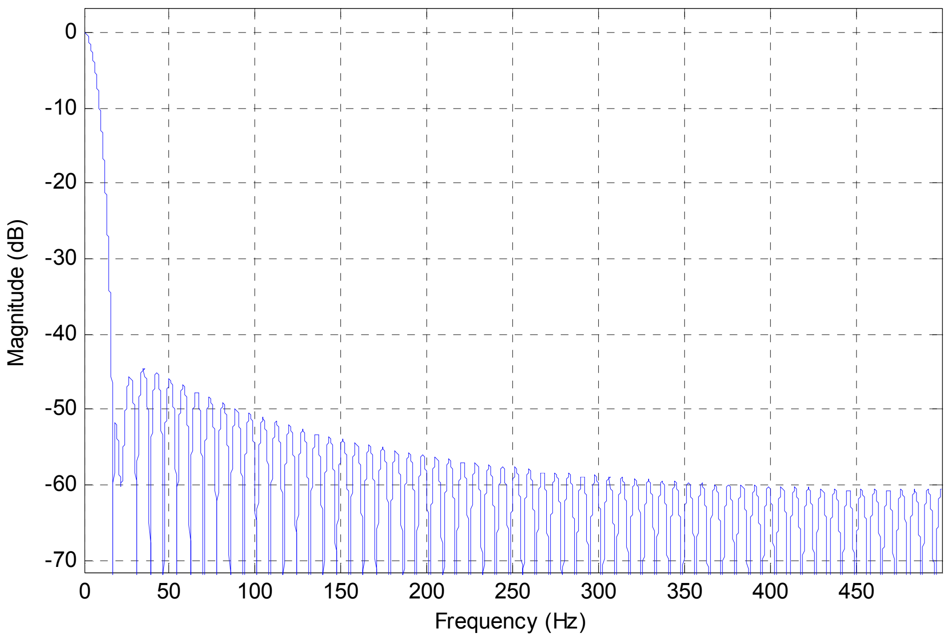


Figure 5-17 Magnitude response of the implemented filter

The output sequence $y(n)$ of the FIR filter in time domain may be expressed in the following way (Lyons 2004), where $x(j)$ is the input sequence of length Q and $h(k)$ sequence of filters coefficients (impulse response) of length P:

$$y(n) = \sum_{k=0}^{P+Q-2} h(k)x(n-k) \qquad (5\text{-}12)$$

Eq. (5–13) is effectively the definition of convolution of two inputs

$$y(n) = h(k) * x(n) \qquad (5\text{-}13)$$

The Eq. (5–13) is implemented as a software function as shown on Figure 5-18.

```
'Convolution
For j = 0 To (N - 1) 'Loop for each point in X()
    For k = 0 To (M - 1)  'Loop for each point in H()
        Y(j + k) = Y(j + k) + X(j) * H(k)
    Next k
Next j

'Sum
For k = M To N
    Y1 = Y1 + Y(k)
Next k

'Mean of Y1 - the filtered result
Y1 = Y1 / (N - M)
```

Figure 5-18 Software implementation of the filter

The results in Figure 5-19 confirm the filter's performance of attenuating unwanted high frequency components. Filtering reduces the overall noise ratio from a level of –8.56 dB to –59.8 dB. However, there is a residual component of –73 dB at principal excitation frequency (67 Hz) which corresponds to a magnitude of 1.5 g (Figure 5-20). As expected, some noise (up to 1.6 g) is also evident in the pass band and filter's roll off zone (1–10 Hz).

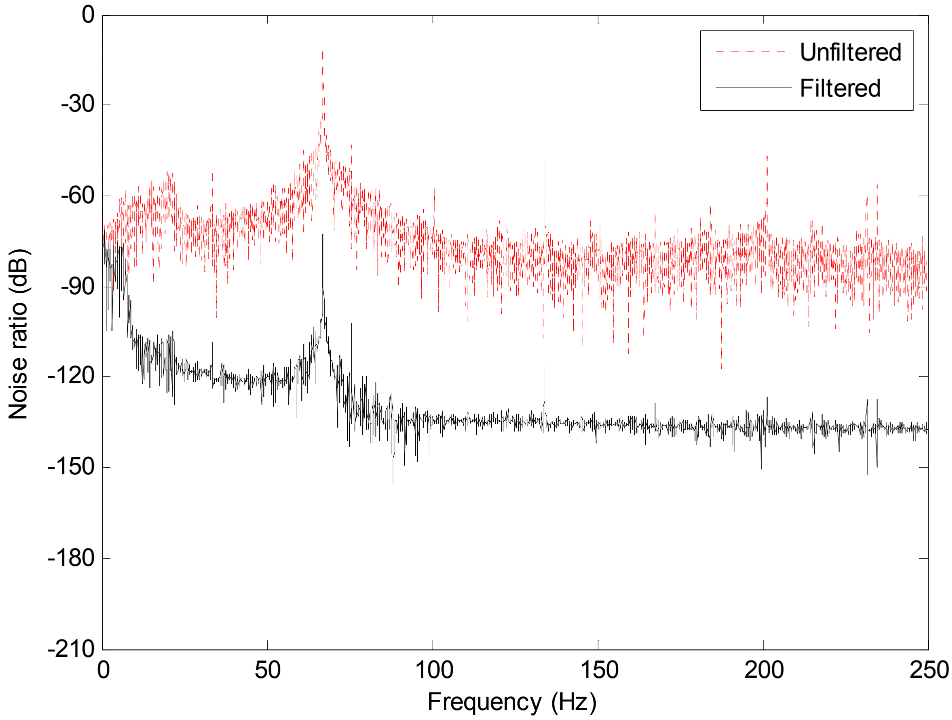


Figure 5-19 Frequency spectrum of the output signal at engine 2000 r/min and 600 grams static mass in the weighing funnel

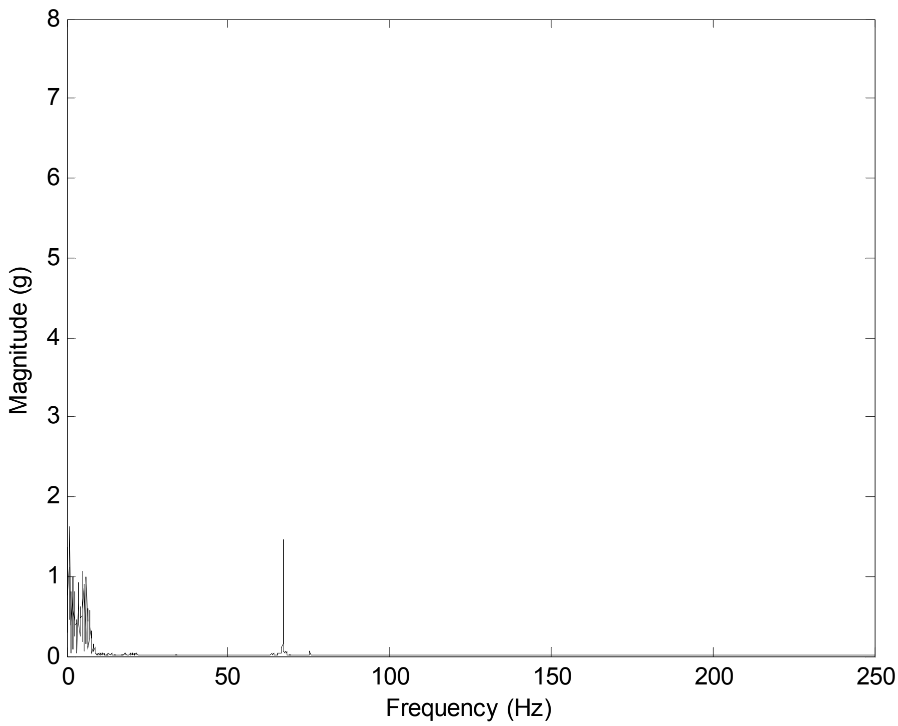


Figure 5-20 Magnitude spectrum of the filtered output signal at engine 2000 r/min and 600 grams static mass in the weighing funnel

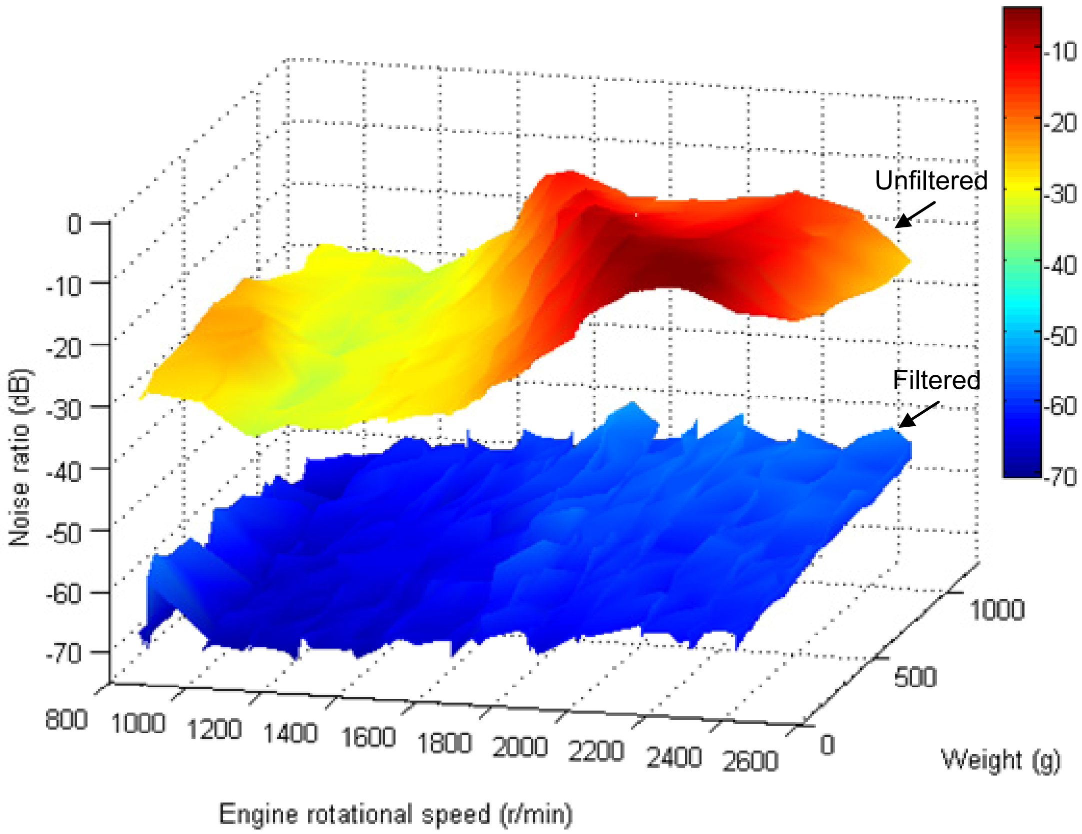


Figure 5-21 The effect of 3 Hz cut off low pass filter on the noise ratio

As a result of filtering, a digital low pass filter with 3 Hz cut off frequency reduces the noise ratio to a level of –52 to –70 dB (Figure 5-21).

The investigation of the working accuracy of the weighing system after implementing the digital low pass filter demonstrated a variation seen on the screen of 9 grams which indicated the need for extra smoothing to achieve stipulated resolution (Section 4.4.3). A second stage of rolling mean of 5 values was added to the low pass filter which provided sufficient stability to the output value displayed on the screen to the operator. However, the mean of 5 values slowed down the response of the system, resulting in a response time in the order of 2 seconds as the averaging window moves through the data. That was observed to cause overdosing if dispensing liquid at a high rate near the target amount from a container with large neck diameter.

This issue was resolved by designing an additional visual feedback device – an 8 segment LED bar (see Section 4.5.8). Numerical data on the screen is precise but slower for humans to read and react. Although the LED bar has high increments, it is much faster for humans to read and to understand the progress of a process. The lower resolution of the LED bar allowed receiving of low pass filtered signal before averaging for fast update rates without loosing in performance.

5.5.5. Verification of filter implementation

The performance of the filter was verified by loading water, target amounts ranging 100, 200, 500, 600 and 1200 grams, into the weighing funnel under real working conditions and identifying maximum error seen on the screen both at the start of weighing and at target amount. The engine of the sprayer was set to operate at typical working speed (2000 r/min), and all services (pump and valves) switched on.

On the example of loading 200 grams: without filtering, the output on the screen is fluctuating with a range of 2240 grams. After applying 3 Hz low pass filtering, the range is reduced to 8.8 grams (Figure 5-22). Further reduction to the level of 2.7 grams is achieved by averaging with a window of 5 (second stage) with a cost of a time lag (Figure 5-23).

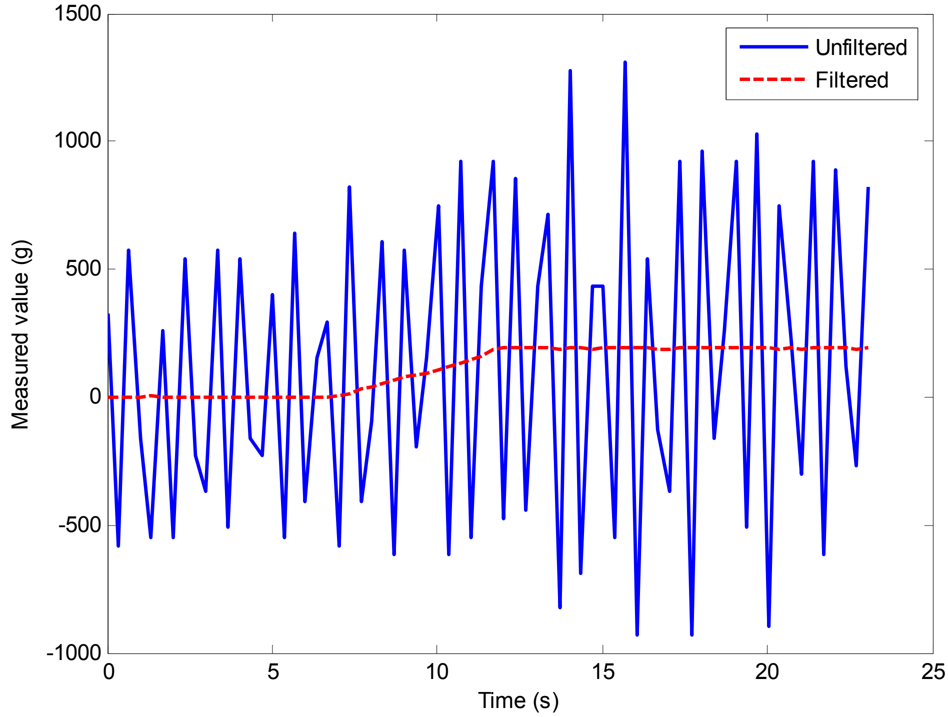


Figure 5-22 The effect of 3 Hz cut off low pass filter on the screen output

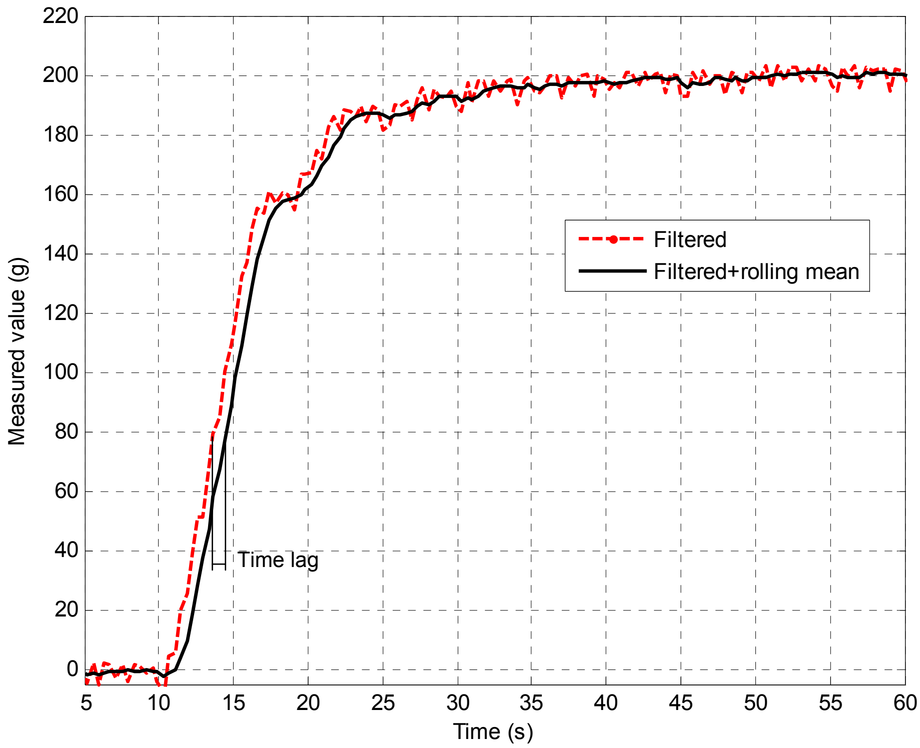


Figure 5-23 The effect of second stage filter rolling average of 5 on the screen output

The overall results in Table 5-2 demonstrate a variation of 7.6–11.0 grams after filtering signal and 2.0–3.6 grams after filtering with additional rolling mean.

Although the original specification (1.2 g/ha) has not been attained, the demonstrated resolution of 3.6 grams allows insertion of amounts as small as 36 grams with an error smaller than ±5% (see Section 4.4.2).

Table 5-2 Maximum variation of the screen output

Target amount (g)	Start (0 g)		Target	
	Filtered (g)	Filtered+mean (g)	Filtered (g)	Filtered+mean (g)
100	10.7	3.6	10.7	3.1
200	7.6	2.0	8.8	2.7
500	8.8	3.3	9.8	3.2
600	10.7	3.0	9.6	2.6
1200	9.4	3.1	11.0	3.0

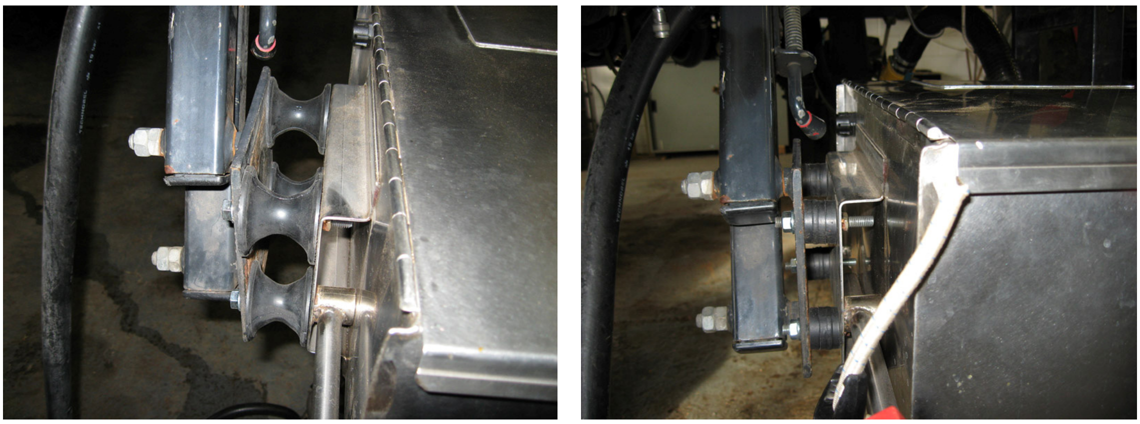
5.5.6. Mechanical damping

An experiment was undertaken to investigate the introduction of rubber mounts to reduce the propagation of mechanical vibration to the induction hopper. The principal aim was to quantify the general potential of a simple unoptimised rubber mounting system.

Commercial rubber mounts are often designed to work in compression, shear or both at the same time. The arrangement of the mounting plate on the induction hopper required the rubber mounts to be attached transversely by which is at right angles with the direction of the chief vibration force and sets the two top mounts under tension. The attenuation rate of the rubber mounts at lower frequencies increases with stiffness (deflection). The operational weight of the induction hopper varies in the range of 12–32 kg depending on the amount of liquid in it.

Two sets of rubber mounts, Diabolo and cylindrical, were selected for investigation. The Diabolo mounts were found to be insufficiently stiff: the large deflection under static load approached the limits of the mounts (Figure 5-24a). Cylindrical mounts (Figure 5-24b) had sufficient mechanical strength with a cost of lower deflection. The principal exiting force was reduced significantly compared to the case directly connected to the sprayer, however the lower stiffness reduced the resonant frequency sufficiently that noise passed through the digital filter (Figure 5-25). The noise ratio was –27 dB, filtering reduced it to –48 dB which is higher than in case of directly connected mounting. Rubber mounts were not able to completely absorb the peak at principal excitation frequency (67 Hz) as shown in Figure 5-26. The magnitude at filter's roll off zone was higher (5.7 g) than on direct connection. The variation of the screen output was in the range of 2.8–10.0 g as a result of applying filtering and rolling mean. This variation was greater than in case of direct mechanical connection.

The investigation indicates that in order to obtain benefit from rubber or other isolation mounts a more detailed study is required, using alternative mechanical designs and detailed selection of components.



(a) (b)

Figure 5-24 Induction hopper attached with rubber mounts: (a) Diabolo, (b) cylindrical

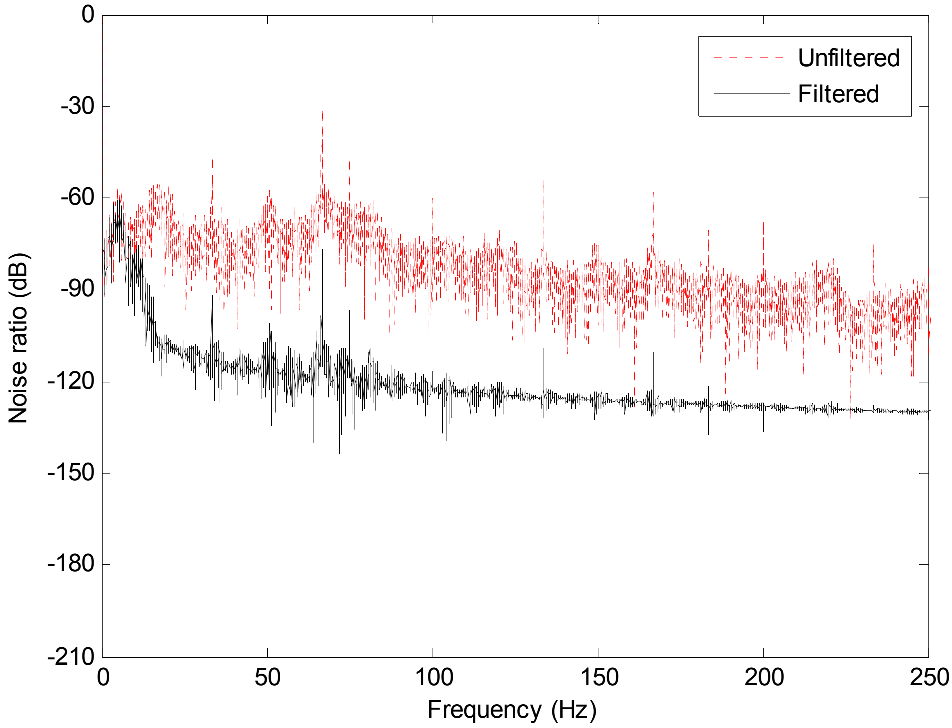


Figure 5-25 Frequency spectrum of the output signal with rubber mounts at engine 2000 r/min and 600 grams static weight in the weighing funnel

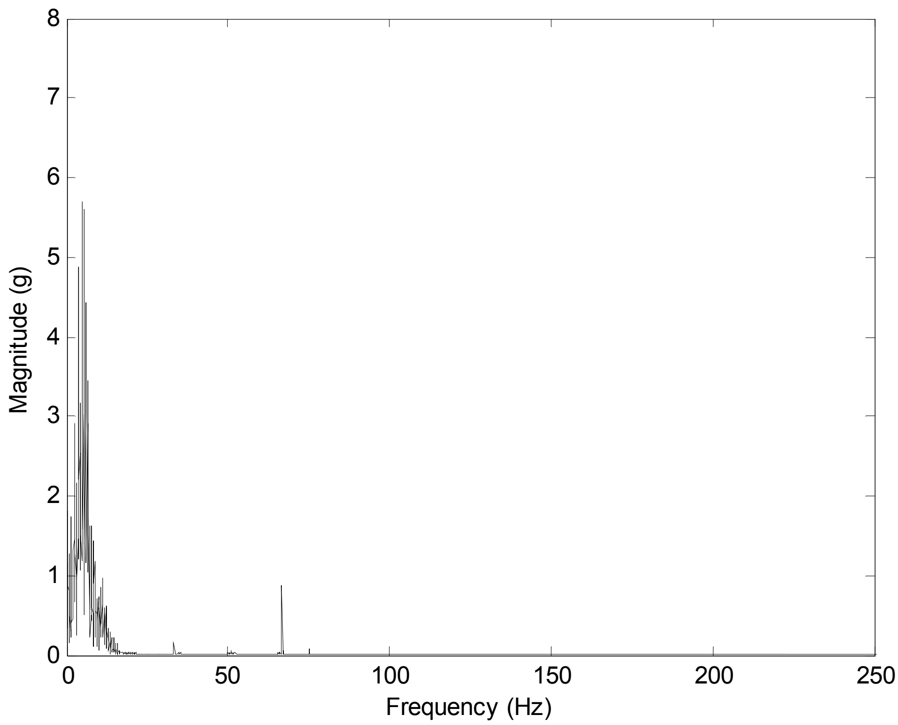


Figure 5-26 Magnitude spectrum of the filtered output signal with rubber mounts at engine 2000 r/min and 600 grams static weight in the weighing funnel

5.5.7. Mechanical isolation

The approach of isolating the induction hopper mechanically from the chassis of the tractor was investigated. For the trial the induction hopper was mounted on an independently standing metal frame which allowed complete mechanical isolation. The results in Figure 5-27 demonstrated a significant reduction of the noise in the output signal: both the peak magnitude and noise ratio (–34 dB) have been reduced. The filter was able to attenuate the main noise component (67 Hz) below –100 dB. However, the overall noise ratio of –57 dB is similar to the case of direct connection. The magnitude spectrum at the filter's roll zone (Figure 5-28) was similar to that of mounted on the sprayer. The variation of the screen output was in the range of 2 grams.

5.5.8. Engine switched off

Logically, the lowest level of noise is attained if the engine is switched off. In that case at all of the frequencies through the spectrum the ratio of noise is below –100 dB level (Figure 5-29). The overall ratio of noise is –70.0 dB which can be reduced to –89.1 dB with filtering. The magnitude of 0.05 g is negligible (Figure 5-30).

5.5.9. Analogue filtering combined with digital filtering

The desired option is to have the induction hopper directly mounted on the sprayer without any additional mechanical components for simplicity. Although the digital low pass filter implemented provides a significant suppression of noise some leakage was evident at the principal excitation frequency. A common approach is to use commonly available standard parts analogue filtering as the first stage for signal conditioning such as anti aliasing. For herein application, a maximally flat response low pass analogue filter with no DC error is required. For example a suitable filter is a 5th order low pass Butterworth filter such as Linear Technology LTC1063 (http://www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1154,C1008,C1148,P1264,D4050). Matlab software may be used to simulate the analogue components. Such filter with –3dB point at 3 Hz (Figure 5-31) demonstrated a performance as shown in Figure 5-32.

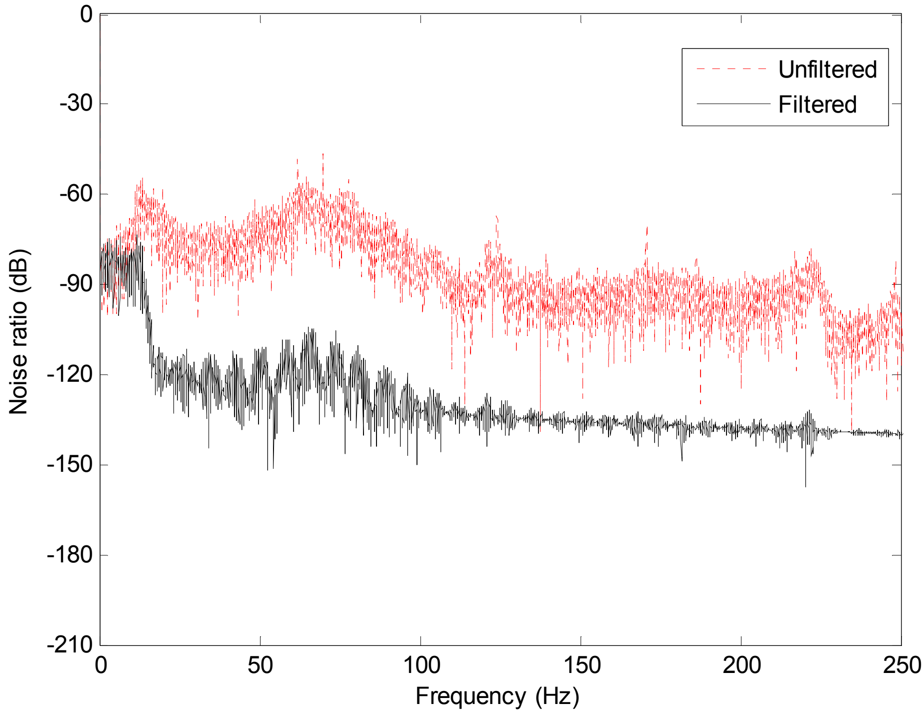


Figure 5-27 Frequency spectrum of the output signal if mechanically isolated at engine 2000 r/min and 600 grams static weight in the weighing funnel

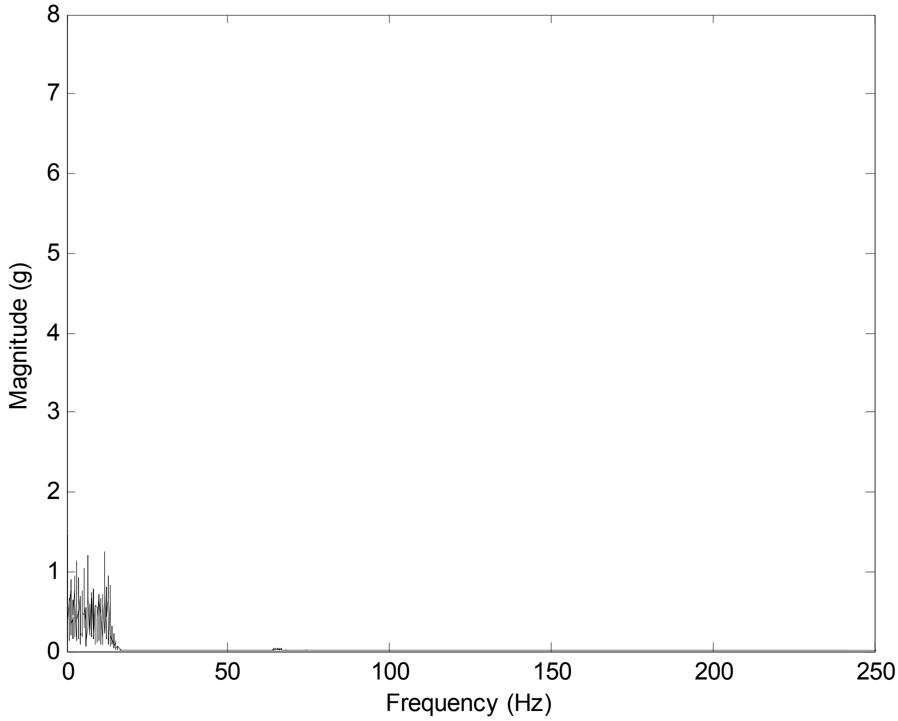


Figure 5-28 Magnitude spectrum of the filtered output signal if mechanically isolated at engine 2000 r/min and 600 grams static weight in the weighing funnel

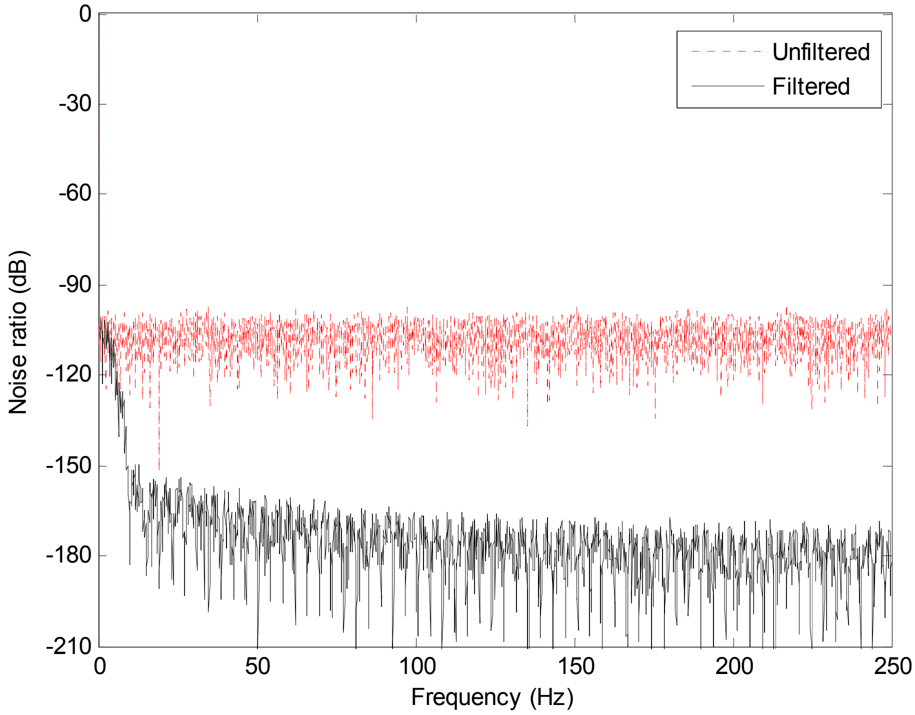


Figure 5-29 Frequency spectrum of the output signal if 600 grams static weight in the weighing funnel and engine switched off

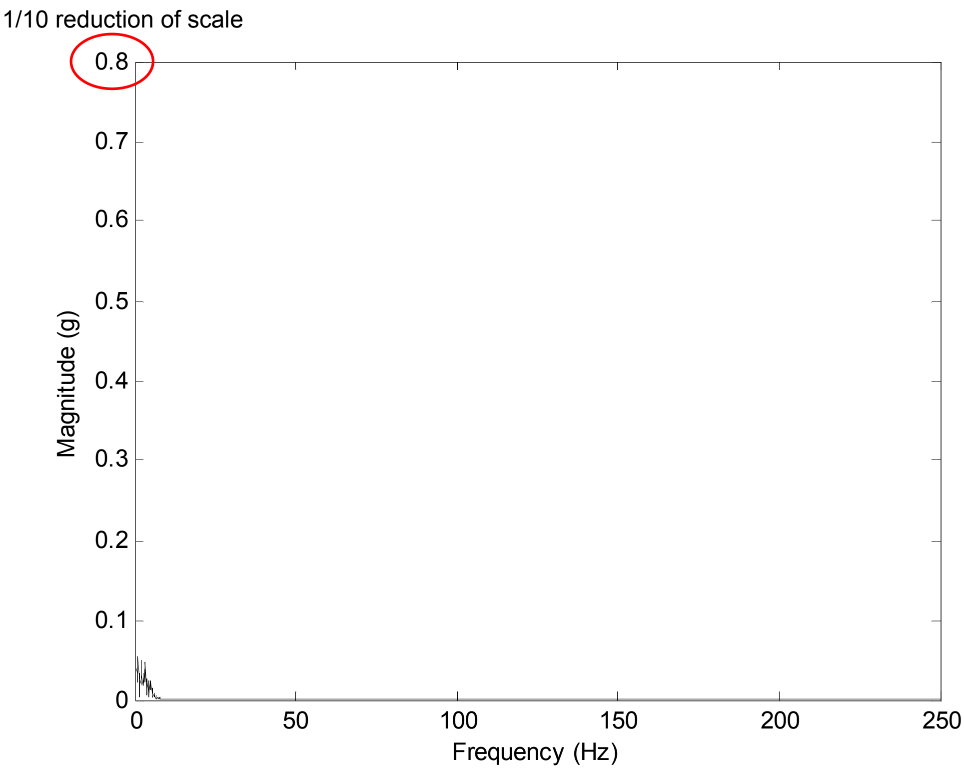


Figure 5-30 Magnitude spectrum of the filtered output signal if 600 grams static weight in the weighing funnel and engine switched off

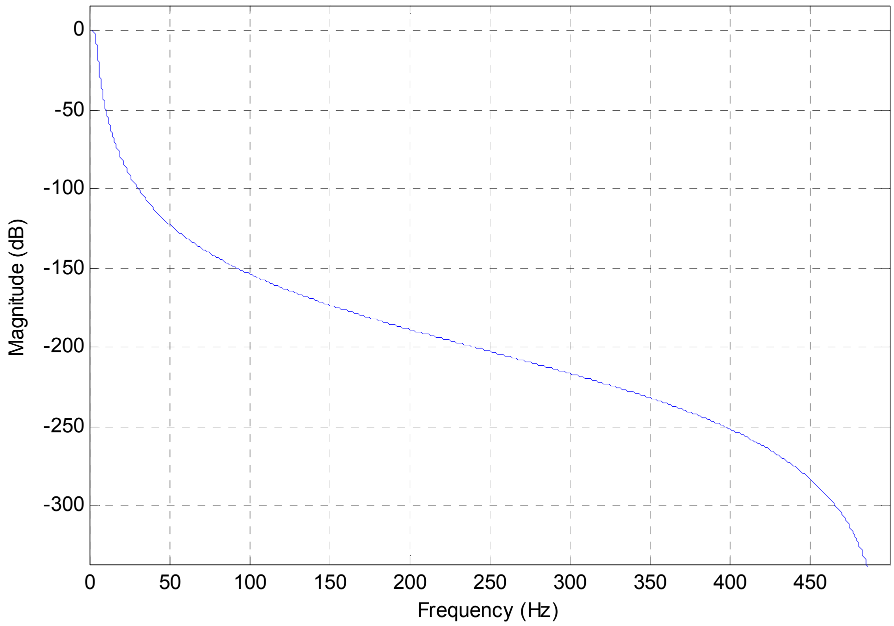


Figure 5-31 Magnitude response of the 5th order Butterworth low pass filter with a cut off frequency of 3 Hz

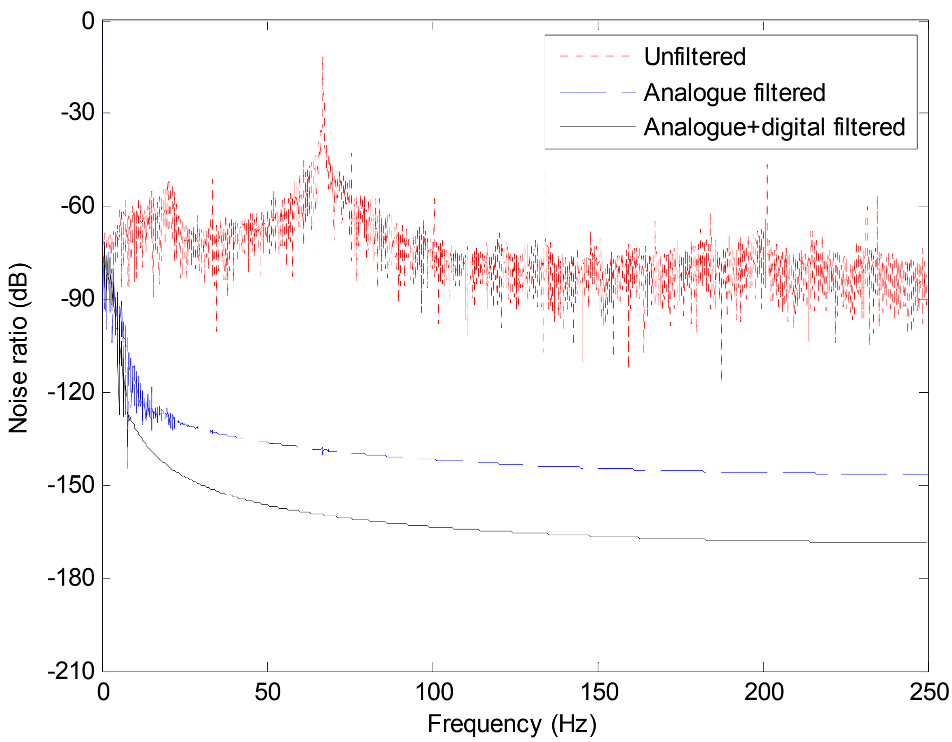


Figure 5-32 Frequency spectrum of the analogue and analogue plus digital filtered output signal if 600 grams static weight in the weighing funnel

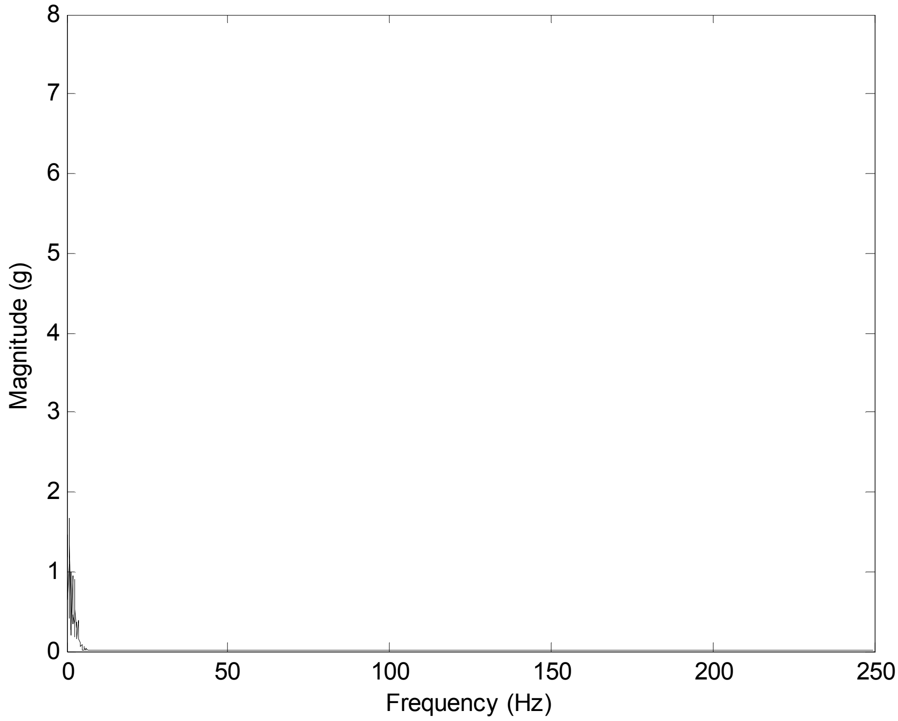


Figure 5-33 Magnitude spectrum of the analogue plus digital filtered output signal if 600 grams static weight in the weighing funnel

The overall noise ratio after "analogue" filtering is reduced to –62.0 dB which is –2.2 dB lower than digital filter. Further digital filtering reduces it to –62.7 dB. The critical area in terms of noise passing for both filters is the roll off zone as shown in Figure 5-32. The magnitude of the noise remains within 1.7 g (Figure 5-33). Only for analogue filter the magnitude is 1.9 g.

5.6. Discussion

The work herein chapter has demonstrated digital filtering is an appropriate approach to suppress the unwanted high frequency noise in the output signal of the weighing system. Although the design and reconfiguration of digital filters is very flexible there are some aspects to consider. The requirement of a ripple free response in the pass band means inherently the filter has a smooth roll off curve. Significant noise frequencies in the roll off area may pass through the filter as was found to be the case with rubber mounts which due to the lower stiffness produced a resonant frequency to this area. The requirement of adequate response speed for the operators sets the lower limit of the cut off frequency. A 3 Hz response satisfies a mean human reaction time. The significant peak magnitude at the principal excitation frequency in the range of 33–83 Hz requires attenuation in the order of –90 dB. The attenuation rate of around –50 dB allowed noise in the magnitude of 1.5 g leak through the filter implemented at these frequencies. The investigation of signal conditioning demonstrated a suppression of noise from a ratio of –4.7 to –34 dB unfiltered to –52 to –70 dB filtered at a complete range of operating conditions.

The desired option in terms of mechanical simplicity is to have the induction hopper mounted directly on the sprayer. The mechanical vibration induced noise in the output signal can be successfully filtered with a multi stage filtering approach. The investigation demonstrated the suggested route is to implement an analogue filter for primary signal conditioning, secondly a digital filter and for final smoothing of the low frequency fluctuations an averaging filter. However, these stages have to be designed retaining adequate system response time.

The benefits of digital filtering can readily be integrated into the sprayer's ISO 11783 data management. To achieve the best accuracy the controller of the weighing system could be programmed to send automatically a request to the engine ECU to adjust the engine speed to the level of lowest noise input according to the noise map and target amount. The engine speed could then revert after the immediate weighing operation is complete. If very high resolution (1.2 g) is required such as for very low application rates of highly concentrated products, the engine could be switched off temporarily. This measure has no costs associated in contrast to a rarely required very high precision isolated measuring system.

5.7. Conclusions

The following conclusions can be made:

- The most significant source of mechanical noise affecting the performance of the weighing system in this application is the diesel engine. Diesel engine is the main source because the peak in the FFT graph is found on the frequency induced by the engine.

- The highest levels of noise in the raw load cell output in relation to the signal (–4.74 dB) are at 2200 r/min engine operational speed and 100–200 grams of static mass (water) in the weighing funnel.
- Liquid moving independently in the weighing funnel (200 g) induces peak noise ratio of –4.8 dB. Granular material has 3.7 dB (2.3x) lower level of noise (–8.5 dB) at the same static mass in the weighing funnel.
- The circulation valve and the outlet valve of the main induction hopper do not have significant effect on the noise level at previously detected situation with maximum noise ratio (200 g of water in the weighing funnel).
- As a result of filtering, a digital low pass filter with 3 Hz cut off frequency reduces the noise ratio to a level of –52 to –70 dB from –4.7 to –34 dB.
- A low pass digital filter with a cut off frequency of 3 Hz (–3 dB) delivers good performance: the error seen on the screen is reduced to 11.0 grams. Additional smoothing by averaging 5 filtered values reduces the error to 3.6 grams which allows insertion of quantities from 36 grams without an error larger than ±5%.

6. Evaluation of the operator performance

6.1. Objective

The commercial success of the AACTS depends largely on its performance in terms of accuracy, work rate, usability, reliability and ability to generate accurate traceability records. The acceptance of the AACTS by the sprayer operators, i.e. users, depends on their interaction with and perception of many aspects of the AACTS. A true evaluation of performance and perception requires assessment under real working conditions. This chapter will evaluate all technical aspects including RFID data protocol (Chapter 3), measuring system and user interface (Chapter 4), and signal filtering (Chapter 5) when operated by representative users.

An experiment was conducted with ten sprayer operators. The specific objective being to evaluate the accuracy of the prototype in dispensing agrochemicals and record keeping and the relative speed of the operation by comparing the performance with conventional manual methods.

6.2. Methodology

The control box and user interface were mounted on a sprayer (AGCO Spra-Coupe 4440), the modified induction hopper was hydraulically connected to the sprayer pipework. In this case the induction hopper was mechanically isolated from the sprayer and mounted on an independent metal frame standing beside the sprayer chassis. This arrangement provided the noise suppression performance closest to the suggested real implementation (see Chapter 5). During the experiment a realistic operational situation was created with (1) the engine of the sprayer operating at 2000 r/min, (2) the sprayer pump engaged and (3) the recirculation of the tank through induction system switched on.

Each operator followed the same training process where a 15 minute introduction and practice of 2–4 loading cycles was given after which the operators were sufficiently confident to use the automatic recording system. Training was followed by 6 different randomly generated experimental tasks which are detailed in Table 6-1.

During each of the tasks, the operators were asked to load a set of three simulated agrochemical “products” into the sprayer using the automatic system. The tasks were repeated in randomised order with the conventional manual method using a standard induction hopper and a set of standard measuring jugs (Figure 6-1a). The operators were asked to follow recommended good working practice (Defra, 2006) with face shields and rubber gloves used as personal protective equipment (PPE). With the automatic recording system the operators received the instructions electronically on the screen from a task file (Figure 6-1b), with the manual method they received the prescriptions printed on a sheet of paper and were asked to complete the record sheet after measuring and loading of the agrochemicals.

(a) (b)

Figure 6-1 Measuring agrochemicals with (a) manual and (b) automated method

The time to complete each individual loading task (Δt) was measured for both the automatic (Figure 6-2) and manual method. For the manual method the time to write the records of filling was also measured. The containers holding test products were measured before and after each dispensing operation with a calibrated laboratory type electronic balance (Sartorius type 1501, range 12000 g, resolution 0.1 g, linearity 0.1 g). The difference in weight being taken as the quantity of product dispensed. For safety, simulated materials were used in place of active chemical products. These were intended to represent the spectrum of properties of real agrochemicals namely:

1) water named "aqua",
2) water mixed with methylcellulose (1 %) (wall paper paste) to produce a viscous liquid named "gluupy",
3) white granulated "sugar" as water soluble granules.

The containers of products were labelled with ISO 15693 compatible RFID labels (TI Tag-it 13.56 MHz inlay 256 bit).

To obtain a more detailed insight of the operator interaction with the system, the software was arranged to make additional timings during the operation of individual tasks (Δt), the start point of weighing (t_1), the end point of weighing (t_2), and the end point of full pack loading (t_3) were measured during the experiment (Figure 6-2). The system updates at an overall frequency of 3 Hz as described in Chapter 5 therefore the resolution of the time intervals was 1/3 s.

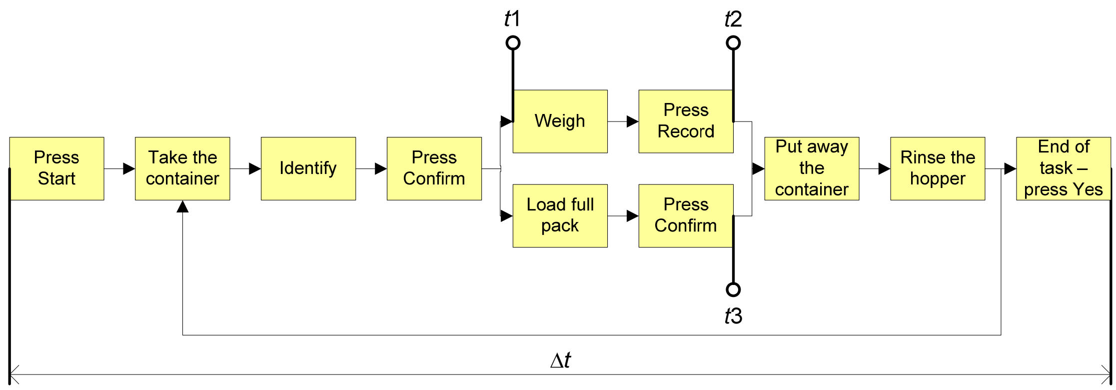


Figure 6-2 Structure of the task and timing points

On each task the amounts were chosen to be different to simulate the situation of loading the first tank. Aqua was the combination of one full and part container, i.e. the weighing system was used to measure the part container, the size of the full container was read from the RFID label and full containers were directly loaded. The amount of aqua on task number five was chosen such that it required two measuring cycles with both the automatic system and measuring jug.

Table 6-1 The experimental tasks for automatic method

Task	Material	Container	Prescribed amount
1	Aqua	5 *l*	6.0 *l*
	Gluupy	5 *l*	0.55 *l*
	Sugar	500 g	190 g
2	Gluupy	5 *l*	0.65 *l*
	Sugar	500 g	210 g
	Aqua	5 *l*	6.2 *l*
3	Sugar	500 g	205 g
	Aqua	5 *l*	6.1 *l*
	Gluupy	5 *l*	0.75 *l*
4	Gluupy	5 *l*	0.5 *l*
	Sugar	500 g	185 g
	Aqua	5 *l*	6.2 *l*
5	Aqua	5 *l*	7.4 *l*
	Gluupy	5 *l*	0.6 *l*
	Sugar	500 g	195 g
6	Sugar	500 g	200 g
	Gluupy	5 *l*	0.7 *l*
	Aqua	5 *l*	6.0 *l*

6.3. Experimental results

6.3.1. Accuracy of dispensing and recording

In order to compare and analyse the different amounts of each material used in the experiment, the results (Appendix M) were normalised to that of the prescribed amount being 100%. An analysis of variance (Appendix N) was performed for the results for dispensing and recording. Based on an analysis of variance the dispensed values were in accordance with the prescribed and recorded values – there is no significant difference with automatic method (Table 6-2 and Table 6-3). With manual method the recorded values are the same as prescribed because the operators always assumed they dispensed the correct amount as prescribed. However, with manual method the dispensed amounts were significantly smaller than prescribed and recorded amounts.

Table 6-2 Accuracy of dispensing and recording by method

Method	Auto dispensed	Auto recorded	Manual dispensed
Means	100.36	100.16	92.61
Difference from target	0.36	0.16	7.39
Difference between dispensed and recorded	0.20		7.39
LSD 5%		2.166	

Table 6-3 Accuracy of dispensing and recording by method and material

		Method			
	Material	**Auto dispensed**	**Auto recorded**	**Manual dispensed**	**LSD 5%**
Means	Aqua	100.51	100.51	92.36	3.752
	Gluupy	100.24	99.78	97.30	
	Sugar	100.33	100.19	88.18	
Difference between target and dispensed	Aqua	0.51	–	7.64	
	Gluupy	0.24	–	2.7	
	Sugar	0.33	–	11.82	
Difference between dispensed and recorded	Aqua	0		7.64	
	Gluupy	0.46		2.7	
	Sugar	0.14		11.82	

The extent of the difference of manual method required closer investigation. The following sources of uncertainty and failures were identified:

- Systematic error of the measuring jugs (e.g. inaccurately placed graduations).
- Visual error reading the graduation marks (e.g. parallax or meniscus errors).
- Uneven distribution of granular material in the jug.

- Random measuring error.
- Human error interpreting the prescribed amount.
- Dispensing a wrong product due to human error.

Similarly for the automatic method:

- The operator is not following the instructions on the screen and is pouring into the weighing funnel without controller being in the measuring mode.
- Spillage whilst pouring into the weighing funnel.
- The tare value is not set to zero.
- Random measuring noise of the weighing system.

An investigation of the measuring jugs used for the manual method revealed some items have a considerable graduation error. They were identified as having been sourced via a variety of routes:

- From local spray retailer (Vass, L W (Agricultural) Ltd).
- From commercial supplier (RS Components).
- Laboratory grade items from the Cranfield University Soil Laboratory.

The graduation error of the jugs was identified by filling them with a gravimetrically measured amount of water at room temperature of 18 °C. The results (Table 6-4) demonstrate that apart from the laboratory jug they all have significant errors, the majority indicating more than the actual amount. The small 100 ml jug was found to show 3% less than actual.

In practice, if repeated throughout the industry, it indicates there is an inherent safety factor against overdose. In that case there is a risk the automatic system will in practice dispense greater quantities of chemical, and therefore may be seen to actually increase residue levels. It may be useful to review agronomic recommendations to identify potential for recommending lower doses, or consider a specified reduction from “standard market rates” when preparing a task file for the automatic system.

The difference between the graduation error of a typical spray jug (+2.5%) and manual dispensing error (–7.44%) implies there are other sources of errors. The visual reading error affects the dispensed amount because normally the measuring jug is on a lower level than eyes of the observer. Therefore by looking down on the graduation marks the level of liquid seems higher than actually. The results demonstrated the error is particularly large for granular material. The volumetric measuring method of granular material is not very precise because of the variability in bulk density and the uniformity of the material level. To reduce visual reading error observer's eye and pointer mark have to be in a line perpendicular to the scale which can be achieved by either stooping forward or lifting the jug to eye level. Both have health and safety implications: the first is fatiguing and the second increases the risk on spillage. The code of practice (Defra 2006) requires agrochemicals to be measured precisely with suitable equipment without further specifying the details how to use particular equipment.

Table 6-4 Results of the investigation of graduation errors of measuring jugs

Source	**Capacity (ml)**	**Minor scale unit (ml)**	**Error (%)**
Spray retailer	2200	50	+2.5
Commercial supplier	100	5	–3.0
	500	10	+6.7
	1000	10	+2.0
	2000	50	+2.5
Laboratory	1000	100	0

By plotting the dispensed amounts against prescribed and recorded the data points are expected to be on a straight line. Ideally Figure 6-3, Figure 6-4 and Figure 6-5 would demonstrate the desired characteristic of $y = x$ with zero intercept and with an $R^2 = 1.00$. The variability for the manual method occurs only on the y-axis because the recorded amount is the same as that prescribed i.e. the operator always assumes that the correct amount was measured. The outliers on the graphs reflect the human error which occurred during the experiment. For manual method considerable over and under dispensing occurred. On one case the operator missed one product and used the other product instead. Failures during the experiment with the automatic recording system occurred only when the operator was not following the instructions on the screen and did not wait for the system to enter the weighing mode. The number of mistakes was higher in case of manual method: 4 operators made 7 mistakes in total. For automatic method 3 operators made 4 mistakes.

The regression line forced through the origin in Figure 6-3 indicates a trend of dispensing 6.76% less than prescribed and recorded in the case of manual loading. Automatic system in contrast shows a tendency to dispense marginally more (2.38%) than prescribed (Figure 6-4). Similarly, dispensed quantities are slightly higher (2.17%) than recorded (Figure 6-5). Thus, the regression lines confirm the results of analysis of variance. Comparing the regression coefficients (R^2), automatic method has a slightly stronger dependency between variables. The graphs confirm the automatic system has less inherent variation.

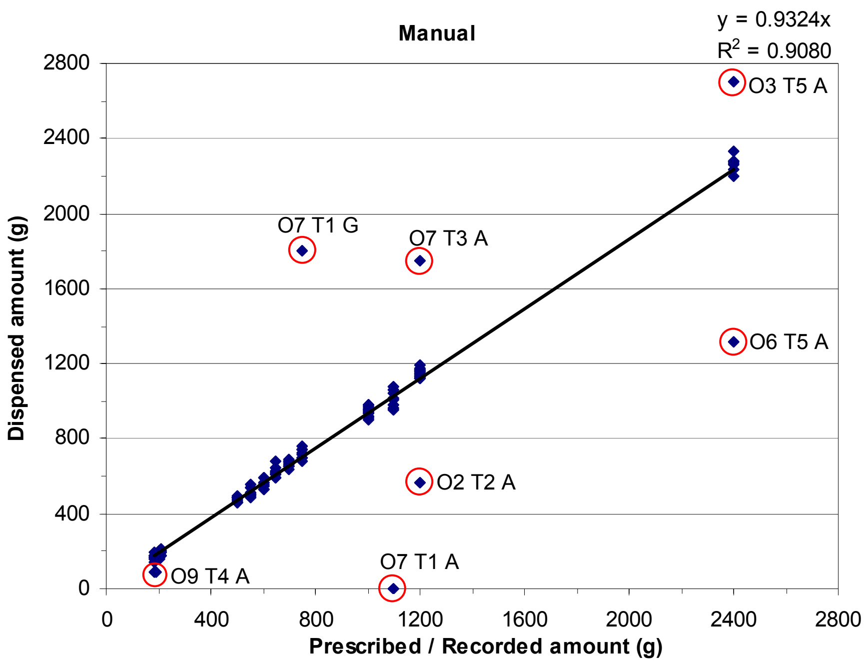


Figure 6-3 Dispensed amount against prescribed/recorded amount with manual method (O – operator, T – task, A – aqua, G – gluupy)

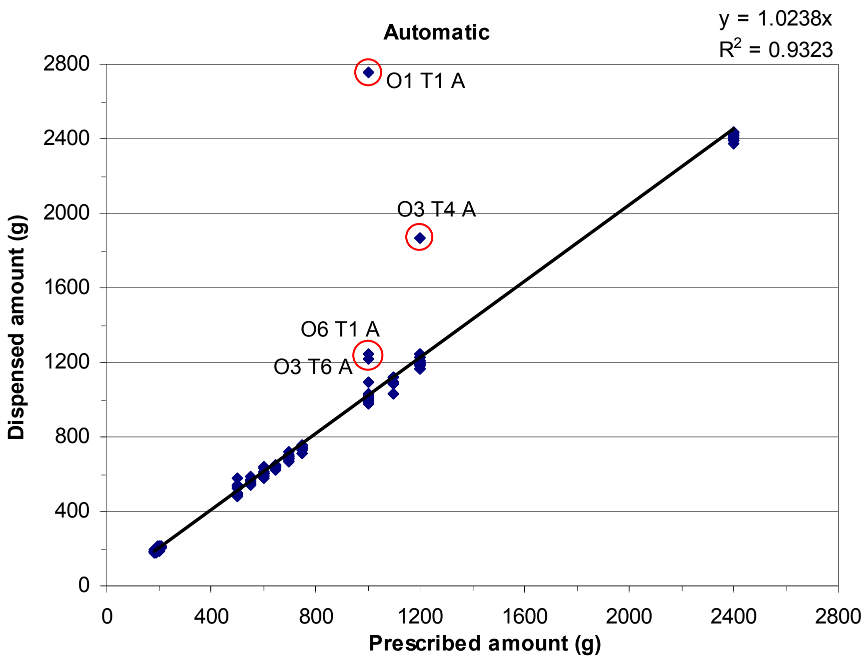


Figure 6-4 Dispensed amount against prescribed amount with automatic method (O – operator, T – task, A – aqua)

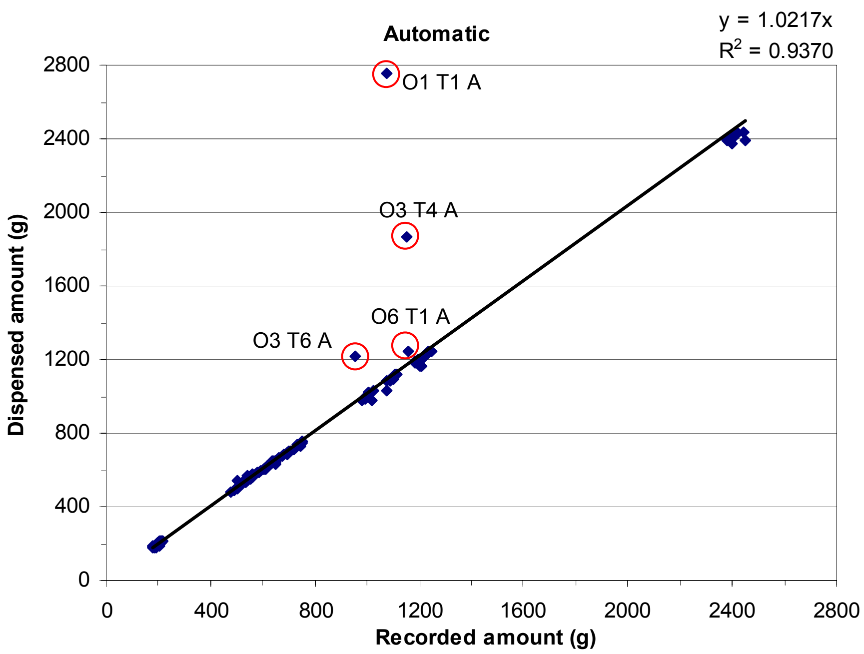


Figure 6-5 Dispensed amount against recorded amount with automatic method (O – operator, T – task, A – aqua)

6.3.2. Speed of operation

The speed of the operation of the prototype system was compared with manual loading time which is the time to measure and load agrochemicals into the sprayer, and manual total time which includes creation of the paper based record (experimental data in Appendix M and statistical analysis in Appendix N). These have to be analysed separately because the time for the total manual operation also includes the time for the manual loading operation, they are not independent datasets.

From the mean times of tasks given in Figure 6-6 it is obvious that although the operators were proficient in the manual method and received a practice with automatic system there is a learning factor involved where the time decreases exponentially with each consecutive task for both methods. Extrapolating the data shows there is no further reduction in loading time after 10 tasks, which is equivalent of 1–2 days field practice.

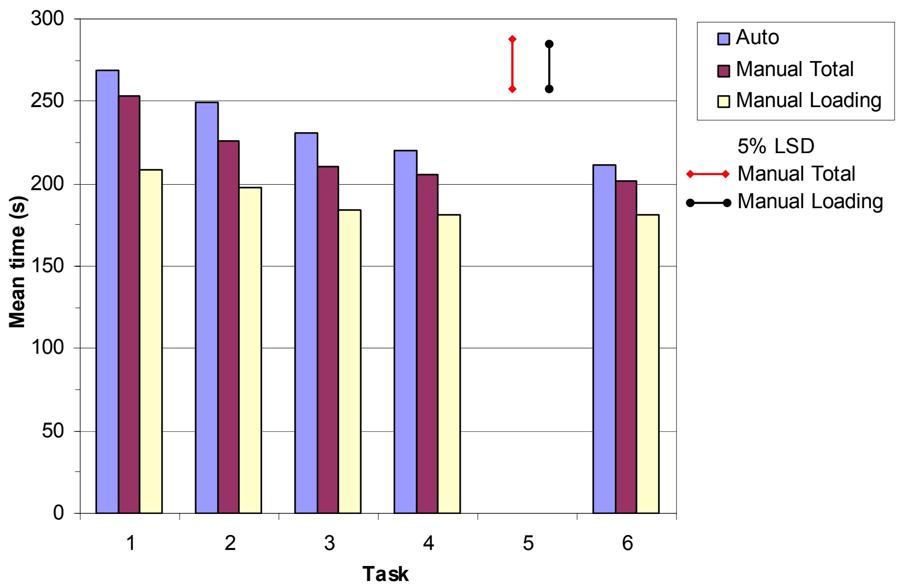


Figure 6-6 Speed of operation by task and method

Investigating the mean overall times, Figure 6-7, the automatic method is in statistical terms significantly slower than the manual method. However, examining the times of the last task number six, Figure 6-8, there is no significant difference between automatic and manual total methods. However, there is a significant difference between the loading time for the manual and automatic methods and it is this factor that is most noticeable to the operator in practice.

Overall, the difference is less than 31 seconds ($LSD_{(5\%)}$ 28.2 s) which it is suggested is insignificant compared to random events during a spraying session and in time moving, checking and storing paper records. The marginal difference of 11 seconds ($LSD_{(5\%)}$ 30.1 s) between the automatic and the manual total methods confirms that the automatic recording system is straightforward and logical to use and the operators achieve skilled level with minimal effort.

The work rate of the chemical loading system is time critical, however, the limiting factor for a whole load operation may be loading water. In the UK, 93% of sprayers were filled indirectly from a water source using a bowser or header tank (Gartwaithe 2004). A typical portable petrol engined water pump (http://ww1.honda.co.uk/brochure/download/energyPumps.pdf (13 February 2009)) is capable of delivering 500 *l*/min which would give 168 seconds filling time for the typical self-propelled sprayer used in this work (1400 *l* tank). If filled directly from the mains, the time may be up to 9 minutes (Appendix B). Hence, an extra 31 seconds is not an issue in field practice.

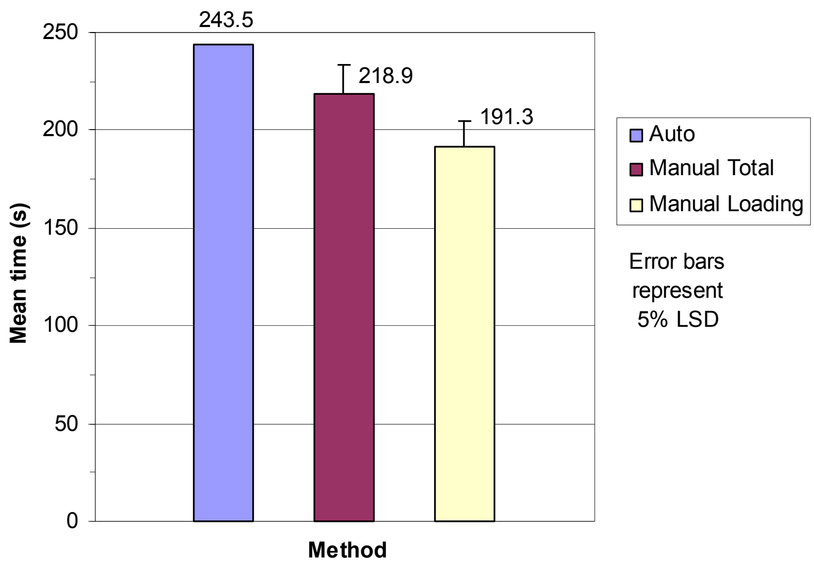


Figure 6-7 Speed of operation by method

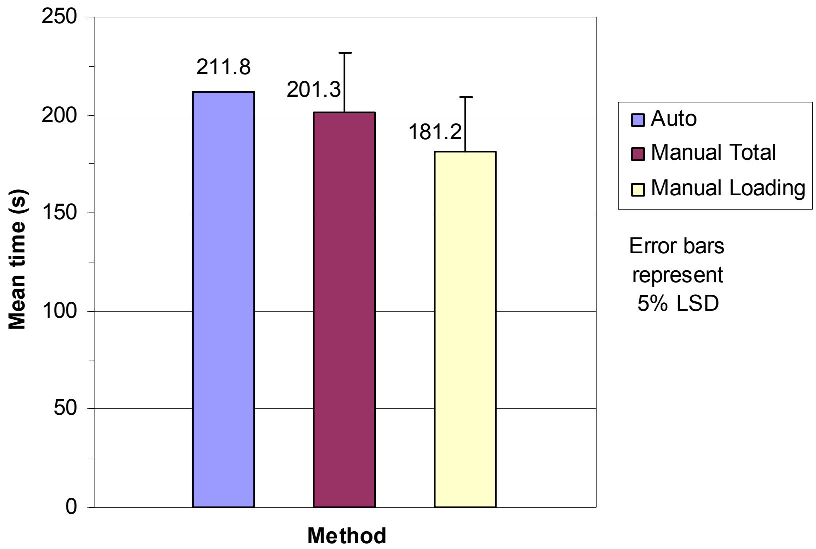


Figure 6-8 Speed of operation by method for the last task (No 6)

6.3.3. Duration of weighing

Based on the time data acquired by the weighing system software, graphs showing the progress of weighing were constructed. That data enables to investigate the duration of weighing cycles and the dispensing rate i.e. amount of product per time of weighing. The measured amounts of products were normalised to the target level in the analysis for comparison. The script files for data analysis are given in Appendix J.

Principally, four phases are distinguishable in the process of weighing: the beginning of measuring ensuring successful tare, rapid dispensing, fine adjustment to the required level, and decision to conclude immediately followed by pressing the record (Figure 6-9). The efficiency of each of those depends on the accuracy, dynamic response, ergonomics of the system and personality of the operator. On the graphs in Figure 6-10, Figure 6-11 and Figure 6-12, the first phase has been omitted to be able to align the curves, the second phase is clearly identifiable, the difference between the third and fourth phase is not clearly distinguishable. The spread of the curves for aqua is relatively small in comparison to the other materials because there the operators had a clear reference mark – the required amount was almost the full weighing funnel. Granular material, on the other hand, is difficult to judge and it does not flow like water.

The large fluctuation on some of the curves for sugar was induced by the increased level of low frequency noise caused by the hydraulic pipe for the induction hopper to the sprayer tank becoming untied. The data clearly demonstrate the effect of this on reduced accuracy, on unstable screen output – it then took the operator a greater period of time to dispense the required amount.

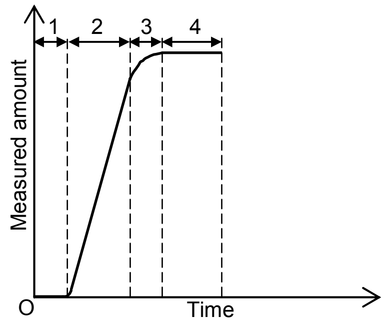


Figure 6-9 The process of measuring agrochemicals

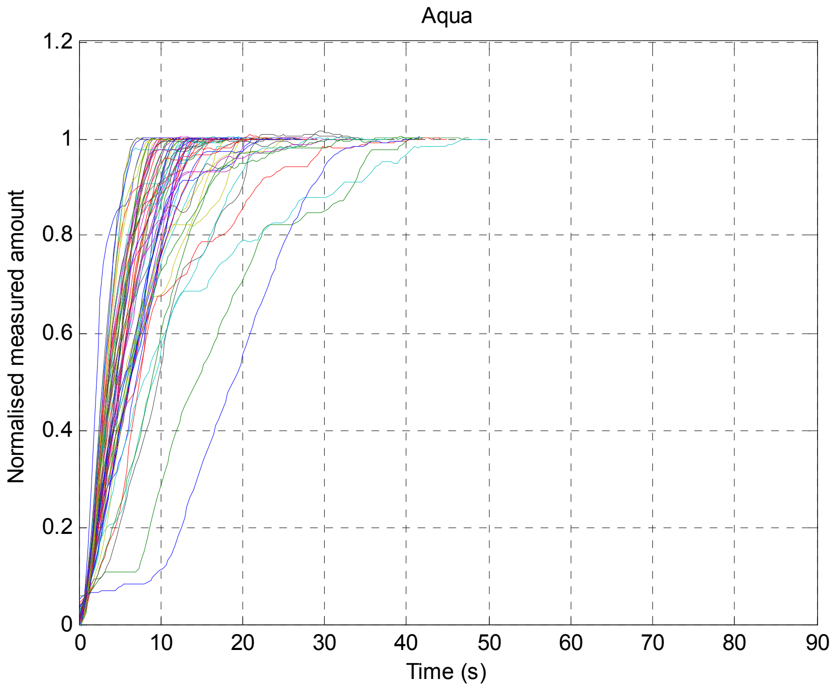


Figure 6-10 Progress of weighing aqua

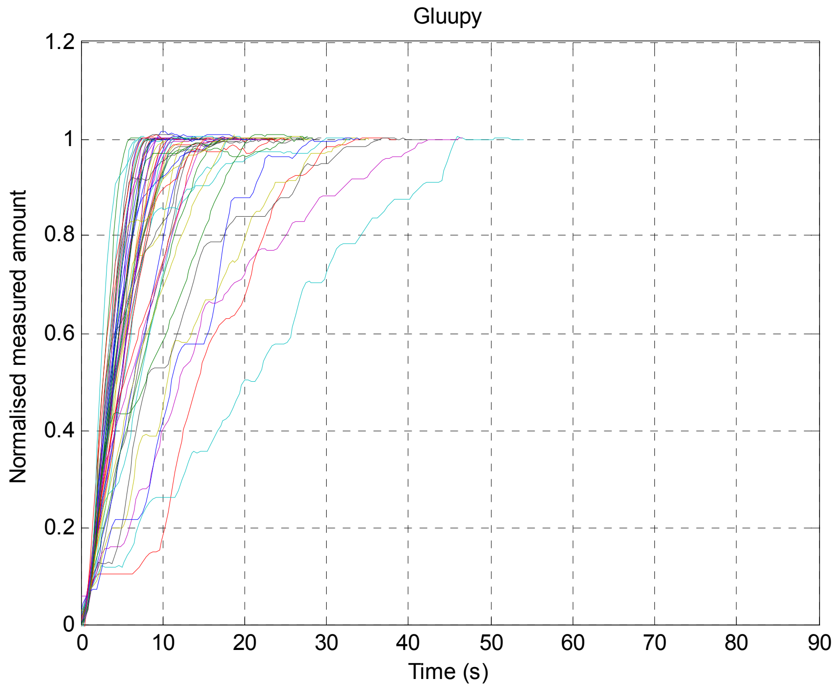


Figure 6-11 Progress of weighing gluupy

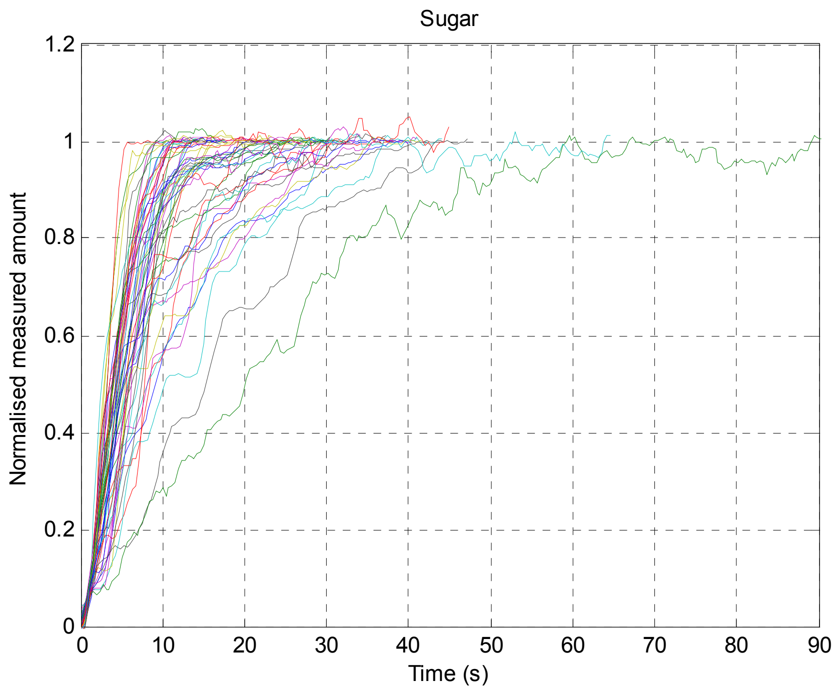


Figure 6-12 Progress of weighing sugar

The difference in the performance of the operators is demonstrated in Figure 6-13: the majority are not significantly different. However, operator No 6 is significantly slower than the others using the weighing system. The peak for the operator at No 7 when measuring sugar is related to the unstable screen output and reduced system accuracy as mentioned above. This data shows that the weighing system is relatively simple and straightforward to use with little variation between the operators.

The comparison of the differences between the tasks demonstrates the differences are insignificant despite a small learning effect for aqua and sugar (Figure 6-14). As a proportion of the overall task time, the weighing system represents 44.6% and the learning curve of the weighing system is similar to the learning curve of the overall task (Figure 6-15). Hence, the system has a balanced design – no individual element stands out as particularly difficult to learn.

The mean duration of measuring per container for all tasks (34.0 s) is significantly smaller than the time (68.5 s) achieved by Watts (2004). The quantities used by Watts (2004) (mean 1140 ml) were larger than quantities used in this trial (mean 633 ml). It might be assumed a larger amount takes longer to dispense than smaller. However, the results above demonstrate there is no significant difference in the time to dispense various amounts of agrochemical. Based on the observations on farm (Appendix B) the time to dispense full packs (5 *l*, 15 *l* and 2.5 kg) is in the range of 15–64 s including time for rinsing.

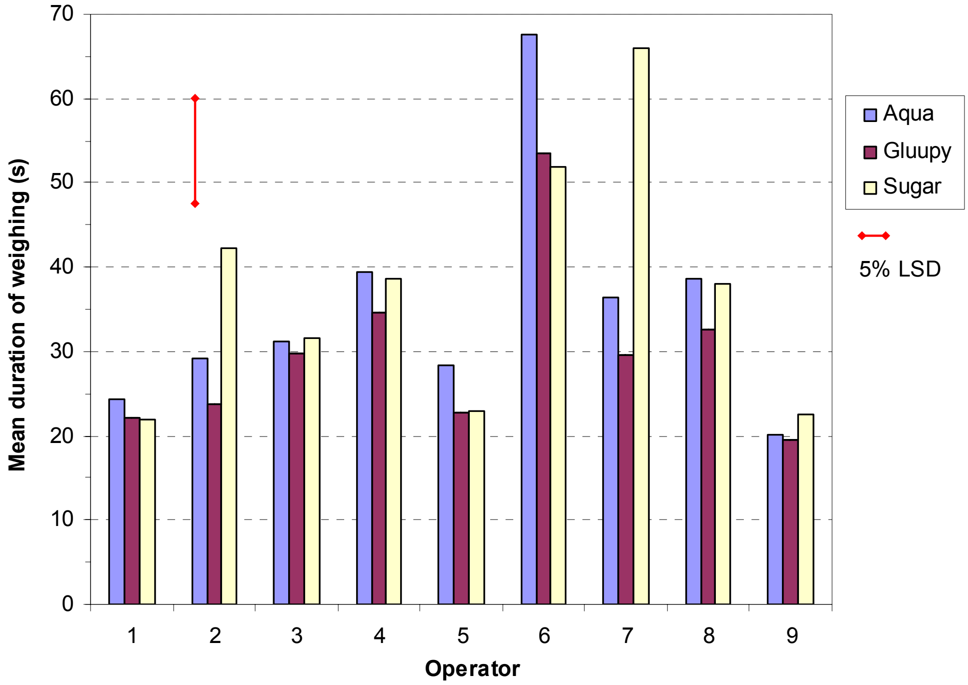


Figure 6-13 Duration of weighing ($t_2 - t_1$) by operator and material

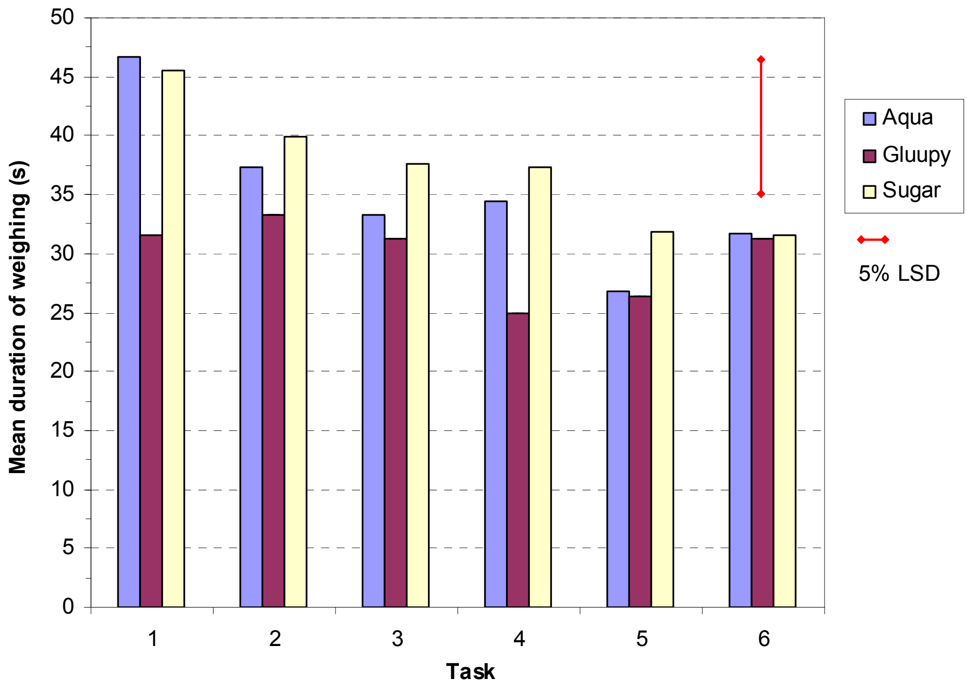


Figure 6-14 Duration of weighing ($t_2 - t_1$) by task and material

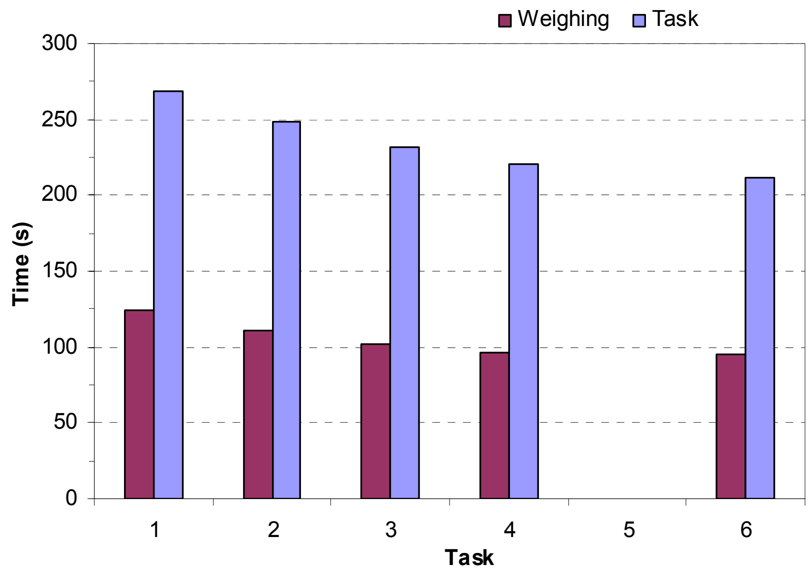


Figure 6-15 Comparison of the operation time of the weighing system and overall task time

6.3.4. Rate of weighing

The investigation of the lines in Figure 6-10, Figure 6-11 and Figure 6-12 indicated the majority of loading curves given are near linear in the rapid dispense phase between 10 and 90% of the target rate. Hence, the slope of the lines over that range can be used to represent the rate of weighing.

The results in Figure 6-16 indicate the distribution of the data is slightly positively skewed. Three groups are distinguishable: slow at 2–6 $\%\cdot s^{-1}$, intermediate 7–12 $\%\cdot s^{-1}$ and fast above 12 $\%\cdot s^{-1}$. That relates to the difference between operators presented in Figure 6-17. Operator 6 is significantly slower and Operator 9 significantly faster with aqua and gluupy. There is no significant difference between tasks (Figure 6-18). The mean dispense rates of products demonstrated significant difference: gluupy (11.26 $\%\cdot s^{-1}$) has a significantly higher rate than aqua (9.53 $\%\cdot s^{-1}$) and sugar (8.86 $\%\cdot s^{-1}$), $LSD_{5\%}$ = 1.177 $\%\cdot s^{-1}$. That can be explained by a relatively small dispensed quantity (0.6 *l*) from a 5 litre container.

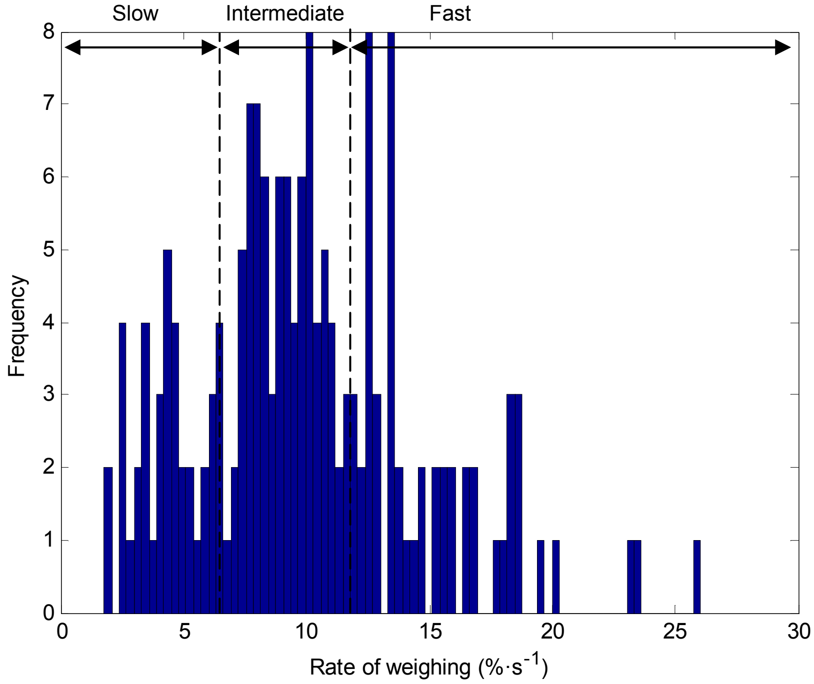


Figure 6-16 The distribution of the rate of weighing

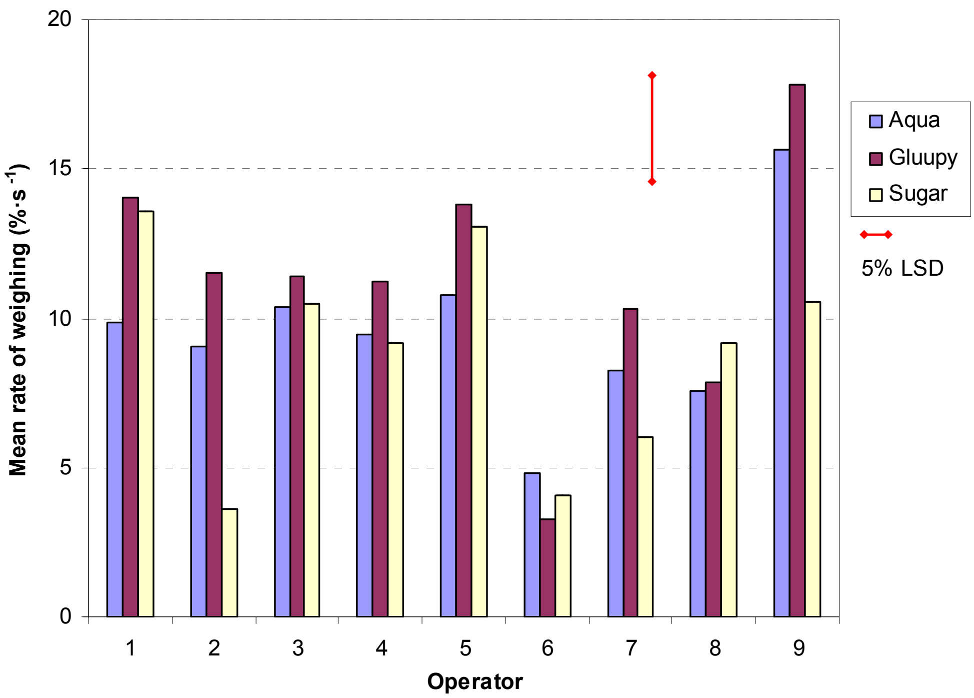


Figure 6-17 Mean rate of weighing by operator and material

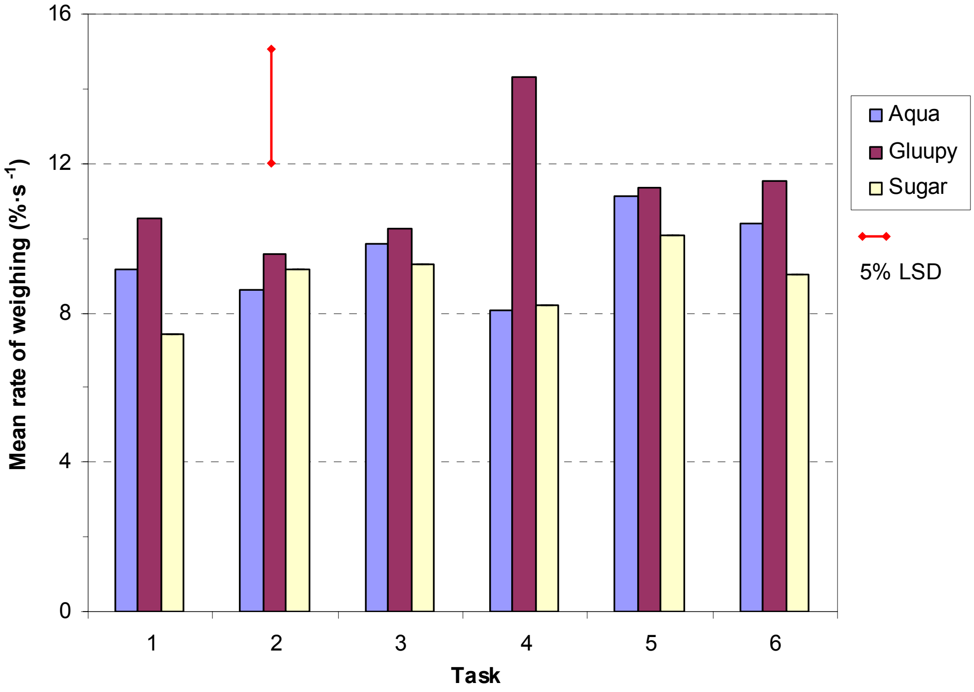


Figure 6-18 Mean rate of weighing by task and material

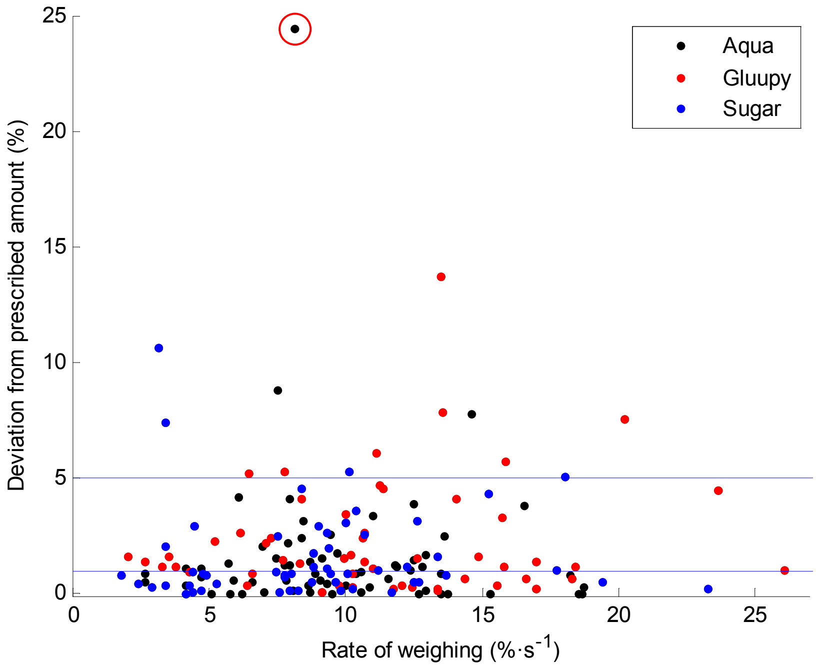


Figure 6-19 The relation between speed and error

Prior to the experiment, it was expected that a positive relationship would exist between the rate of weighing and ultimate error in deviation from the target, i.e. the faster the measuring the larger the error. However, the results demonstrate there is no consistent regression between the speed and error (Figure 6-19). Overall, 92% of the cases are measured within ±5% error and 48% within ±1% error. Referencing the typical graduation error of the measuring jugs (2.5%), 57% of the cases with the automatic weighing system are measured with similar or smaller error (±1.25%). The data point with highest error (marked with a red ring) relates to the point O6 T1 A in Figure 6-5.

6.3.5. Performance of the product identification system

The product identification system was evaluated in terms of successful read rate, reliability of records, and user ergonomics: read distance, read speed, and position of the antenna. The ergonomic results were obtained by interviewing the operators after the trial.

During the experiment more than 250 product identification operations with RFID were carried out without a single failure. In all of the cases the system was able to read the information stored on the RFID product label, decode it, reference with database and record the unique identifications of each container. The RFID system provided a true automatic record of the product containers used in the experiment. The speed of operation (<1 s) and reading distance (100 mm) of the RFID were found to be adequate for agrochemical identification. When questioned afterwards, the operators estimated the position of the antenna is convenient.

6.3.6. User interface and overall usability aspects

The user interface and overall usability aspects were evaluated in the form of unstructured interviews following the trial. The graphical user interface was assessed using the following criteria: size of the screen, the presentation of information, and the flow of the program. The overall assessment included criteria such as safety, user friendliness, capacity of the weighing funnel, efficiency of discharge valve and rinsing. The evaluation was conducted in conjunction with Gasparin (2009) who investigated the perception of the AACTS by the sprayer operators.

The participating operators accepted the new user interface very well. The robustness of the system was seen as a key commercial success factor. Reliability was a major concern of the participating operators. Cost was also important. The operators assumed the automatic system is more accurate than manual measuring without knowing trial results. Thus accuracy is an important marketing argument. The concept of the electronic system to assist on the sprayer was found to be beneficial. A system that keeps track of the job reduces the possibility of human error.

Screen size, the buttons, and the presentation of information were found to be straight forward and good but four operators preferred a bigger screen. Although 200×200 pixels is the minimum requirement for ISO 11783 terminals and entirely adequate to present the required information, the common recommendation is at least 240×240 pixels. It was commented that the screen should be movable or positioned in the direct line of sight e.g. on the lid of the induction hopper. That issue will be addressed by the design of the production prototype with dedicated hardware. In the development prototype, the LED bar was complementing the main screen. The LED bar was rated as good addition. However, some operators did not follow it.

The flow of the program and prompts was clear and logical based on the evaluation. The amount of information presented on the screen was adequate and explicit. The operation of the user interface was simple and easy. The warning messages on the screen were conspicuous to the operators.

The weighing system was rated to be safer than the manual method because there is less chance of spilling due to reduced handling of chemicals. The product is dispensed directly into the induction hopper. There is no need to rinse the measuring jugs. Although the induction hoppers are equipped with a rinsing nozzle for agrochemical containers, it is not very well suited for rinsing measuring jugs because of their large diameter. They may slip off the nozzle's spigot as noticed during the trial.

The overall construction of the weighing system including the valve arrangement and rinsing was ranked as good. Five operators recommended a larger weighing funnel with larger capacity and induction area. Depending on the combination of the full and part packs it would increase the work rate. However, a larger weighing range suggests issues with achieving a good low end resolution for minimum application rate. Larger funnel requires stronger rinsing system and bigger outlet valve.

The operators perceived a need for an automatic recording system. They saw great advantage in its capability to generate electronic records. That would be a significant improvement to the current paper based system which is very labour intensive with many different records. All in one electronic record would simplify the stock management, bookkeeping, field records, proof of compliance with environmental requirements, and farm assurance. The maximum benefit is achieved with a complete electronic data management system, where the agronomist issues electronic spray sheet, which is linked with the farm resources management system, and field records.

An evaluation to rank the AACTS against the manual method was undertaken by Gasparin (2009) where the operators compared both methods in terms of six attributes: operator safety, accuracy of the data gathered, avoid use of unregistered agrichemicals, minimise time taken to fill the sprayer, minimise investment cost and ease of retrieval of agrochemical data. The ten sprayer operators perceived the sprayer with AACTS in overall performs better (rank 68.2%) than the sprayer without (rank 31.8%) in terms of the above attributes.

6.4. Economic benefits

The evaluation of the AACTS demonstrated similar work rate on the field and significantly better accuracy compared to the manual method. From this, there is apparently no benefit in terms of time or labour savings, the analysis of accuracy highlighted under-dosing from conventional means. These combine to suggest no direct economic savings. However, there is a range of indirect benefits deriving from the availability of electronic records and accurate dispensing.

The feature of preventing human error such as misidentification of agrochemical product, hence misapplication can be quantified by looking at avoided cost or damage. If a crop is grown on more than one field but the fields require different treatment, a mistake may happen in practice where the operator sprays the wrong field because of the error differentiating between the fields. For cereals the cost of spraying is in the range of £10–56 ha^{-1} including machinery and material cost according to Nix (2007). Considering the investment cost of the AACTS of £3164 (Chapter 4) it is equivalent to 57–316 ha of spray. If the chemical was sprayed wrongly then there is an additional time cost to renew the chemical stock in order to spray the correct field.

If as a result of the misapplication the crop is lost then for winter wheat the losses would be £517 ha^{-1} gross margin according to Nix (2007). Considering lost crop, the investment cost is equivalent to 6.1 ha of mistakenly sprayed winter wheat.

Two cases have been reported following a review by Gasparin (2009) where a farmer sprayed Roundup instead of growth regulator on 32 ha of wheat and the total lost value of the crop was £36,000. On the second case an operator confused products where a fungicide meant for wheat was applied for beans on 80 ha. There was no harm to the crop but loss of chemicals was £2500 plus the time of spraying.

The overall benefits of electronic records are in systems management. Electronic task management enables to issue tank orders automatically eliminating the need for the farm manager or spray operator to carry out the calculations of required amounts per tank. Easier record management enables to save labour time in post processing of the spray records.

Precise dispensing of agrochemicals gives better stock planning. If the correct rate of agrochemicals is applied there is reduced possibility of reapplication. Reapplication is associated with cost and timeliness. Precise stock control allows minimising the amount of leftovers in the chemical store. That reduces the problem of disposal of agrochemicals which is associated with cost and environmental issues.

6.5. Conclusions

The following conclusions can be made:

- The automatic recording system is significantly more accurate in comparison with manual sprayer loading method. The dispensed amounts (100.66% of target level) and recorded (100.54% of target level) are in accordance with prescribed values ($LSD_{(5\%)}$ 1.987%). This compares to the results of the studies with the manual method where the dispensed amount (92.56%) differs significantly from prescribed and recorded value mainly due to the graduation error of measuring jugs, visual reading error and volumetric measuring of granular products.

- In combined loading and recording cycle the automatic recording system delivers the same work rate (207.8 s) as manual method (195.0 s) (Δt = 12.8 s, LSD(5%) 27.3 s). Considering only the loading time (174.1 s) of manual method, most noticeable to the operator in practice in case the records are created outside spraying hours, the difference is 33.7 s (LSD(5%) 26.8 s) which is negligible when waiting for water filling. The time of using the weighing system of the overall task time is 44.6%.

- 92% of the cases are measured within ±5% deviation of the target with the automatic recording system.

- During the experiment more than 250 product identification operations with RFID were carried out without failure. The speed of operation (<1 s) and reading distance (100 mm) of the RFID is adequate for agrochemical identification.

- The automatic recording system proved to provide very good assistance to the sprayer operators in keeping track of the progress of the filling job. The automatic system significantly reduces the risk of human error by controlling the workflow and prompting the operator through a simple two-way user interface.

- The flow of the program and prompts were clear and logical based on the evaluation. The amount of information presented on the screen was adequate and explicit. The operation of the user interface was simple and easy. The size of the screen was adequate, four operators preferred slightly bigger screen.
- The weighing system was rated to be safer than the manual method because there is less chance of spilling due to reduced handling of chemicals.
- The investment cost of the AACTS is equivalent to 6.1 ha of erroneously sprayed winter wheat considering the loss of crop.
- The operators accepted the AACTS very well and were keen to know when commercially available.

7. Discussion

The analysis of market requirements indicates there is a need for robust farm traceability records as the basis for all later systems (Gasparin 2009). Agrochemicals are a major farm input, and a particular source of general concern. Currently there is no automatic generation of records for sprayer agrochemical inputs. Manual process records are made after the event, error prone and would be difficult to increase in detail without very large increases in time and manual time cost. The work by Watts (2004) has proved the basic suitability of RFID technology and introduced the possibility of electronic weighing system for automatic creation of records of sprayer inputs. However, this work left many issues in resolution of measuring, work rate and level of integration. This work has made a contribution by developing a novel, realistic Automated Agrochemical Traceability System (AACTS) for crop sprayers.

The following specific issues have been identified and developed as part of the automated agrochemical traceability system:

1) identification of agrochemical products,
2) association of the product identity with the national agrochemical database,
3) quantification of the required amount of product,
4) assistance of the sprayer operator and control of the workflow,
5) generation of records of sprayer inputs,
6) interfacing with the sprayer ISO 11783 data network.

Although RFID technology is known to be suitable for product identification in the agricultural environment, there is no current solution to define the data that must be stored on the tag to deliver the required features. In this work (Chapter 3) an RFID tag standard for unique identification of agrochemical inputs has been developed.

The investigation showed that the best design solution would be to store a minimal amount of essential information on RFID labels in addition to a unique serial number.

This should include country of registration, registration number, chemical type, container size, specific gravity, unit of measure and verification mark; and space for an optional product name and logistics data. Data beyond this standard set is more market variable and often larger in size (e.g. application guidance) and should employ a separate database to minimise tag cost. With this solution the RFID label identifies the product type and other key parameters independently at any location using a basic RFID reader and greatly reduces the size of the database held on-farm or on the label – it does not include every individual tagged item in the world. This solution focuses on forward traceability (“up”) of farm outputs, demonstrating the history of a farm product, by including item level data from individual pack serial numbers. It is also desirable that a system can deliver backward traceability (“down”) of farm inputs, so that, for example, a chemical manufacturer can identify the current location of items of agrochemical product for their own recall process and quality management. This may also prevent theft or unauthorised use if it is widely known that chemicals are individually traced. The tag format proposed provides both forward and backward traceability (Chapter 3). Currently, agrochemical manufacturers are not using RFID tags for electronic labelling of agrochemical containers. However, these benefits and the suitability for agricultural environment are a strong driver for adoption.

The suggested RFID tag protocol uses the existing national agrochemical registration number as the main identifier and links with the worldwide national agrochemical databases held digitally on the sprayer. This to prevent the use of unregistered agrochemicals, or forces the operator to enter a traceable exception case. The unique identification of products means the individual packs can be traced from the manufacturer to the field area of application if the identifier is incorporated into the ISO 11783 field record file and associated with the as applied maps. The individual tracking of containers eases the stock control for the farmers and the inventory could be linked with the electronic spray order issued by the agronomist who can also issue the purchase order based on the current farm inventory. The incorporated information about full pack size allows rapid loading of full packs without using the measuring function which saves the time.

When the requirements to create a tank mix are for amounts of product less than a whole pack the products dispensed into the sprayer have to be quantified in a way allowing automatic generation of records, but maximising speed of operation and safety and assistance of the operator. A greatly refined electronic weighing system has been designed and constructed (Chapter 4), based on a 1.4 litre self cleaning weighing funnel mounted inside the induction hopper on a 3 kg load cell to measure part containers. The weighing system operates within a standard induction hopper without any external parts and is compatible with liquids and granules and any type of packaging for manual handling. Where appropriate in a market, the construction allows compatibility with closed transfer systems with an interface simply mounted on the lid of the hopper.

Communication with the operator during the loading of agrochemicals is a major opportunity to introduce process aids (automatic calculation, job transfer and record keeping). A simple two-way user interface was developed (Chapter 4) to provide the required functionality in field conditions, when wearing the required personal protective equipment. Through the user interface the AACTS is able to control the workflow: the assistance given to the operator is by displaying instructions on the screen, and the user confirmation is from three logically labelled buttons. This solution minimises the possibility of human error because the system is keeping an account of the progress of the job and the operator is always aware of the current status. From trials, the introduction of a visual indicator directly in the line of site of the filling operation (e.g. 8 segment LED bar) has been found to greatly aid communication, maximise loading rate and improve the user experience.

Being part of a farm traceability system a logical requirement is the integration into the existing data communication hardware and software. The AACTS is designed to accept the job description in the form of a prepared task file as set out in ISO 11783. To achieve this it is recommended the industry should continue the adoption of the international standard ISO 11783-10 because it embraces a suitable, comprehensive, generic structure for management of field activities. However, this work has introduced specific recommended extensions and common methods of operation of the standard ISO 11783-10 to integrate the new features offered by the AACTS. A concept was developed (Chapter 4) to integrate the unique identifier of agrochemical containers (RFID) and records of tank content into the standard task data file. Tank mixes resulting from the loading task are then considered as individual products as inputs for the spraying task. The limitation of this suggestion is that there will be a large number of products (although the system can handle 10^{11} (ISO 11783-10)) but the advantage of the proposed solution is that it provides tank level traceability.

The high levels of mechanical vibration (33–83 Hz) induced by the diesel engine at operational speeds require noise suppression for the output signal of the weighing system in order to achieve the accuracy required. The investigation of the performance of the prototype weighing system (Chapter 5) resulted in comprehensive characterisation of the noise signals: the noise to signal ratio was mapped across the operational range of the weighing system and the frequency spectrum of the signal was analysed and described. That knowledge is applicable in the development of the commercial prototype. Appropriate mechanical measures should be taken to reduce the vibration imparted to the weighing system from the engine. Beyond this design aim, this work has shown that very great benefits can be obtained from appropriately designed digital filters. Here, a resolution of 1 gram (engine switched off) to 3.6 grams (sprayer fully operational) were demonstrated by implementing digital filtering; Watts (2004) achieved ±10 grams with a weighing platform. The research undertaken has set the principles of reducing resonant frequencies for further development of filtering and control strategies. The investigation demonstrates there is little benefit in simply using general purpose rubber mounts to isolate the induction hopper because of the lower stiffness which shifts the resonant frequencies to a lower region close to the signals of interest, where they cannot be attenuated by a filter. The combination of analogue and digital filtering proposed has been shown to deliver similar performance to mechanical isolation of the induction hopper. Thus, after the general principle of isolation has been adopted, the mechanical parts of the commercial unit can be simply designed to suit a range of different machines where the particular requirements are satisfied using customised software. This allows great flexibility in solving the problems of the different resonant frequencies of a range of different hopper and sprayer design combinations. Applying the features of an ISO 11783 data network a wider view can also be taken to adjust the engine speed to the level of the lowest noise input according to the noise map and target amount. The engine speed could then revert after the immediate weighing operation is complete. For extreme cases when measuring very small quantities, e.g. 12 grams, the engine can be switched off because this measure has no associated cost opposed to a rarely used very precise measuring function.

A considerable evaluation of the prototype AACTS has been undertaken (Chapter 6) to verify the likely performance when available for use on farms. The results verify the superiority of the AACTS over the manual method in terms of accuracy, reliability of traceability records and possibility of human error. The AACTS is significantly more accurate in comparison with manual sprayer loading method. The dispensed amounts (100.36% of target level) and recorded (100.16% of target level) are in accordance with prescribed values ($LSD_{(5\%)}$ 2.166%). This compares to the results of the studies with the manual method where the dispensed amount differs significantly (92.61% of target level) from prescribed and recorded value due to the graduation error of spray jugs and visual reading error.

The AACTS has generally been found to be simple and easy to use and the difference observed in direct work rate (211.8 s/task) compared to a manual method (201.3 s/task) is marginal and not significant, statistically (Δt = 10.5 s/task, $LSD_{(5\%)}$ 30.1 s/task) or practically in a combined loading and recording cycle. Considering only the loading time (181.2 s/task) of manual method, most noticeable to the operator in practice in case the records are created outside spraying hours, the difference is 30.6 s/task ($LSD_{(5\%)}$ 28.2 s/task) which it is suggested is insignificant compared to the time required to load the water, random events during a spraying session and in time moving, checking and storing paper records. The electronic records are a basis for a significant time saving at later stages of the data management in farm computer. Generally, this work rate is a considerable improvement over previous proposals.

The mean duration of measuring per container for all tasks (34.0 s) is approximately half the time (68.5 s) achieved by Watts (2004). The results demonstrated there was no significant difference in dispense time between the products and amounts used in the trial. With liquids, operators were able to judge the required amount and dispense rapidly until close to the target (aqua 9.53 %·s^{-1}, gluupy 11.26 %·s^{-1}). Although granular material is typically dispensed in smaller amounts than liquids (and this was the case in the trial), it took similar time to dispense because the amount is visually more difficult to estimate and flows less well (8.86 %·s^{-1}).

The results demonstrate 92% of the cases using AACTS are measured within ±5% deviation from the target regardless of dispensing speed. 57% of the cases are within ±1.25% error which means the majority of sprayer operators are able to achieve better accuracy with the system than the systematic error (2.5%) found in the trial from using common measuring jugs.

A benefit of a precise dispensing system is improved agrochemical stock management: pre ordered quantities correspond to the actual need and there are fewer leftovers which reduce the cost of disposal and environmental burden. There is also a reduced risk of running out of chemical in the middle of the spraying job. The rapid renewal of the stock may be a problem during the busy spraying season when valuable spraying time is lost because of the delays. Precise application rate means the active ingredient works as expected. The unique identity of chemical containers enables keeping track of the remaining amount in the container whilst dispensing. When the remaining amount is close to zero rinsing can be instructed and the known remaining quantity of product included.

Incremental manual errors lead to the discrepancies in stock inventory. The electronic measuring system and RFID tagging (Chapter 3) gives an opportunity for automated stock control. The benefit is the rapid error detection opposed to the manual control where if a spraying error is suspected the containers have to be counted manually in the chemical store.

Overall, the AACTS fits into the market as a practical management tool for farmers and spray operators. However, interviews suggest some reservations towards a policing tool that would record every action as the real practice does deviate from what reported. There may be unrealistically simple expectations which currently appear to be satisfactory due to the lack of detailed data. If data is available there is a perceived need for some interpretation of context to determine any real effect on food product rather than failure to comply with over-simplistic regulation. Logically, the AACTS will change the current open loop process traceability of annual process validation, trust and relatively infrequent chemical residue testing to a fully monitored process, where records are interpreted to individually certify each batch of product leaving a farm. AACTS has features to be a tool to prove the good practice and with the help of digital verification marks on the spray job records the line can be drawn properly between the responsibilities of different parties (agronomist, farm manager, and operator). This is currently a very poorly defined area, with operators legally responsible when in practice they blindly follow recommendations. The sprayer operators who participated in the evaluation rated the sprayer with the AACTS preferable than the sprayer without (Gasparin 2009). They saw the benefits in the automated record generation and the weighing system, the operators expressed interest in buying a unit. However, cost is a significant restraining factor. The selling price of the AACTS could be £3164 for production volume of 1001–2000 according to Gasparin (2009) which is 3.5% of a price of a self propelled sprayer (see Section 4.10 and Table 4-4).

The knowledge about the content of the tank available can be used in expert systems to assist operators in planning and executing jobs:

1) Field area for quantity optimisation (e.g. exact number of tanks to minimise transport).
2) Product for application technique optimisation (e.g. automatically selecting water dilution rate based on all tank mix components).
3) Machine for cost optimisation (e.g. spray nozzle setup).

The availability of current process data could be integrated into the software for cabin controller (ISO 11783) to modify the spray application strategies as suggested by Miller et al. (2008). The information about the physical properties of the agrochemical products, nozzles and the optimal settings for the sprayer made available to the sprayer controller can be used to improve the spray application. The application strategy can be aimed to reduce the spray drift at the boundaries of the field to improve the compliance with the regulation and reduce the surface water contamination. In the middle of the field the performance of the agrochemical can be enhanced by matching the spray droplet according to the crop requirements. The treatment maps and optimised pre-defined field courses (Palmer et al. 2003) can be used to optimise the application strategy to exactly match the requirements of the field size and shape. This allows the preparation of the exact amount of dilution required for the field and controlling the boom or nozzle switch off according to the shape of the field. Exact amount enables adjusting the tank loads to aim for minimum leftover which reduces the cost of disposing of unused dilution.

Overall, the features of AACTS provide compliance with the traceability requirements for food safety and quality and environment. The automatically generated records have practical value for farm management, especially when transferred directly to the farm computer systems. The monitoring of workflow reduces the possibility of human error in misidentification and misapplication of agrochemicals. A significant contribution compared to the manual dispensing method and weighing platform by Watts (2004) is the improvement upon health and safety of the operators by minimising the handling of chemicals (weighing function within induction hopper) as rated by Plom (2009) and trial group of 10 sprayer operators.

By design, the AACTS is a combination of functions. Although the greatest benefit is obtained when these are all integrated, the actual adoption may be modular depending on the market requirements and readiness. The interest by the operators participating in the evaluation suggested that a device that weighs and assists in dispensing agrochemicals (functions of weighing, user interface and prompting) can be productised immediately, even without wider integration with job planning, traceability records etc. This is directly desired by sprayer operators. The implementation of RFID readers for agrochemical identification on sprayers on the other hand requires auxiliary services to be in place – chiefly the RFID labelling of product containers by the agrochemical industry.

8. Conclusions and recommendations

8.1. Conclusions

The following conclusions result from this work:

1) A novel prototype Automated Agrochemical Traceability System (AACTS) has been developed, where the results of the design, construction and evaluation phases have proven such a system capable of

   - identifying and weighing agrochemical products,
   - controlling the workflow and prompting the operator,
   - recording and transferring data

   can be successfully used to generate automatic records of tank contents of crop sprayers. The results of this can be directly used as the design parameters for a commercial prototype.

2) The integration of a high frequency 13.56 MHz Radio Frequency Identification (RFID) reader-antenna system into the induction hopper of the spraying machine has been demonstrated to be a robust and reliable method for the automated identification of agrochemical containers. A format has been proposed as a standard for data held on RFID tag applied to agrochemical containers. This uniquely identifies single packs whilst associating the product type with existing national agrochemical databases. The proposed format allows verification of authenticity and current chemical registration, while being operable on-sprayer without live access to an international item level database. Widespread adoption of this or a similar system is a recommendation of this work.

3) A greatly improved embodiment of a weighing function providing gravimetric quantification of dispensed quantities has been designed and constructed. This has a pyramidal stainless steel weighing funnel with a capacity of ~1.4 litres mounted inside the induction hopper on a 3 kg load cell. A weighing system

operating within the induction hopper without any external parts is an appropriate method for measuring agrochemicals both in liquid and granular form. The ability to dispense products directly into the induction hopper improves the health and safety of operators and reduces contamination of the environment.

4) The operating environment and gravimetric embodiment requires signal processing in order to achieve the required resolution and accuracy. Primary source of noise is mechanical vibration imparted by the engine principal exciting force of 33–83 Hz. A low pass digital filter with a cut off frequency of 3 Hz (–3 dB) combined with second stage averaging filter with a window of five values demonstrated a reduction of the error seen on the screen from 2240 grams to 3.6 grams with system response appropriate to suit human reaction time. A combination of analogue and digital filtering delivers noise suppression similar to total mechanical isolation. The value indicated to the operator varies by less than 2 grams. Digital filtering enables advanced software controlled strategies such as alteration of engine operating speed or complete switch off to be implemented in integration with ISO 11783 engine control unit for further improvements of measuring accuracy. The error seen on the screen was within 1 gram if the engine is switched off which satisfies the design specification.

5) Following an examination of the ISO 11783 task management logic an integrated system layout has been demonstrated where the tasks are divided between the farm computer, tractor task controller and the AACTS. Data flow where an electronic task file initiated in the farm computer carries the information through the system and stores the records utilises the functionality of each unit in the most efficient way. Minimal but significant extensions have been proposed to the ISO 11783-10 international standard: incorporation of the unique identifier of agrochemical container (RFID) and records of the tank contents as individual products. The following benefits may be obtained from such a system:

- traceability at the tank load level,
- traceability back to the manufacturer of the chemical at individual pack level and
- enhanced sprayer control strategies.

6) A simple two-way user interface for the chemical loading task has been proven to be highly effective. The investigation of the operating conditions and market expectation determined the specification of the user interface:

    - a black and white 200×200 pixel screen for communication to the user,
    - 8 segment coloured LED bar for fast response indication of quantity,
    - three buttons (Yes, No, Back) for user input.

    The trial demonstrated that such a user interface is most economical and efficient for prompting the operator and taking commands regarding the task of filling the sprayer. The ability to assist the operator and control the workflow is beneficial in terms of reducing human errors.

7) The AACTS is significantly more accurate when compared to a manual sprayer loading method as determined from the operator trial. The dispensed amounts (100.36% of target level) and recorded (100.16% of target level) are in accordance with prescribed values ($LSD_{(5\%)}$ 2.166%). This compares to the results of the trials with the manual method where the dispensed amount differs significantly (92.61% of target level) from prescribed and recorded value. It demonstrates the AACTS improves the precision of the dispensing rates and traceability records.

8) The results demonstrated 92% of the cases are measured within ±5% deviation from the target regardless of dispensing speed. 57% of cases are measured within ±1.25% error which means the majority of sprayer operators are able to achieve better accuracy with the system than the systematic error (2.5%) with measuring jugs.

9) In a combined loading and recording cycle the automatic recording system delivers not significantly different work rate (211.8 s/task) as manual method

(201.3 s/task) (Δt = 10.5 s/task, $LSD_{(5\%)}$ 28.2 s/task). Considering only the loading time (181.2 s/task) of manual method, most noticeable to the operator in practice in case the records are created outside spraying hours, the difference is 30.6 s/task ($LSD_{(5\%)}$ 30.1 s/task). In practice the difference is believed to be marginal compared to the time required to load the water, random events during a spraying session and in time moving, checking and storing paper records. The automated electronic records are a basis for significant labour time saving in further processing of records in farm management and traceability systems.

10) The investment cost of the AACTS is equivalent to 6.1 ha of erroneously sprayed winter wheat when considering total loss of crop. The results of this work do not show any significant saving in operator or recording time over manual processes on the field, however AACTS is a tool providing traceability, management and operator assistance which enables indirect benefits such as prevention of human errors, electronic records and precise stock control to be obtained at no extra cost.

8.2. Recommendations

Following this work it is recommended that the industry should:

1) Adopt the ISO 11783-10 data interchange standard with the extensions developed in this work to achieve agrochemical traceability at individual product container and tank load level. This can be deployed regardless of particular system implementation.

2) Pilot the RFID labelling of agrochemical containers at local distributor or grower cooperative levels in collaboration with larger farms or spray contractors. Introduce the benefits of having a robust traceability link from manufacture to the point of application, such as direct feedback of product efficacy, to the leading agrochemical manufacturers to promote the large scale adoption of RFID technology.

3) Take the development prototype and produce a production prototype following the design methodology, analysis techniques and performance drivers presented in this work.

4) Develop the features of user interface, file store capability, records of tank content into the software for ISO 11783-10 cabin task controller to deliver the business benefits identified here to the farming industry.

5) Explore the existing routes to market following the development of the modular functionality of the AACTS: original part of the machine, after market product, retro fit. The modularity allows functions (identification, weighing, user interface, ISOBUS interface) to be deployed independently because some are cheaper and quicker to develop but benefit in longer term such as ISOBUS, while other are complex to deploy but benefit immediately, such as the weighing system.

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Appendices

Appendix A. Review of agrochemical products

A.1. Bulk density of agrochemicals

In order to get an overview of bulk densities of agrochemicals a review was undertaken. The following products were randomly selected from Syngenta's product catalogue of 57 UK approved products.

Product name	**MAPP No**	**Formulation**	**Bulk density**
ACANTO PRIMA	11864	Granule	0.506 g/cm^3
AMISTAR	10443	Liquid	1.09 g/cm^3
AMISTAR OPTI	12515	Liquid	1.271 g/cm^3 at 20°C
BRAVO 500	10518	Liquid	1.24 g/cm^3
FOLIO GOLD	10704	Liquid	1.24–1.28 g/cm^3 at 20°C
CHEROKEE	12768	Liquid	1.21 g/cm^3
HAWK	12507	Liquid	1.08–1.12 g/cm^3
RADIUS	09387	Granule	0.49 g/cm^3
TOPAS	09717	Liquid	0.97–1.01 g/cm^3
UNIX	11512	Granule	0.4–0.7 g/cm^3
ADIGOR	ADJ0522	Liquid	0.91–0.95 g/cm^3

A.2. Most extensively used active ingredients

Table A-1 Application rates of most extensively used active ingredients on arable crops

Fungicides	**Application rate, kg/ha**	**Formulation**
Chlorothalonil	1.0–2.5	liquid, granule, powder
Epoxiconazole	0.125	liquid
Azoxystrobin	0.100–0.375	granule
Trifloxystrobin	0.050 cereals, 0.187 cucurbit crops	liquid, granule
Herbicides	**Application rate, kg/ha**	**Formulation**
Glyphosate	1.5–2.0	liquid, granule
Isoproturon	1.0–1.5	liquid, powder
Fluroxypyr	0.180–0.400	liquid
Mecoprop-P	1.2–1.5	liquid
Trifluralin	0.5–1.0	liquid, granule
Insecticides	**Application rate, kg/ha**	**Formulation**
Cypermethrin		liquid, granule
Lambda-cyhalotrin	0.002–0.005	liquid, granule, powder
Zeta-cypermethrin	0.0075–0.030	liquid, powder
Tau-fluvalinate	0.036–0.048 0.072 max on vegetables	liquid
Deltamethrin	0.0025–0.021	liquid, powder, granule
Esfenvalerate	0.005–0.025	liquid
Pirimicarb	0.125–0.375	liquid, powder, granule
Plant growth regulators	**Application rate, kg/ha**	**Formulation**
Chlormequat	0.8–1.6	powder, liquid

A.3. Fungicides

Table A-2 Fungicide Chlorothalonil

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Agriguard Chlor. 12201	suspension concentrate	500 g/*l*	5 *l*		2–3 *l*/ha
Bravo 500 10518	suspension concentrate	500 g/*l*	1–20 *l*	45 mm	2–3 *l*/ha
Jupital 10528	suspension concentrate	500 g/*l*	5 *l*	63 mm	2–3 *l*/ha
Cropguard 11835	suspension concentrate	500 g/*l*	1–10 *l*	45 mm for 5 *l*, 63 mm over 5 *l*	2–3 *l*/ha
Visclor 75 DF 09361	water disper-sible granule	750 g/kg	1–10 kg bag		1.33–2 kg/ha

Table A-3 Fungicide Epoxiconazole

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Epic 12136	suspension concentrate	125 g/*l*	1–4 *l*, 5–10 *l* wide-necked	45 mm for 5–10 *l*	1 *l*/ha
Greencrop Martello 12318	suspension concentrate	125 g/*l*	1–4 *l*, 5–10 *l* wide-necked	45 mm for 5–10 *l*	1 *l*/ha
Opus 12057	suspension concentrate	125 g/*l*	1–4 *l*, 5–10 *l* wide-necked	45 mm for 5–10 *l*	1 *l*/ha

Table A-4 Fungicide Azoxystrobin

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Amistar 10443	suspension concentrate	250 g/*l*	1–10 *l*		1 *l*/ha
5504 12351	suspension concentrate	250 g/*l*	1–10 *l*		1 *l*/ha

Table A-5 Fungicide Epoxiconazole/fenpropimorph/kresoxim-methyl

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Asana 11934	suspo-emulsion	125:150:125 g/*l*	1–10 *l*	45 mm for 5–10 *l*	1 *l*/ha
Mastiff 11747	suspo-emulsion	125:150:125 g/*l*	1–10 *l*	45 mm for 5–10 *l*	1 *l*/ha
Cleancrop Chant 11746	suspo-emulsion	125:150:125 g/*l*	1–10 *l*	45 mm for 5–10 *l*	1 *l*/ha

Table A-6 Fungicide Trifloxystrobin

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Swift SC 11227	suspension concentrate	500 g/*l*	1–10 *l*		0.5 *l*/ha
Aprix 11220	emulsifiable concentrate	125 g/*l*	1–10 *l*		2 *l*/ha
Twist 500 SC 11231	suspension concentrate	500 g/*l*	1–10 *l*		0.5 *l*/ha

A.4. Herbicides

Table A-7 Herbicide Glyphosate

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Barclay Barbarian 12714	soluble concentrate	360 g/*l*	1–20 *l*		1.5–4 *l*/ha
Envision 10569	soluble concentrate	450 g/*l*	1–20 *l*		3.2–4.8 *l*/ha
Glyphosate 360 12669	soluble concentrate	360 g/*l*	1–20 *l*		1.5–4 *l*/ha
Touchdown Quattro 10608	soluble concentrate	360 g/*l*	1–25 *l*		3–4 *l*/ha
Samurai 12674	soluble concentrate	360 g/*l*	1–20 *l*		1.5–4 *l*/ha

Table A-8 Herbicide Isoproturon

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Aligran 11761	water dispersible granule	830 g/kg	6 kg 12 kg		3 kg/ha
Emrald Wotsit 12060	suspension concentrate	500 g/*l*	5–10 *l*	55 mm internal 63 mm external	5 *l*/ha
IPU MinRinse 12457	water dispersible granule	800 g/kg	6–12 kg 0.5–12 kg sacks		2.6–3.1 kg/ha
Luxan Isoproturon 500 12426	suspension concentrate	500 g/*l*	5–20 *l*		5 *l*/ha
Arelon 500 11639	suspension concentrate	500 g/*l*	5–10 *l*	55 mm internal 63 mm external	5 *l*/ha

Table A-9 Herbicide Fluroxypyr

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Greencrop Reaper 12261	emulsifiable concentrate	200 g/*l*	1–5 *l*		0.75–2 *l*/ha
Starane 2 12018	emulsifiable concentrate	200 g/*l*	1–5 *l*		0.75–2 *l*/ha
Tomahawk 09249	emulsifiable concentrate	200 g/*l*	1–5 *l*		0.75–2 *l*/ha

Table A-10 Herbicide Mecoprop-P

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Clenecorn Super 09818	soluble concentrate	600g/*l*	1–20 *l*		2.3 *l*/ha
Compitox Plus 10077	soluble concentrate	600g/*l*	1–20 *l*		2.3 *l*/ha
Isomec 11156	soluble concentrate	600g/*l*	1–20 *l*		2.3 *l*/ha

Table A-11 Herbicide Trifluralin

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Alpha Trifluralin 48 EC 07406	emulsifiable concentrate	480 g/*l*	5–20 *l*		2.1–2.5 *l*/ha
Treflan 05817	emulsifiable concentrate	480 g/*l*	5–20 *l*		2.3 *l*/ha
Triflurex 48EC 07947	emulsifiable concentrate	480 g/*l*	5–20 *l*		2.1–2.5 *l*/ha

A.5. Insecticides

Table A-12 Insecticide Cypermethrin

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
AgriGuard Cypermethrin EC 12134	emulsifiable concentrate	100 g/*l*	1–5 *l*		250 ml/ha
Jundi 100EC 10848	emulsifiable concentrate	100 g/*l*	1–5 *l*		250 ml/ha
Permasect C 11121	emulsifiable concentrate	100 g/*l*	1–5 *l*		250 ml/ha

Table A-13 Insecticide Lambda-cyhalotrin

Product name	Formulatio n type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Hallmark With Zeon Technology 12629	capsule suspension	100 g/*l*	0.25–5 *l*		50–75 ml/ha
Landgold Lambda-Z 12383	capsule suspension	100 g/*l*	0.25–5 *l*		50–75 ml/ha
Stealth 11514	wettable granule	25 g/kg	1–3 kg		0.2 kg/ha

Table A-14 Insecticide Zeta-cypermethrin

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Fury 10 EW 12248	oil in water emulsion	100 g/*l*	100–1000 ml		100–150 ml/ha
Minuet EW 12304	oil in water emulsion	100 g/*l*	100–5000 ml		100–150 ml/ha

Table A-15 Insecticide Tau-fluvalinate

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Klartan 11074	oil in water emulsion	240 g/*l*	1–5 *l*		0.15–0.20 *l*/ha
Mavrik 10612	oil in water emulsion	240 g/*l*	1–5 *l*		0.15–0.20 *l*/ha

Table A-16 Insecticide Deltamethrin

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Agrotech Delta-methrin 12165	emulsifiable concentrate	25 g/*l*	1 *l*		250–300 ml/ha
Decis Protech 11502	oil-in-water emulsion	15 g/*l*	0.25–5 *l*		420–500 ml/ha
Pearl Micro 08620	emulsifiable granule	62.5 g/kg	50–500 g 0.5–5 *l*		100–200 g/ha

Table A-17 Insecticide Esfenvalerate

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Sumi-Alpha 10401	emulsifiable concentrate	25 g/*l*	0.5–1 *l*		165–200 ml/ha

Table A-18 Insecticide Pirimicarb

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Aphox 10515	water dispersible granule	500 g/kg	560–5000 g		280–420 g/ha
Phantom 11954	water dispersible granule	500 g/kg	560–5000 g		280–420 g/ha
Milentus 12268	water dispersible granule	500 g/kg	1000 g		280–420 g/ha

A.6. Plant growth regulators

Table A-19 Plant growth regulator Chlormequat

Product name	Formulation type	Active ingredient content	Container	Min neck Ø of container for liquid	Max dose of the product
Adjust 05589	soluble concentrate	620 g/*l*	5 *l*		0.9–2.3 *l*/ha
K2 10370	soluble concentrate	620 g/*l*	5 *l*		0.9–2.3 *l*/ha
Clayton Manquat 09916	soluble concentrate	400 g/*l*	5–20 *l*		1.2–4.2 *l*/ha
Stabilan 750 09303	soluble concentrate	750 g/*l*	1–20 *l*		1.12–2.25 *l*/ha

Appendix B. On-farm observations on loading the sprayer

Date: 17/04/2006

Place: Duck End, Wilstead

Sprayer: Spra-Coupe 4440

1400 *l* tank

Speed 11 km/h and pressure 2.8 bar equal to a water volume of 163 *l*/ha.

XR TeeJet nozzles

Agronomist gives the crop management recommendation sheet which contains field name, crop area, problems (reasons to treat), product rate per hectare, water volume, and comments. The sprayer operator calculates the total litres of solution, number of tank loads, total amount of chemicals and chemicals per tank load based on the recommendation sheet and configuration of the sprayer.

The following set of agrochemicals was prescribed:

- Doonberg granular herbicide in 2.5 kg container
- Rookie liquid adjuvant in 5 *l* container
- Stabilan 700 chlormequat liquid growth regulator in 15 *l* container
- Agriguard chlorothalonil liquid fungicide in 5 *l* container

Chemicals were poured manually into the induction hopper. Time needed to dispense 4 *l* with a 2 *l* jug from a 15 *l* container was 52 s. Loading and rinsing times for full containers were as follows:

- 2.5 kg granule 51 s
- 15 *l* liquid 37–64 s
- 5 *l* liquid 15–20 s

A tank mixture of 1300 *l* for 8 ha consisted of the following agrochemicals:

Product	Amount			
	Total	Actual	Agronomist	Maximum
Doonberg	2.5 kg	0.31 kg/ha	0.4 kg/ha	0.4 kg/ha
Rookie	5+2 *l*	0.875* *l*/ha	1* *l*/ha	0.815* *l*/ha
Stabilan	15+4 *l*	2.4 *l*/ha	2.3 *l*/ha	2.4 *l*/ha
Agriguard	5+1 *l*	0.75 *l*/ha	1 *l*/ha	3 *l*/ha

*– Maximum dose for Rookie was specified as 0.5% of volume. Agronomist recommended min 200 *l*/ha water volume. However the actual water volume was 163 *l*/ha which means the chemical rate was 0.54% of volume (0.875 *l*/ha).

The overall time for loading the sprayer with the above listed chemicals and filling the tank with water from the mains was 9 min.

Appendix C. Technical information about the load cell

CALIBRATION CERTIFICATE

Calibration of transducer

Date: 27 November 2007

Customer:

Cranfield University
Finance Department
Cranfield
Beds
MK43 0AL

Customer Order Ref: 712835 AML Order Ref: S231107G

APPLIED MEASUREMENTS LIMITED
3 MERCURY HOUSE
CALLEVA PARK
ALDERMASTON
BERKSHIRE
RG7 8PN
UK
Tel: (+44) 0118 981 7339
Fax: (+44) 0118 981 9121
e-mail: info@appmeas.co.uk
Internet: www.appmeas.co.uk

Calibration Results:

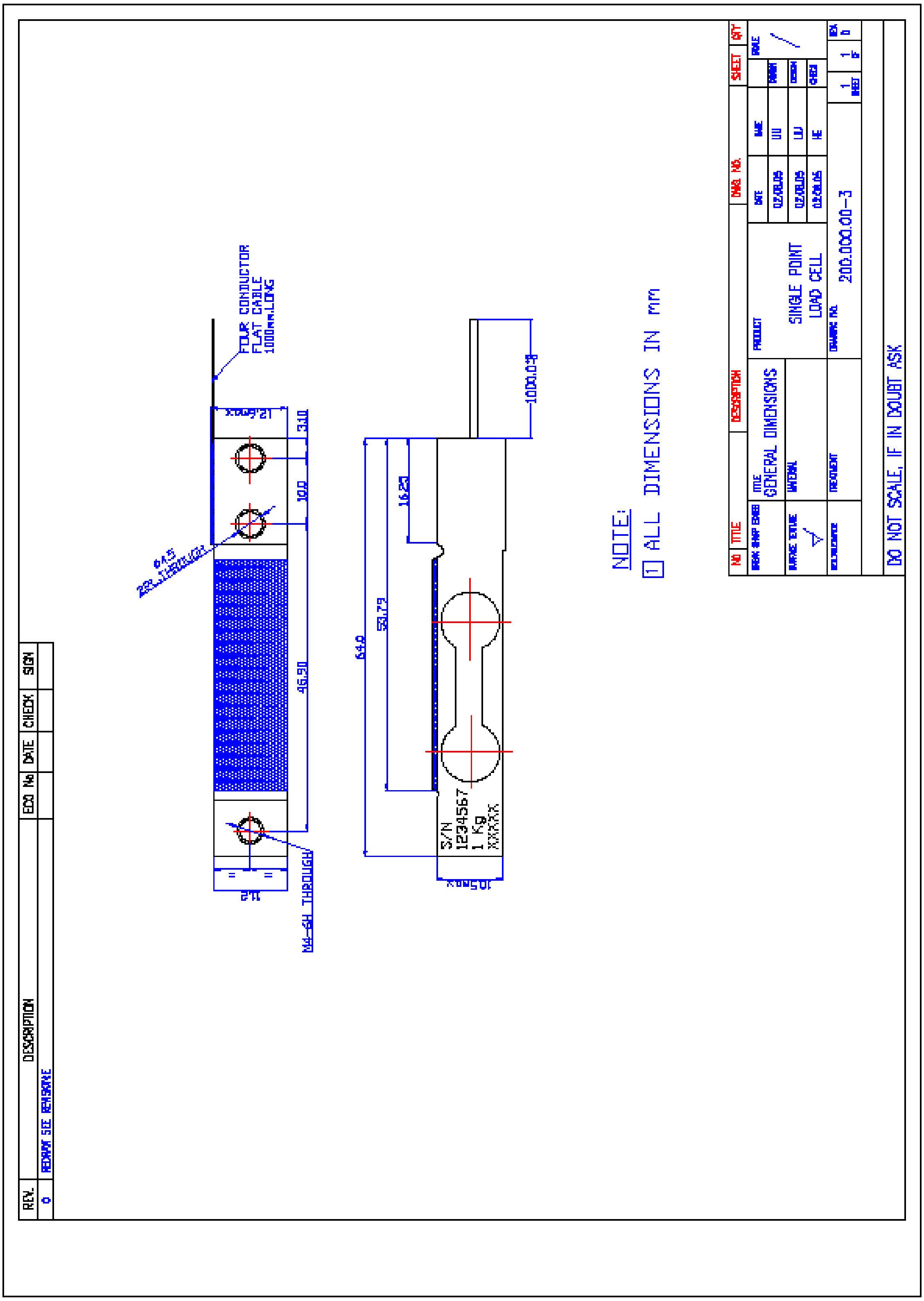
Transducer Type:	1005-3kg
Serial No:	19408187
Load rating:	3kg
Proof rating:	4.5kg
Zero output:	-0.277mV @ 10Vdc
Sensitivity:	1.4590mV/V
Linearity:	0.007% FS
Hysteresis:	0.007% FS
Supply voltage:	10.00Vdc
Bridge Resistance:	350 ohms

Connections:		
	Red:	+ve excitation
	Green:	-ve excitation
	Black:	-ve signal
	White:	+ve signal

Applied Measurements Limited hereby certifies that the above item has been inspected, tested and calibrated in all respects with the requirements of the customer's order.

Director:
PETER LEWIS

Reg. No. 2583968


FOUR CONDUCTOR FLAT CABLE 1000mm LONG
S/N 1234567 1 Kg XXXXX
NOTE:
1 ALL DIMENSIONS IN mm
GENERAL DIMENSIONS
SINGLE POINT LOAD CELL
200.000.00-3
DO NOT SCALE, IF IN DOUBT ASK

Appendix D. Selection of the spring for the valve

In order to select an appropriate spring, hydrostatic pressure on the valve and clamp force of the gasket need to be calculated.

Hydrostatic pressure

$$p = \rho \ g \ h \ = 1300 \cdot 9.81 \cdot 0.143 = 1824 \ \text{ Pa (N/m}^2\text{)} \tag{D-1}$$

where ρ is density of the liquid (kg/m^3)

g is acceleration due to gravity (m/s^2)

h is height of the liquid column (m)

Hydrostatic force

$$F_h = p \ S = 1824 \cdot \pi \cdot 0.015^2 = 1.3 \ \text{ N} \tag{D-2}$$

S is the area of the valve (m^2)

Clamp force

$$F_k = F_h + p \ m_g A = 1.3 + 1824 \cdot 0.5 \cdot 0.000254 = 1.53 \ \text{ N} \tag{D-3}$$

m_g is gasket factor (0.5 for rubber)

A is effective area of gasket, A = 0.000254 m^2

Total force on the spring is

$$F_t = F_h + F_k = 1.3 + 1.53 = 2.83 \ \text{ N} \tag{D-4}$$

Allowing a safety factor of 4 the required spring clamp force is 11.3 N.

An appropriate spring is RS 751-540 stainless steel

Length 67 mm & 23.8 mm, rate 0.44 N/mm

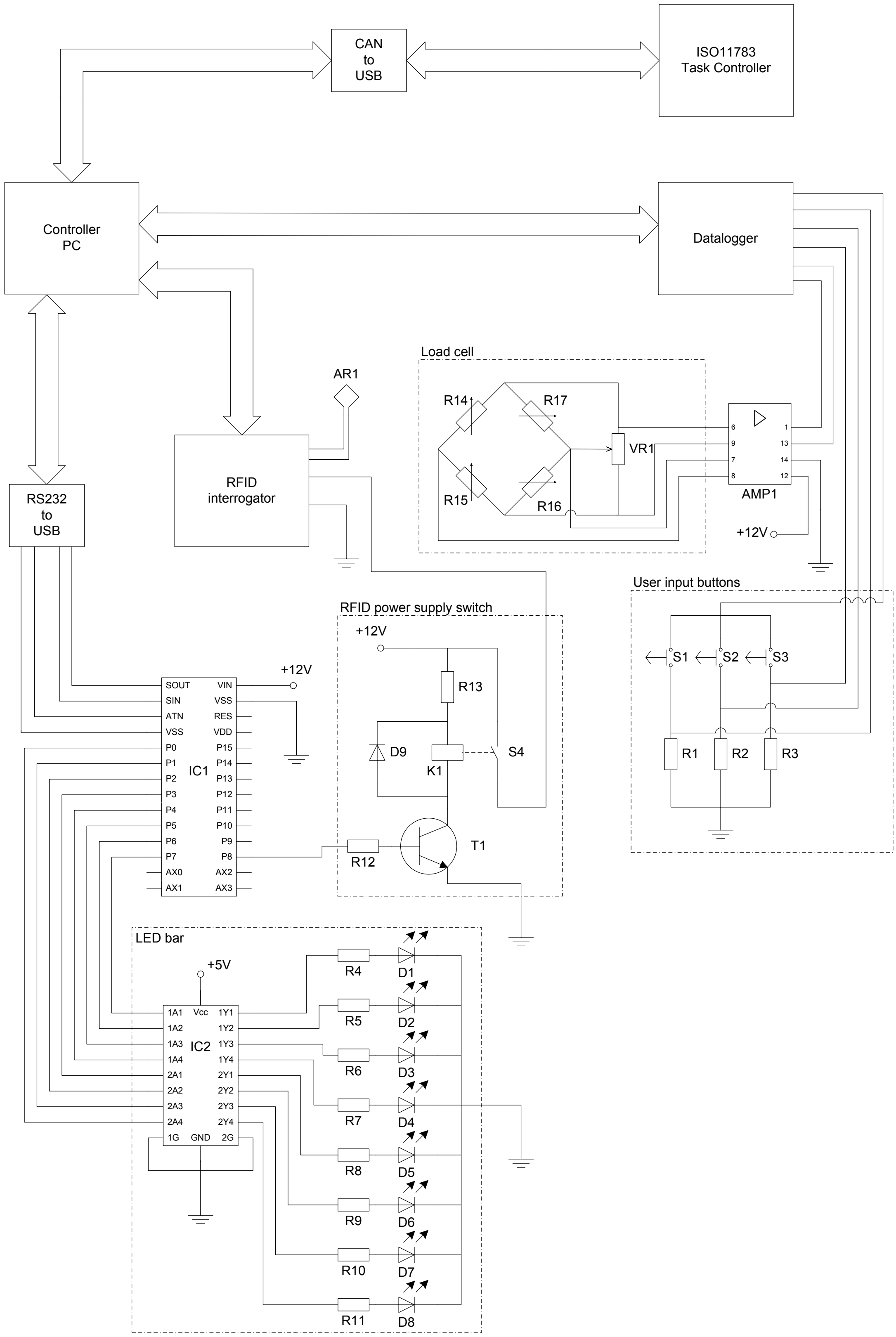
On 40 mm ~ 12.32 N (valve closed)

On 30 mm ~ 16.72 N (valve opened)

Appendix E. Electrical wiring diagram of the experimental system

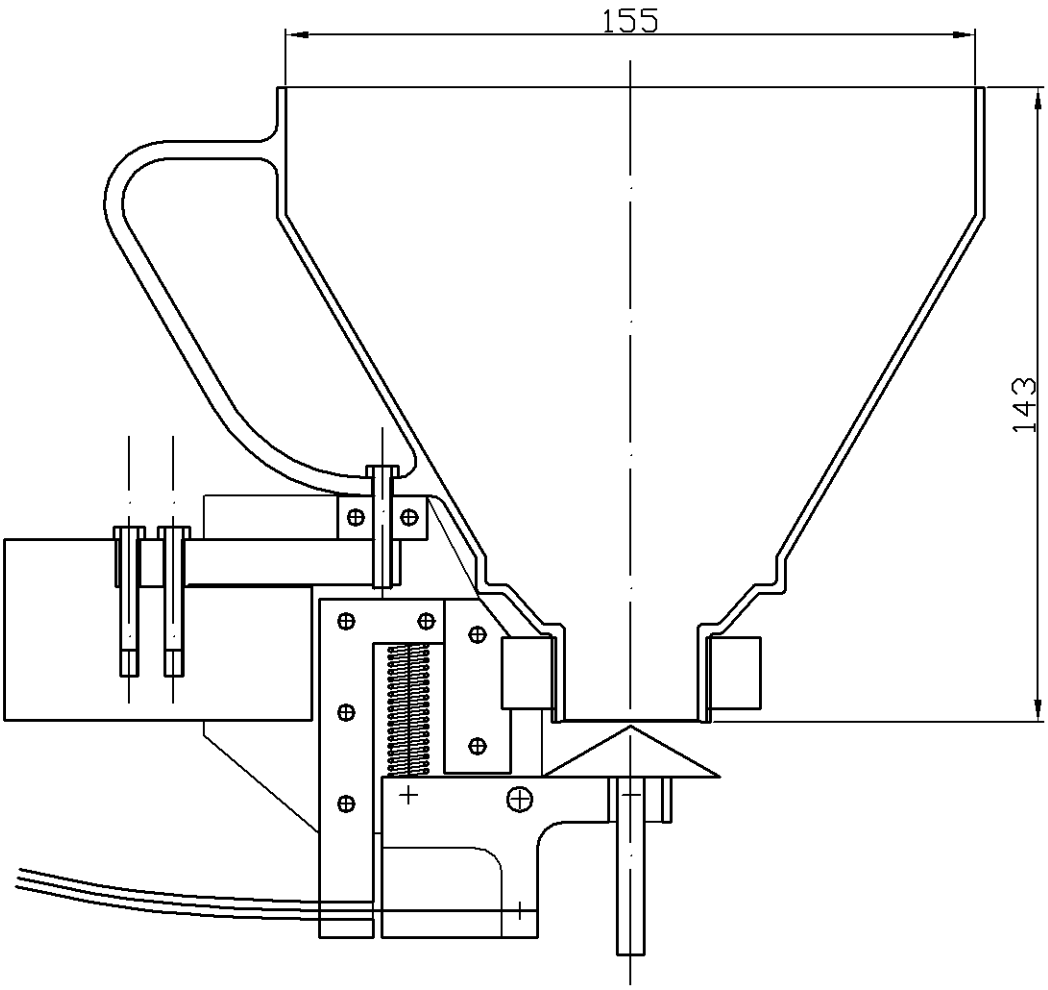
Parts list

AMP1	Load cell amplifier ICA2S Applied Measurements, UK
AR1	Aerial RFID 13.56 MHz
D1	Light emitting diode, red
D2	Light emitting diode, amber
D3–D8	Light emitting diode, green
D9	Diode IN4003
IC1	Basic Atom 28 pin
IC2	Octal buffer SN74LS240N
K1	Relay 2 A, 30 V
VR1	Trimmer (potentiometer) 10 kΩ
R1–R3	Resistor 10 kΩ
R4	Resistor 270 Ω
R5–R11	Resistor 120 Ω
R12	Resistor 390 Ω
R13	Resistor 180 Ω
R14–R17	Load cell OBUG 1005-3 kg, R=350 Ω
S1–S3	Industrial push button
S4	RFID power switch
T1	Transistor 2N3053
Controller PC	Notebook IBM T23
RFID reader	Feig MR100
CAN to USB	Sontheim CAN-USB interface
Datalogger	C-cubed Dataq Compact Flash 2, 24 bit resolution


CAN
to
USB
ISO11783
Task Controller
Controller
PC
Datalogger
RS232
to
USB
RFID
interrogator
AR1
Load cell
R14
R17
R15
R16
VR1
AMP1
+12V
User input buttons
S1
S2
S3
R1
R2
R3
RFID power supply switch
+12V
R13
D9
K1
S4
R12
T1
SOUT
SIN
ATN
VSS
P0
P1
P2
P3
P4
P5
P6
P7
AX0
AX1
VIN
VSS
RES
VDD
P15
P14
P13
P12
P11
P10
P9
P8
AX2
AX3
IC1
+12V
LED bar
+5V
1A1
1A2
1A3
1A4
2A1
2A2
2A3
2A4
1G
GND
2G
Vcc
1Y1
1Y2
1Y3
1Y4
2Y1
2Y2
2Y3
2Y4
IC2
R4
R5
R6
R7
R8
R9
R10
R11
D1
D2
D3
D4
D5
D6
D7
D8

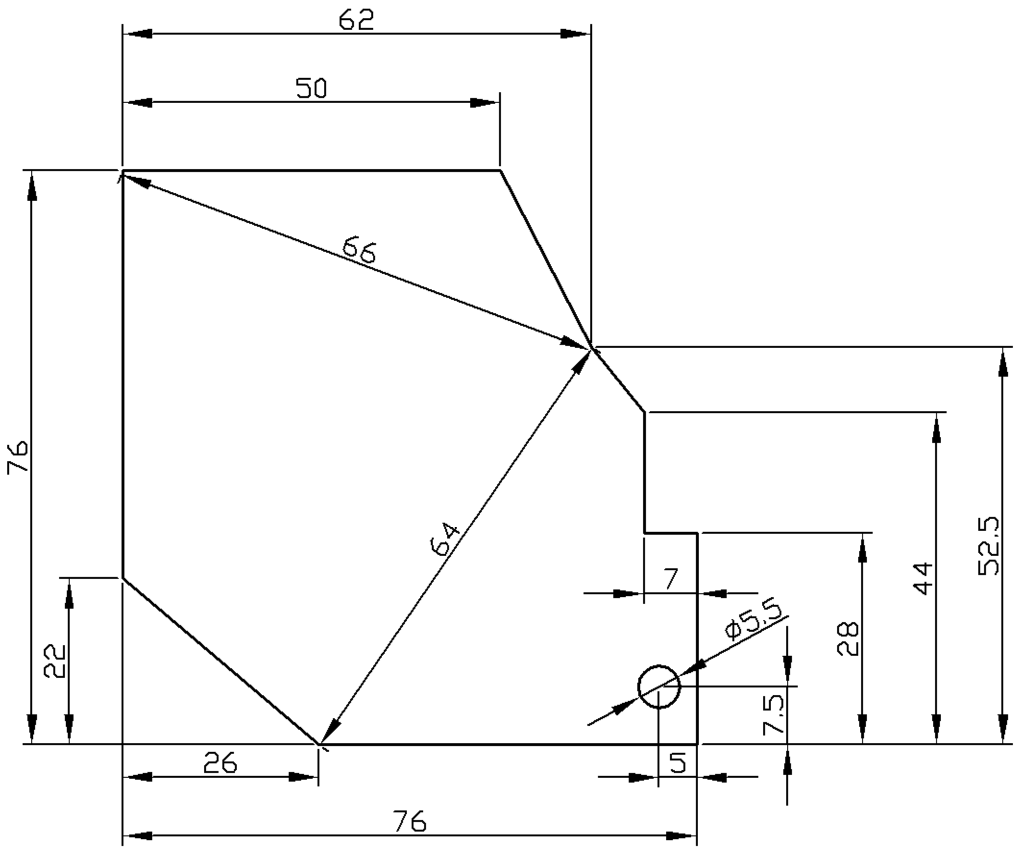
Appendix F. Technical drawings of the weighing system

General arrangement



Dimensions are in millimetres.

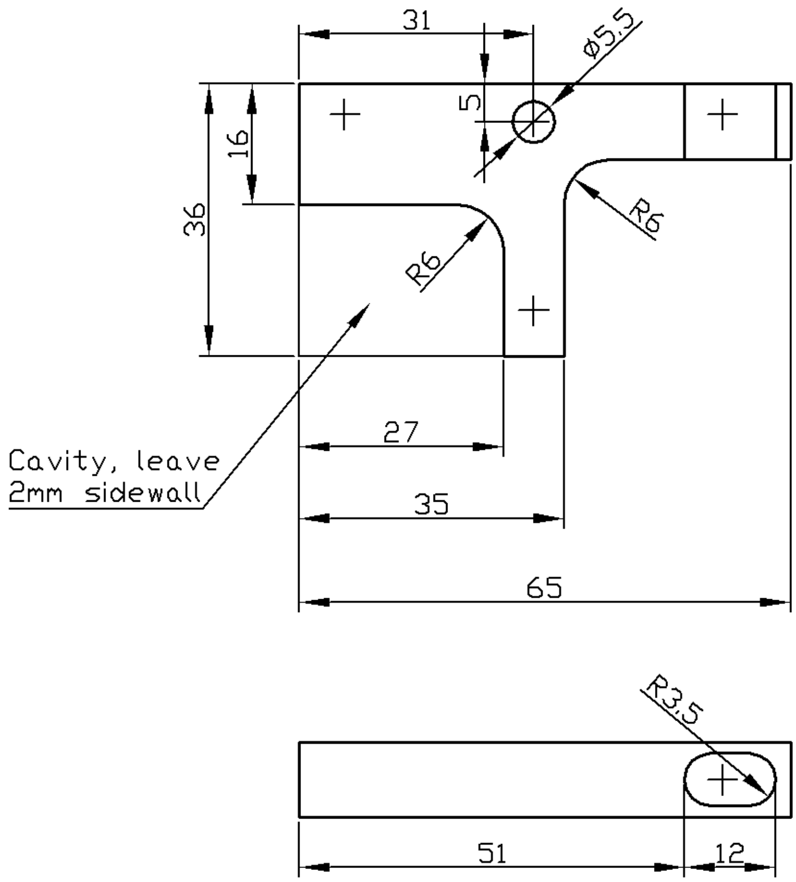
Sideplates



Thickness 5 mm

Total 2 plates

Pivoting arm

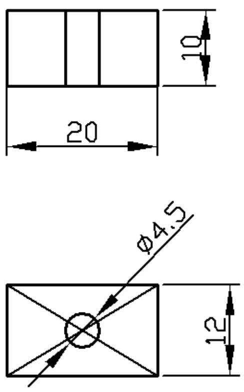


Thickness 10 mm

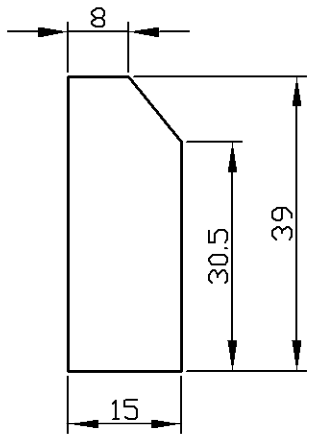
Distance blocks

Thickness 12 mm

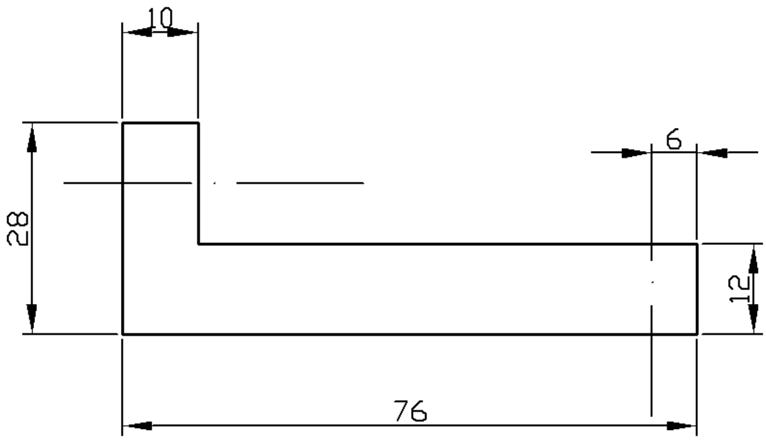
1.



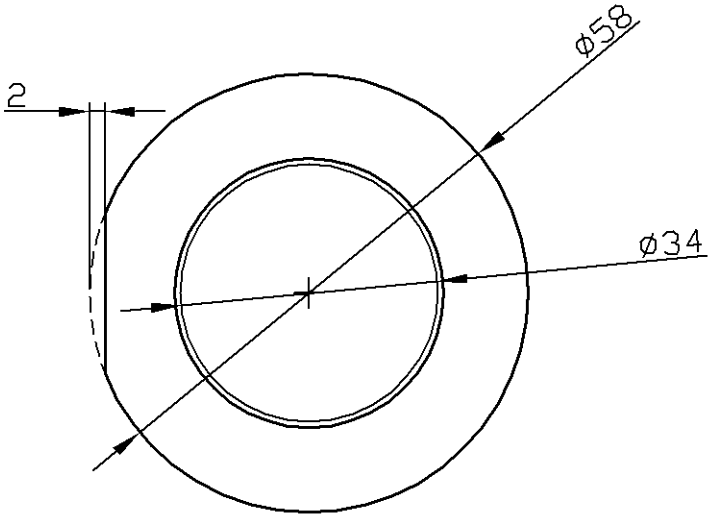
2.



3.



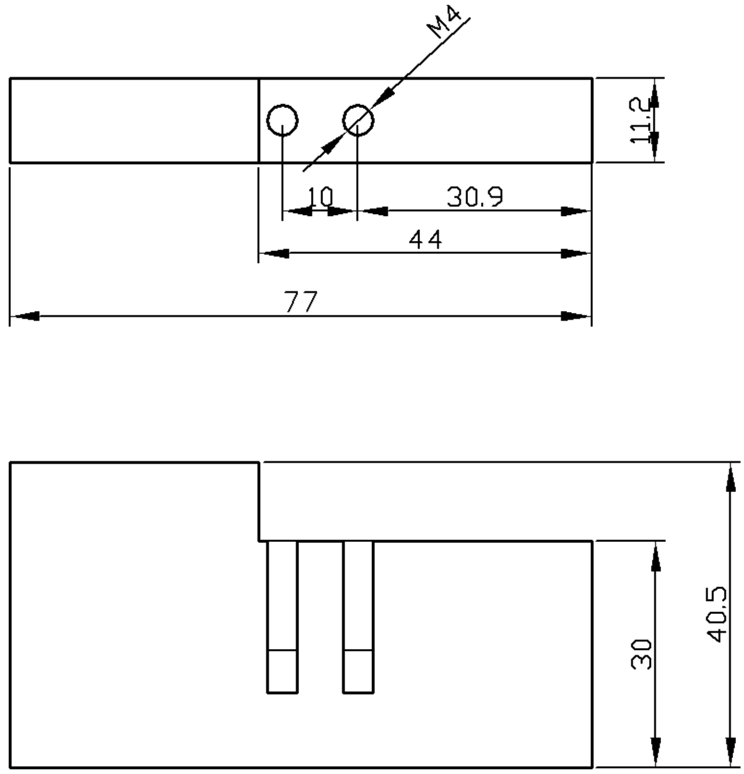
Support ring for the funnel



Height 16 mm

Thread
Height 0.8 mm
Width 1.8 mm
Root 2.6 mm
Pitch 4.4 mm

Mounting block for the load cell



Material brass

<u>Holes</u>
M4 thread
Threaded 16 mm deep

Appendix G. Calibration of the weighing system

The calibration of the weighing system was carried out indoors minimising the disturbances (no wind, engine switched off). Static load, measured with a calibrated laboratory type electronic balance (Sartorius type 1501, range 12000 g, resolution 0.1 g, linearity 0.1 g), in the weighing funnel was increased from 0 to 1250 grams with an increment of 250 grams and 18432 samples of the output voltage of the weighing system logged at a sampling frequency of 3000 Hz. The procedure was repeated three times. A mean value of the data range was used. The calibration constant was determined by plotting the mean values of voltage (Table G-1) on a graph (Figure G-1). The calibration constant was 3579.777807 g/V.

Table G-1 Calibration data of the load cell

Load (g)	Voltage (V)
0	1.012762361
0	1.013077155
0	1.016037120
250	1.083259878
250	1.082849648
250	1.085916999
500	1.152877193
500	1.152439570
500	1.155156401
750	1.222954584
750	1.222249369
750	1.224827958
1000	1.293579071
1000	1.291998719
1000	1.294794918
1250	1.363331362
1250	1.361812778
1250	1.364384507

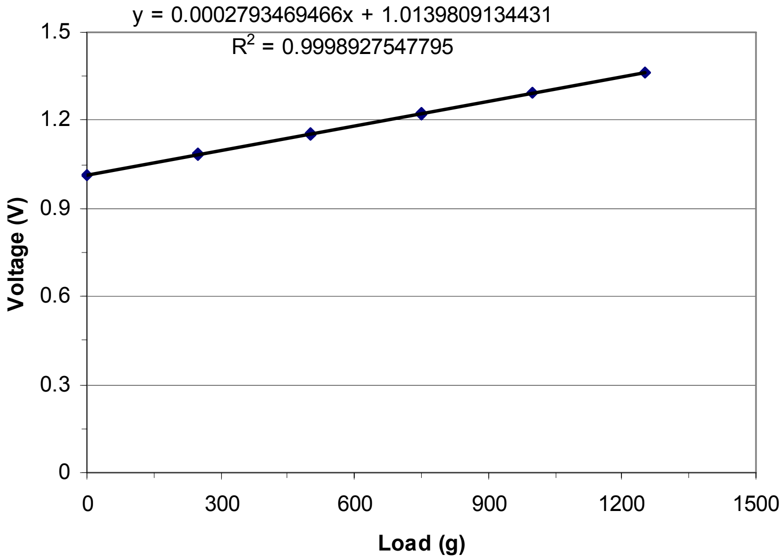


Figure G-1 Calibration curve of the weighing system

Appendix H. Program code

This appendix is the directory /Program on the CD enclosed and comprises of the AACTS program files as follows:

/Data/task_file.csv
BasicAtom.bas
CRC32.cls
data
DataqCF2.bas
Dataq_variables.bas
FECOM.bas
FEISC.bas
files.txt
frmConfirmed.frm
frmConfirmTank.frm
frmData.frm
frmFullpack.frm
frmIdentified.frm
frmJob.frm
frmLoadChem.frm
frmManual.frm
frmMessage.frm
frmRFIDMessage.frm
frmTank.frm
frmWeigh.frm
frmWeighMessage.frm
frmWeighMsgRinse.frm
Group1.vbg
h_129.csv
mdlDefaultEngine.bas
mdlFileIO.bas
mdlHex2Dec.bas
mdlProcheckdata.bas
mdlUnitConversion.bas
procheckdata.DCA
procheckdata.Dsr
procheckdata.mdb
PubFunctions.bas
PubVariables.bas
userinterface.vbp
userinterface.vbw

Appendix I. Data files of the AACTS

This appendix is the directory /Datafiles on the CD enclosed and comprises of an example task file, record file and agrochemical container record file of the AACTS. The files are as follows:

task_file.csv
filling_record.csv
RFID_labels_1.csv

Appendix J. MatLab scripts for data analysis

This appendix is the directory /Scripts on the CD enclosed and comprises of the MatLab script files used in data analysis. The files are as follows:

01_fft_psd.m
02_moving_average.m
03_plot_moving_average.m
04_fft_psd_filter.m
05_fft_psd_3d.m
06_fft_psd_3d_mean.m
07_plot_3d.m
08_fft_psd_engine0.m
09_fft_psd_filter_3d.m
10_fft_psd_sugar.m
11_fft_psd_sugar_mean.m
12_plot_compare_sugar.m
13_fft_psd_circul0_outlet0.m
14_plot_compare_circul0_outlet0.m
15_unfiltered.m
16_filtered.m
17_plot_weighing.m
18_time_weighing.m
19_rate_weighing.m
20_accuracy_speed.m

Appendix K. Characteristics of the output signal of the weigh cell based on the FFT analysis

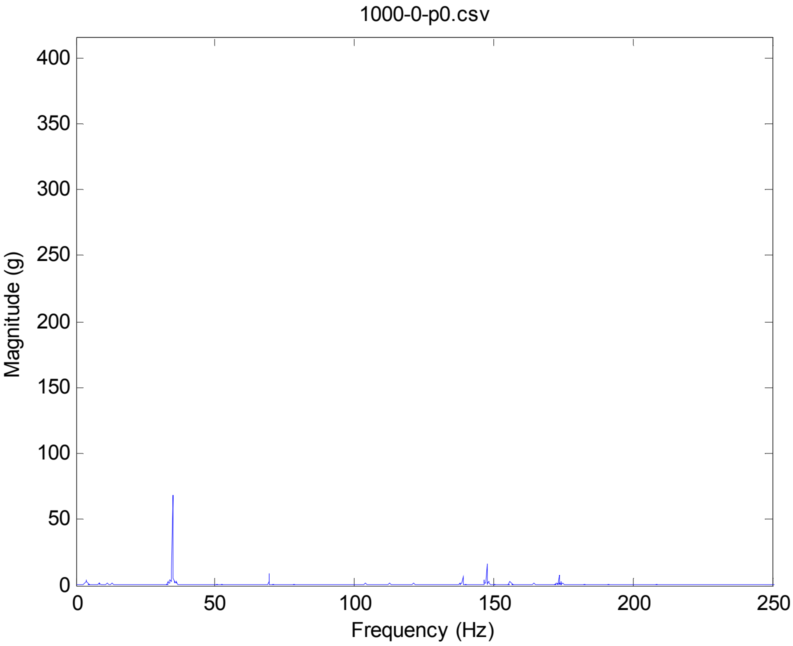


Figure K-1 Frequency spectrum of the output signal at engine 1000 r/min, 0 g of weight in the funnel, pump off

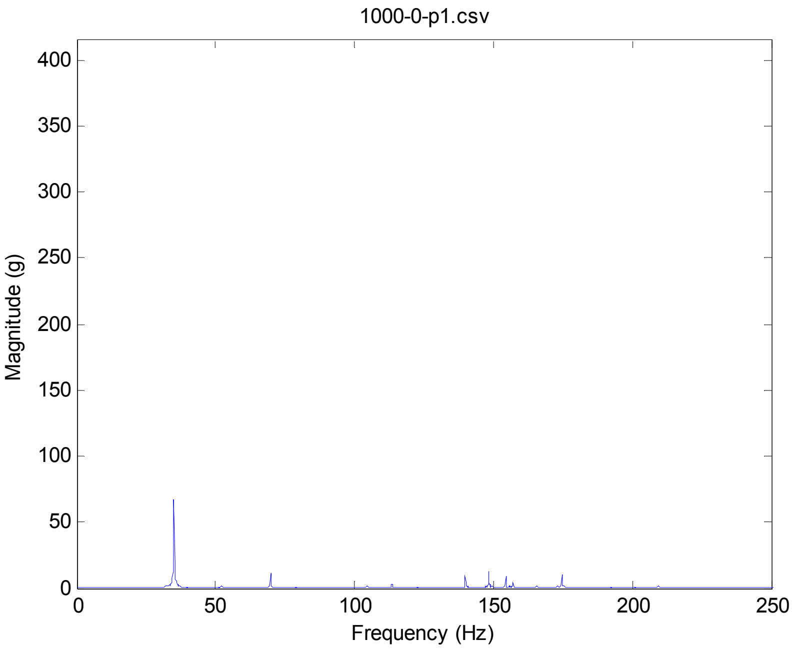


Figure K-2 Frequency spectrum of the output signal at engine 1000 r/min, 0 g of weight in the funnel, pump on

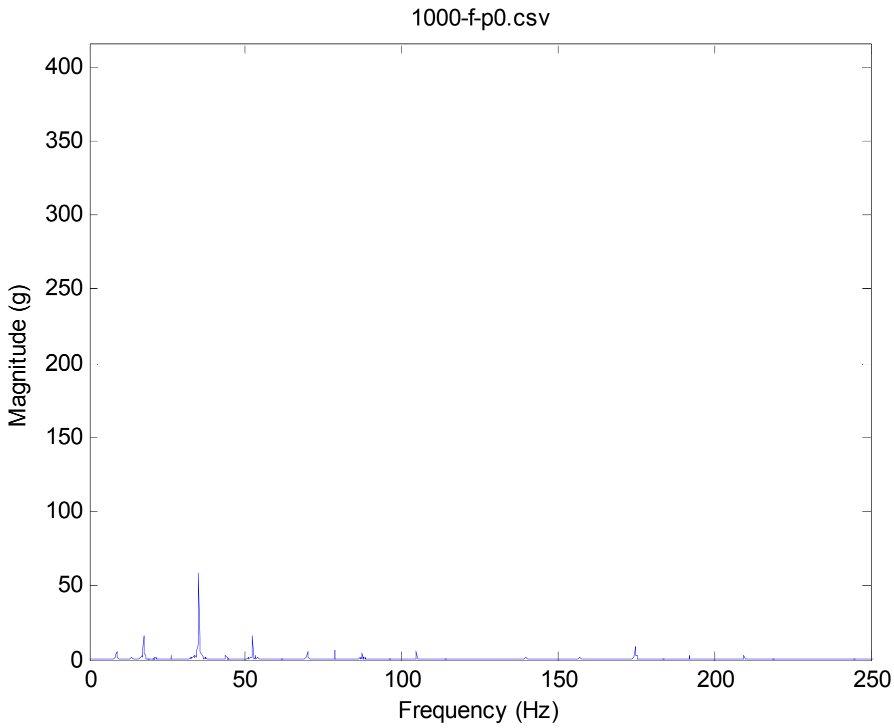


Figure K-3 Frequency spectrum of the output signal at engine 1000 r/min, 1000 g of weight in the funnel, pump off

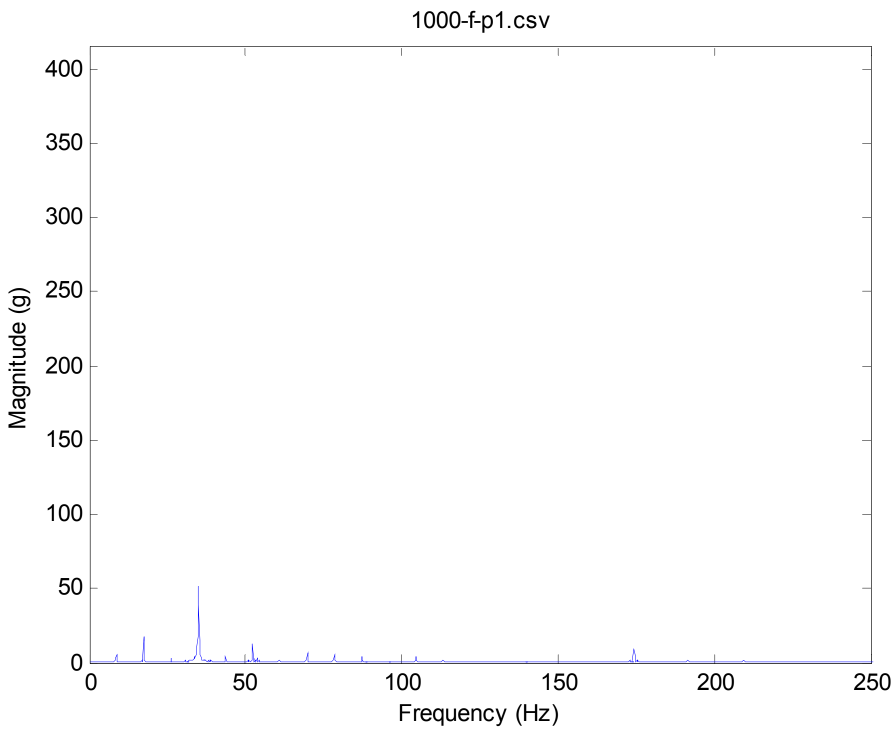


Figure K-4 Frequency spectrum of the output signal at engine 1000 r/min, 1000 g of weight in the funnel, pump on

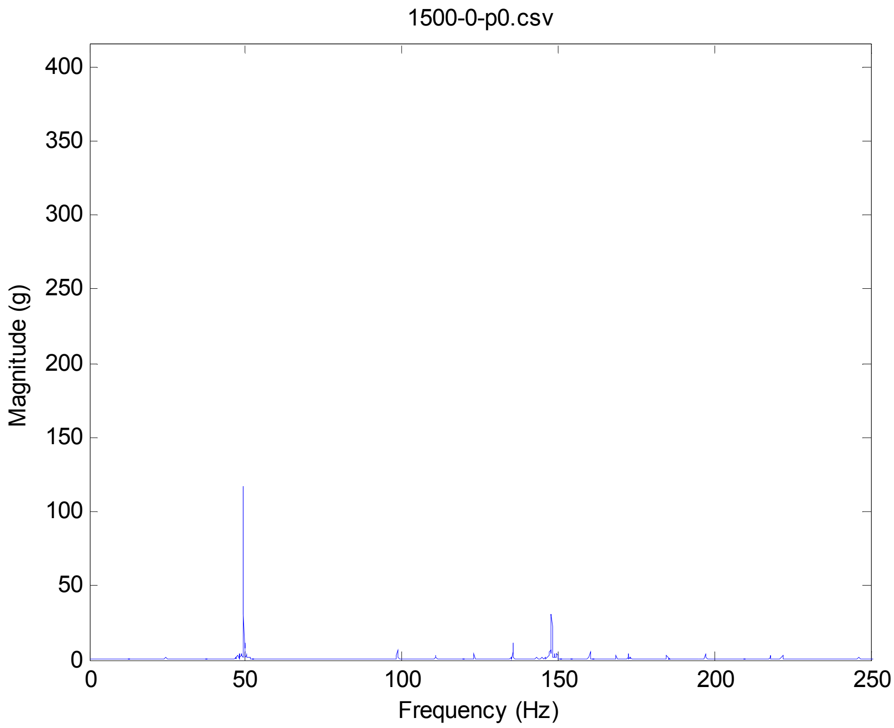


Figure K-5 Frequency spectrum of the output signal at engine 1500 r/min, 0 g of weight in the funnel, pump off

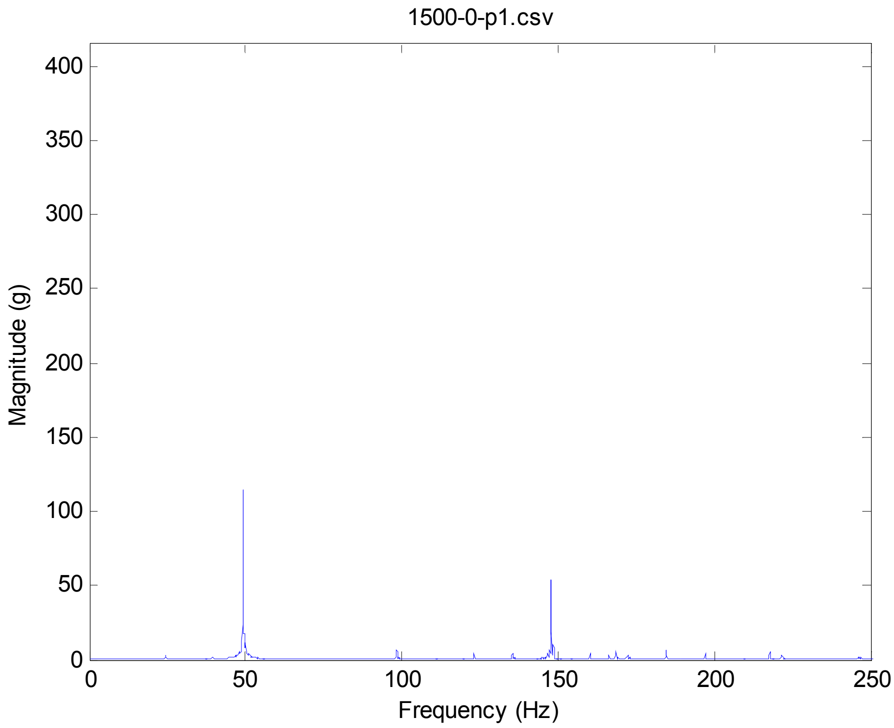


Figure K-6 Frequency spectrum of the output signal at engine 1500 r/min, 0 g of weight in the funnel, pump on

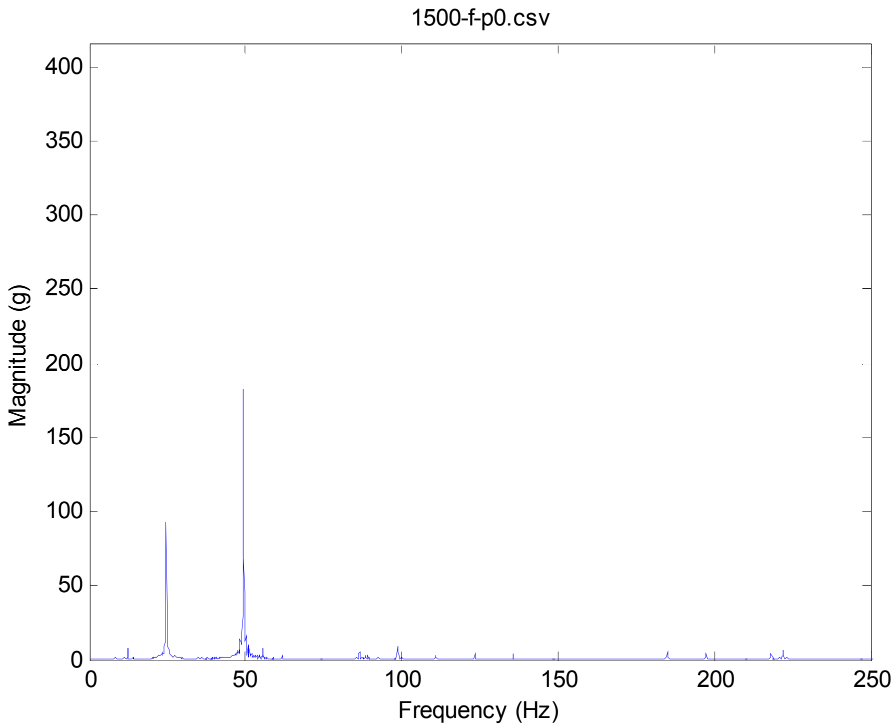


Figure K-7 Frequency spectrum of the output signal at engine 1500 r/min, 1000 g of weight in the funnel, pump off

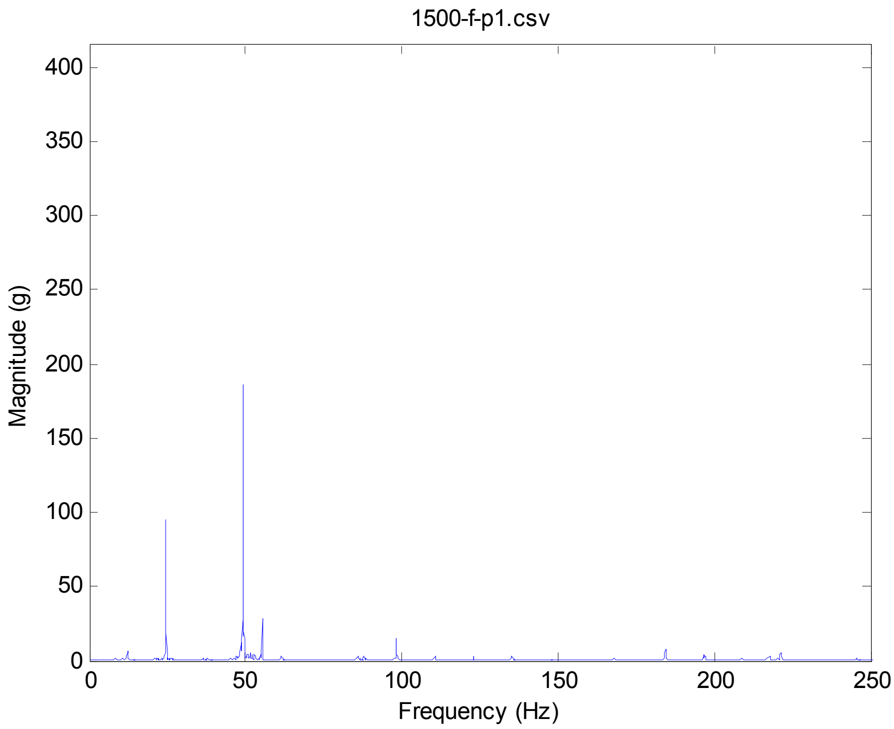


Figure K-8 Frequency spectrum of the output signal at engine 1500 r/min, 1000 g of weight in the funnel, pump on

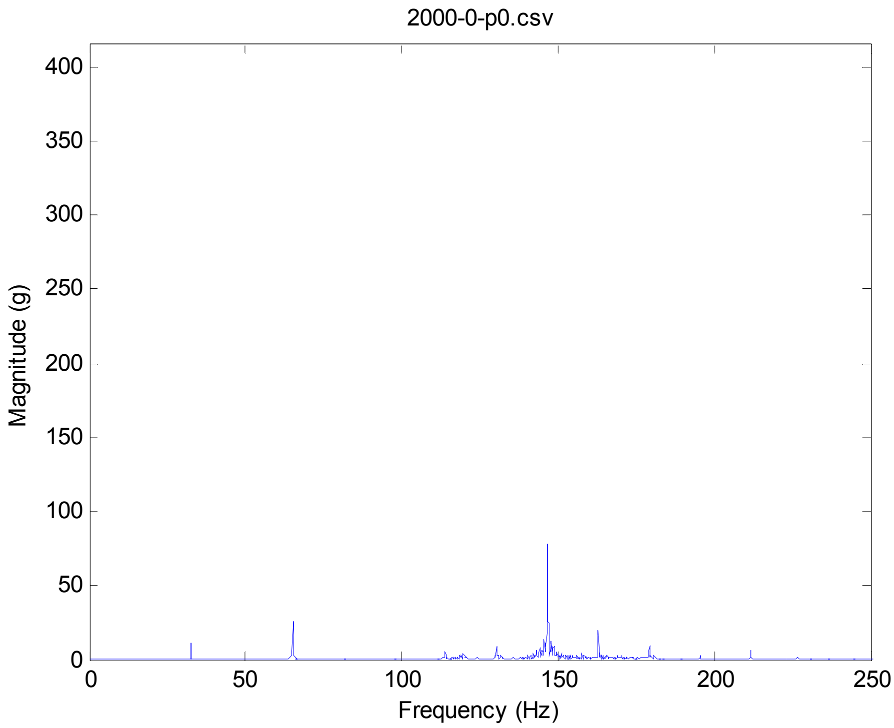


Figure K-9 Frequency spectrum of the output signal at engine 2000 r/min, 0 g of weight in the funnel, pump off

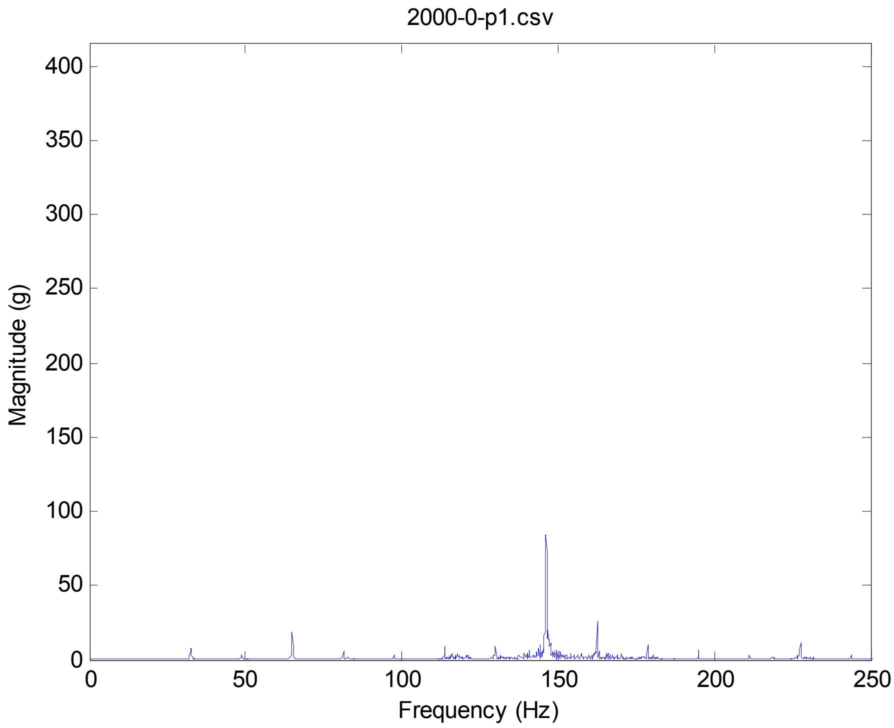


Figure K-10 Frequency spectrum of the output signal at engine 2000 r/min, 0 g of weight in the funnel, pump on

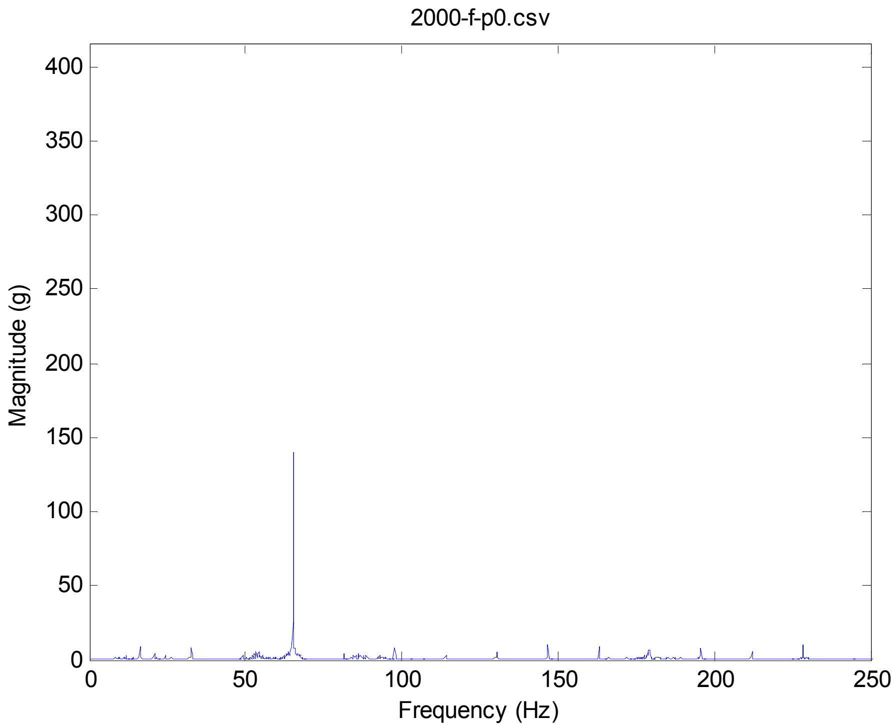


Figure K-11 Frequency spectrum of the output signal at engine 2000 r/min, 1000 g of weight in the funnel, pump off

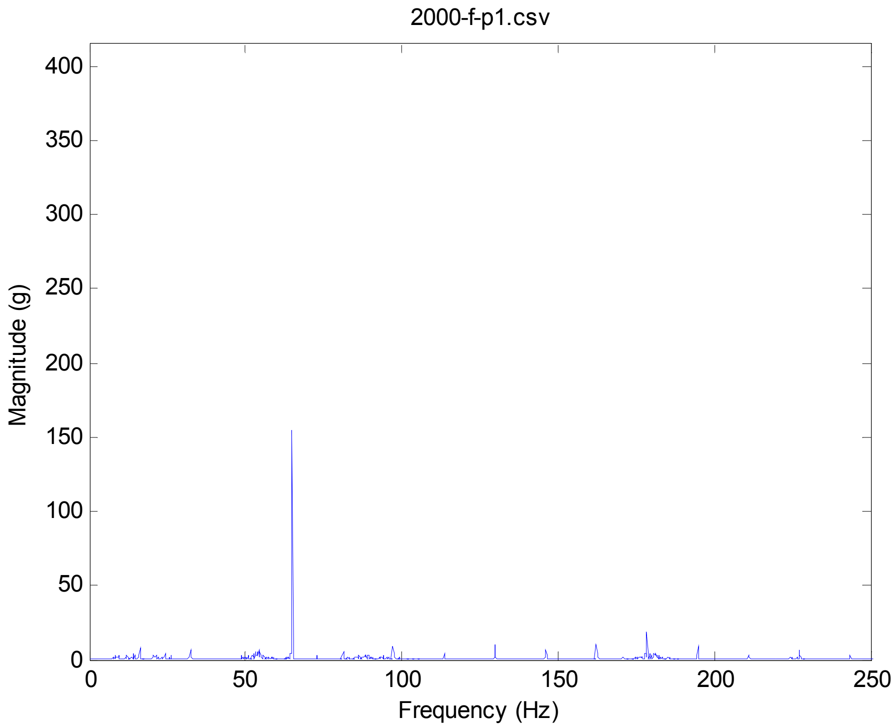


Figure K-12 Frequency spectrum of the output signal at engine 2000 r/min, 1000 g of weight in the funnel, pump on

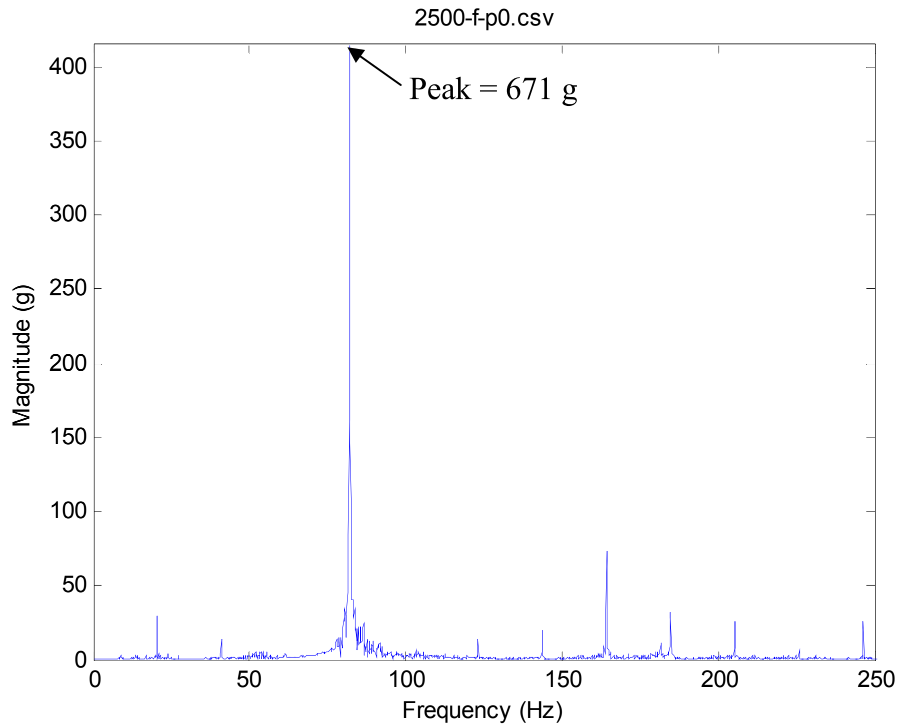


Figure K-13 Frequency spectrum of the output signal at engine 2500 r/min, 1000 g of weight in the funnel, pump off

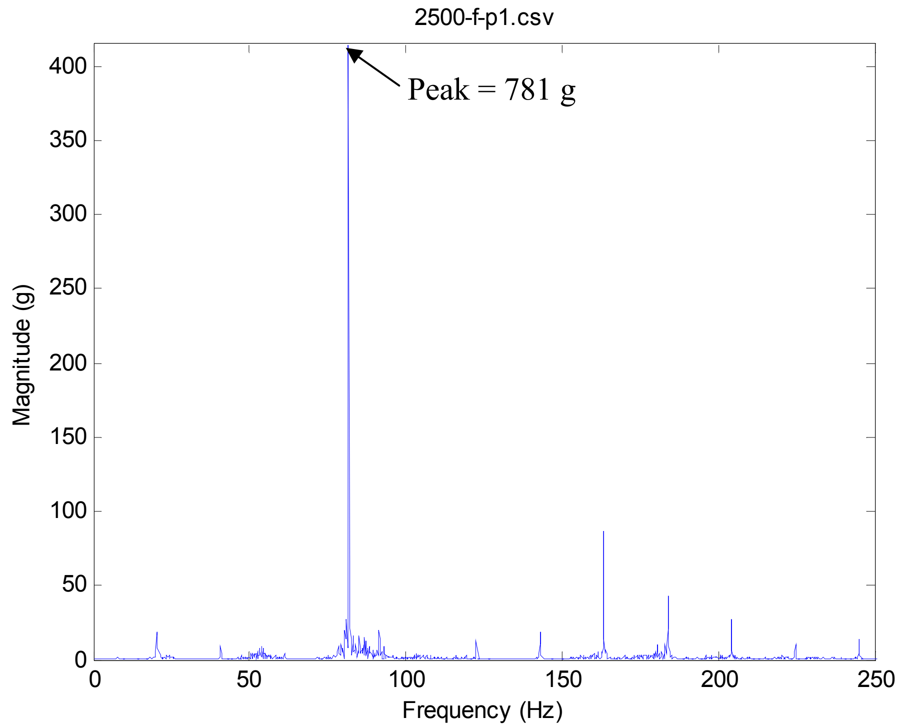


Figure K-14 Frequency spectrum of the output signal at engine 2500 r/min, 1000 g of weight in the funnel, pump on

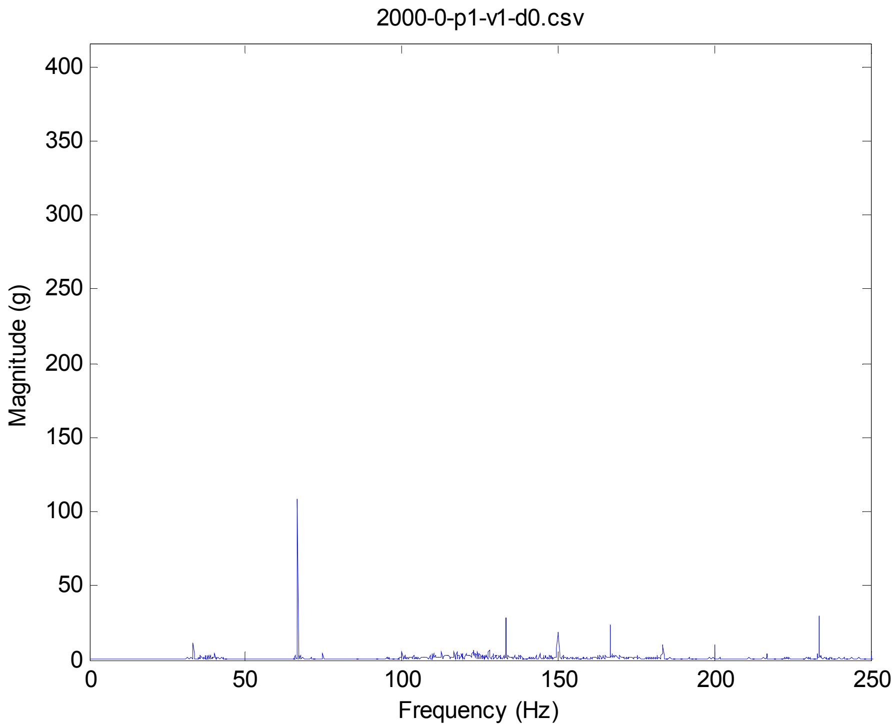


Figure K-15 Frequency spectrum of the output signal at engine 2000 r/min, 0 g of weight in the funnel, pump on, circulation valve open and outlet valve shut

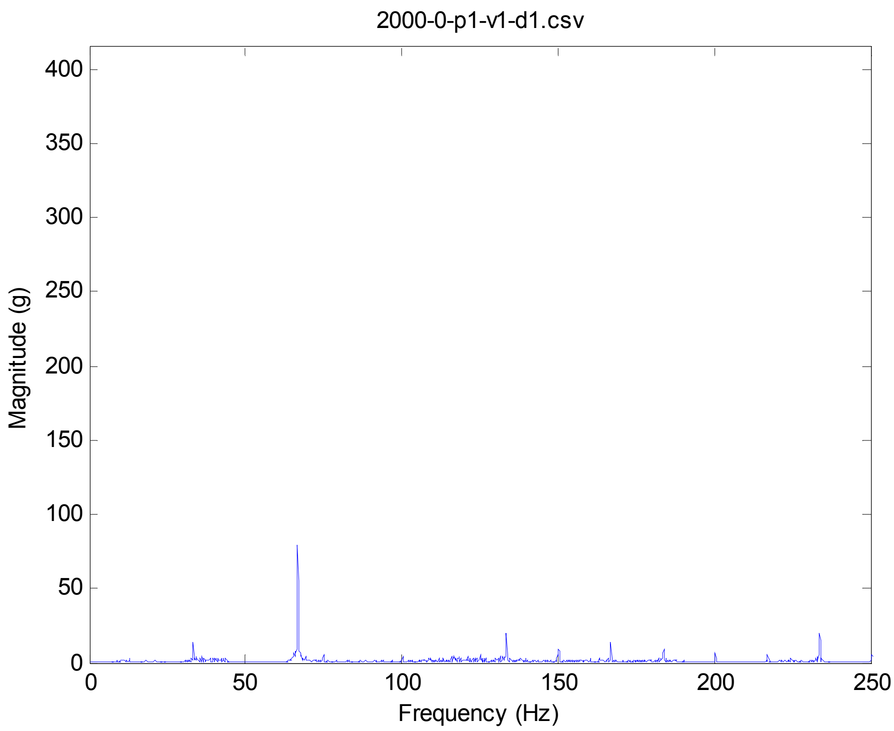


Figure K-16 Frequency spectrum of the output signal at engine 2000 r/min, 0 g of weight in the funnel, pump on, circulation and outlet valves open

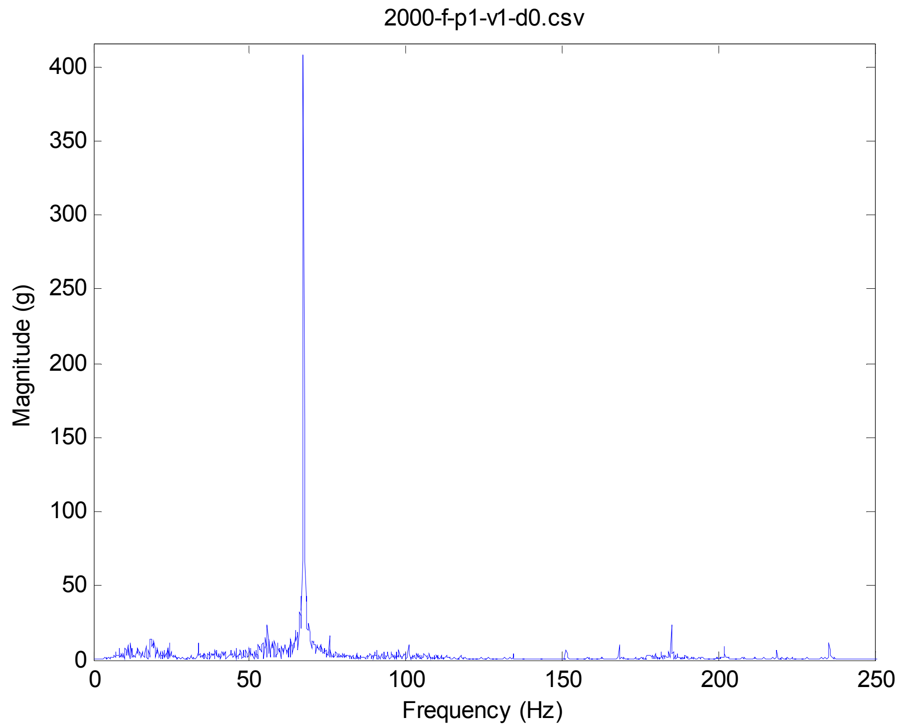


Figure K-17 Frequency spectrum of the output signal at engine 2000 r/min, 1000 g of weight in the funnel, pump on, circulation valve open and outlet valve shut

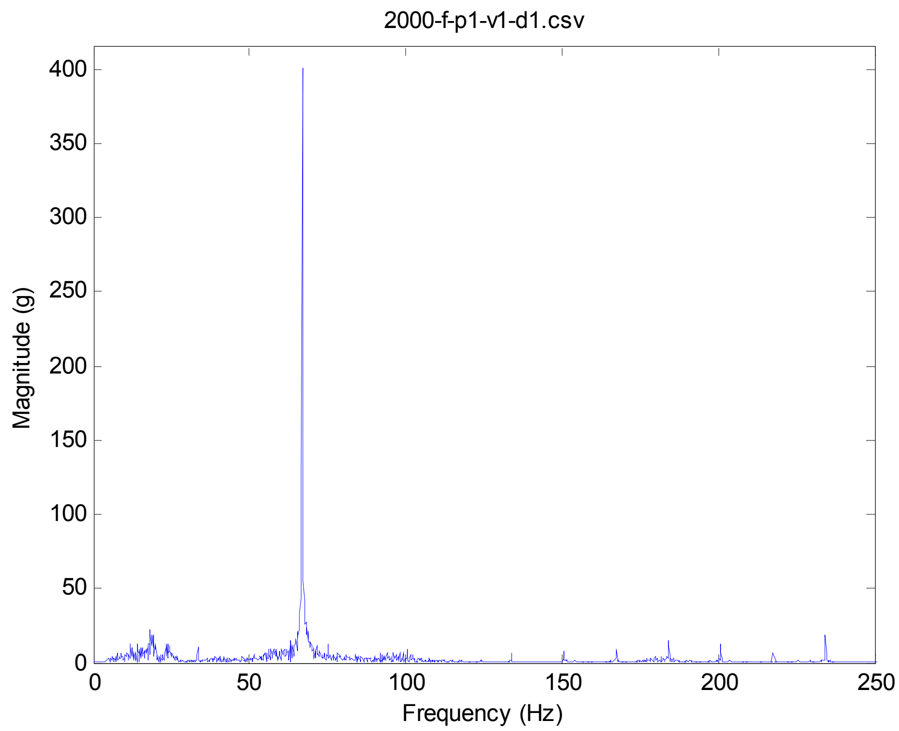


Figure K-18 Frequency spectrum of the output signal at engine 2000 r/min, 1000 g of weight in the funnel, pump on, circulation and outlet valves open

Appendix L. Natural frequency of the load cell

In order to determine the natural frequency of the load cell, the stiffness of the load cell must be known. An experiment to measure the deflection of the load cell was carried out (Figure L-1) where the deflection was measured with an indicator clock by applying force in the range of 0 to 28 N on the load cell.

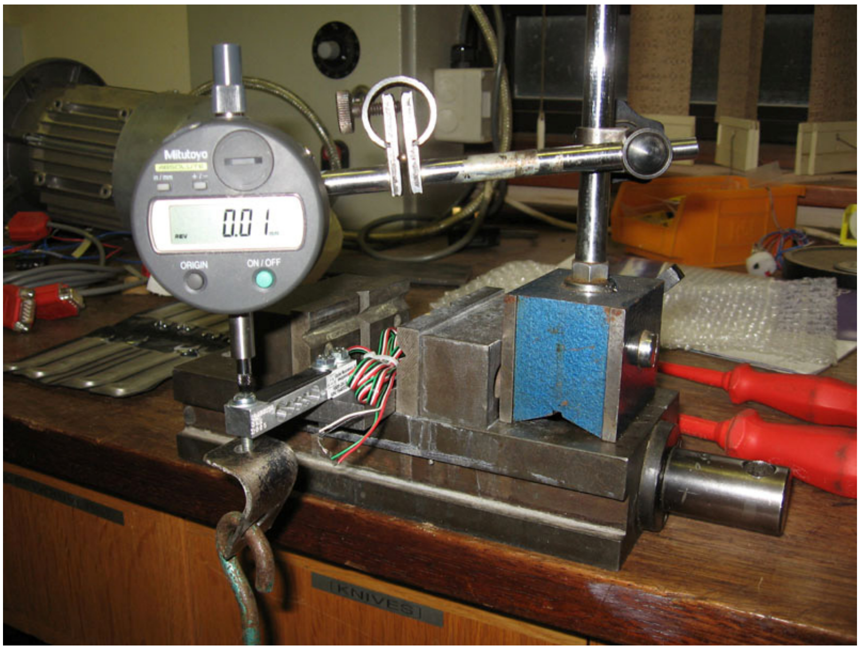


Figure L-1 Measuring the deflection of the load cell

The stiffness of the spring is defined as

$$k = -\frac{F_s}{x}$$

From the deflection curve in Figure L-2 the relation between the force and deflection is

$$x = 5.1 \cdot 10^{-6} F_s - 22.7 \cdot 10^{-6}$$

Hence, the stiffness of the load cell is k = 196,078 N/m

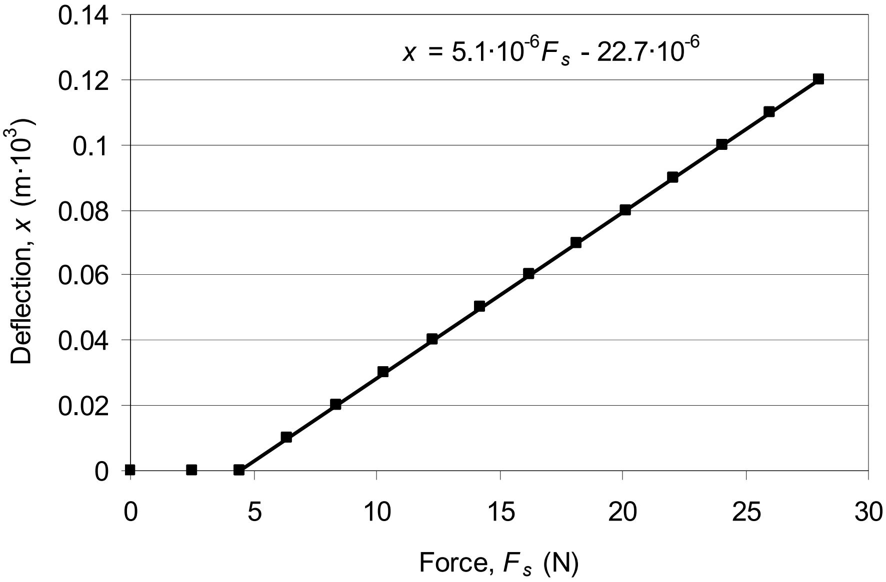


Figure L-2 Deflection of the load cell

Natural frequency is defined as

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

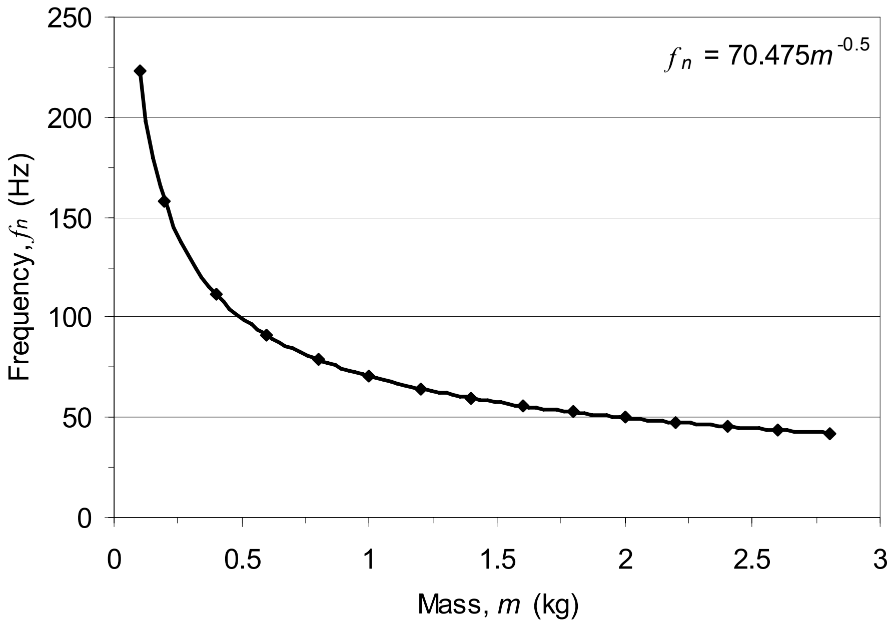


Figure L-3 Natural frequency of the load cell

Appendix M. Data of the operator performance experiment

Table M-1 Data of the operator performance experiment

Operator	Automatic							Manual							
	Task	Material	Container	Amount Prescribed	Amount Dispensed	Amount Recorded	Time, s Total	Material	Container	Amount Prescribed	Amount Dispensed	Amount Recorded	Time, s Loading	Time, s Writing	Time, s Total
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0 28/01/2008	1	Aqua	5 l	6.1	6.1132	6.11484	223	Aqua	5 l	6.1	6.0088	6.1	132	100	232
		Gluupy	5 l	0.3	0.3355	0.334601		Gluupy	5 l	0.3	0.3045	0.3			
		Sugar	500 g	200	194.1	192.9395		Sugar	500 g	200	179.3	200			
	2	Gluupy	5 l	0.4	0.4239	0.422879	250	Gluupy	5 l	0.4	0.3882	0.4	131	52	183
		Sugar	500 g	190	184.5	185.5959		Sugar	500 g	190	166.1	190			
		Aqua	5 l	6.2	6.1561	6.216377		Aqua	5 l	6.2	6.1435	6.2			
	3	Sugar	500 g	210	202.8	205.4464	209	Sugar	500 g	210	193.9	210	137	47	184
		Aqua	5 l	6.0	6.0499	6.056242		Aqua	5 l	6.0	5.9441	6.0			
		Gluupy	5 l	0.3	0.3048	0.33313		Gluupy	5 l	0.3	0.2978	0.3			
	4	Aqua	5 l	6.1	6.2267	6.165143	182	Aqua	5 l	6.1	5.9099	6.1	116	34	150
		Gluupy	5 l	0.3	0.3493	0.349617		Gluupy	5 l	0.3	0.2935	0.3			
		Sugar	500 g	200	212.6	211.9492		Sugar	500 g	200	173.9	200			
	5	Gluupy	5 l	0.4	0.417	0.418826	195	Gluupy	5 l	0.4	0.3784	0.4	136	32	168
		Sugar	500 g	190	186.2	185.4527		Sugar	500 g	190	142.9	190			
		Aqua	5 l	6.2	6.201	6.202522		Aqua	5 l	6.2	6.1364	6.2			
	6	Sugar	500 g	210	203.5	204.8355	172	Sugar	500 g	210	181.5	210	110	28	138
		Aqua	5 l	6.0	6.043	6.047494		Aqua	5 l	6.0	5.9017	6.0			
		Gluupy	5 l	0.3	0.3278	0.326606		Gluupy	5 l	0.3	0.299	0.3			
1 13/02/2008	1	Aqua	5 l	6.0	7.757	6.076929	235	Sugar	500 g	205	206.9	205	259	259	259
		Gluupy	5 l	0.55	0.568	0.557271		Aqua	5 l	6.1	5.9524	6.1			
		Sugar	500 g	190	191.981	193.6349		Gluupy	5 l	0.75	0.7402	0.75			
	2	Gluupy	5 l	0.65	0.642	0.636909	187	Gluupy	5 l	0.65	0.6487	0.65	186	24	210
		Sugar	500 g	210	204.831	211.0311		Sugar	500 g	210	205.9	210			
		Aqua	5 l	6.2	6.195	6.188674		Aqua	5 l	6.2	6.1558	6.2			
	3	Sugar	500 g	205	200.483	200.0578	192	Gluupy	5 l	0.5	0.4858	0.5	203	33	236
		Aqua	5 l	6.1	6.117	6.109575		Sugar	500 g	185	164.1	185			
		Gluupy	5 l	0.75	0.754	0.7527		Aqua	5 l	6.2	6.173	6.2			
	4	Gluupy	5 l	0.5	0.537	0.536664	186	Aqua	5 l	6.0	5.9359	6.0	163	36	199

Table M-1 *Continues*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Sugar	500 g	185	186.957	187.0422		Gluupy	5 l	0.55	0.5544	0.55			
		Aqua	5 l	6.2	6.187	6.181503		Sugar	500 g	190	183.2	190			
	5	Aqua	5 l	7.4	7.414	7.401094	215	Aqua	5 l	7.4	7.2771	7.4	173	27	200
		Gluupy	5 l	0.6	0.629	0.62762		Gluupy	5 l	0.6	0.5489	0.6			
		Sugar	500 g	195	195.942	193.9924		Sugar	500 g	195	179.1	195			
	6	Sugar	500 g	200	200.386	202.1941	180	Sugar	500 g	200	202.9	200	185	21	206
		Gluupy	5 l	0.7	0.672	0.673748		Gluupy	5 l	0.7	0.6853	0.7			
		Aqua	5 l	6	6.016	6.007006		Aqua	5 l	6.0	5.9778	6.0			
2 18/02/2008	1	Aqua	5 l	6.0	6.090	6.087052	253	Sugar	500 g	205	176.2	205	180	20	200
		Gluupy	5 l	0.55	0.544	0.542296		Aqua	5 l	6.1	6.0109	6.1			
		Sugar	500 g	190	191.014	191.5752		Gluupy	5 l	0.75	0.6803	0.75			
	2	Gluupy	5 l	0.65	0.646	0.641454	243	Gluupy	5 l	0.65	0.5927	0.65	164	17	181
		Sugar	500 g	210	210.338	209.6535		Sugar	500 g	210	176.3	210			
		Aqua	5 l	6.2	6.241	6.235623		Aqua	5 l	6.2	5.5661	6.2			
	3	Sugar	500 g	205	204.928	204.3793	198	Gluupy	5 l	0.5	0.4599	0.5	150	13	163
		Aqua	5 l	6.1	6.085	6.087634		Sugar	500 g	185	161.9	185			
		Gluupy	5 l	0.75	0.754	0.753302		Aqua	5 l	6.2	6.124	6.2			
	4	Gluupy	5 l	0.5	0.520	0.520219	220	Aqua	5 l	6.0	5.8991	6.0	163	11	174
		Sugar	500 g	185	184.734	184.7417		Gluupy	5 l	0.55	0.5003	0.55			
		Aqua	5 l	6.2	6.195	6.194118		Sugar	500 g	190	163.6	190			
	5	Aqua	5 l	7.4	7.389	7.381218	246	Aqua	5 l	7.4	7.266	7.4	174	13	187
		Gluupy	5 l	0.6	0.609	0.609427		Gluupy	5 l	0.6	0.5616	0.6			
		Sugar	500 g	195	214.783	216.3708		Sugar	500 g	195	157.4	195			
	6	Sugar	500 g	200	217.005	214.9322	196	Sugar	500 g	200	169.2	200	161	12	173
		Gluupy	5 l	0.7	0.723	0.723135		Gluupy	5 l	0.7	0.6659	0.7			
		Aqua	5 l	6	5.987	5.984995		Aqua	5 l	6.0	5.9365	6.0			
	1	Aqua	5 l	6.0	6.027	6.0243	222	Sugar	500 g	205	176.7	205	167	28	195
		Gluupy	5 l	0.55	0.545	0.5271		Aqua	5 l	6.1	6.059	6.1			
		Sugar	500 g	190	185.604	181.3		Gluupy	5 l	0.75	0.7571	0.75			
	2	Gluupy	5 l	0.65	0.618	0.6159	239	Gluupy	5 l	0.65	0.6261	0.65	165	20	185
		Sugar	500 g	210	206.763	204		Sugar	500 g	210	175.3	210			

Table M-1 *Continues*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
3 19/02/2008		Aqua	5 l	6.2	6.246	6.1588		Aqua	5 l	6.2	6.165	6.2			
	3	Sugar	500 g	205	202.126	201	210	Gluupy	5 l	0.5	0.4846	0.5	169	18	187
		Aqua	5 l	6.1	6.121	6.1168		Sugar	500 g	185	142.9	185			
		Gluupy	5 l	0.75	0.715	0.7173		Aqua	5 l	6.2	6.1597	6.2			
	4	Gluupy	5 l	0.5	0.477	0.4781	192	Aqua	5 l	6.0	5.982	6.0	157	17	174
		Sugar	500 g	185	184.058	181		Gluupy	5 l	0.55	0.542	0.55			
		Aqua	5 l	6.2	6.868	6.1524		Sugar	500 g	190	169.4	190			
	5	Aqua	5 l	7.4	7.426	7.4162	224	Aqua	5 l	7.4	7.7059	7.4	175	17	192
		Gluupy	5 l	0.6	0.576	0.5630		Gluupy	5 l	0.6	0.5947	0.6			
		Sugar	500 g	195	198.841	194		Sugar	500 g	195	175.8	195			
	6	Sugar	500 g	200	197.971	197	240	Sugar	500 g	200	178	200	153	20	173
		Gluupy	5 l	0.7	0.669	0.6640		Gluupy	5 l	0.7	0.6511	0.7			
		Aqua	5 l	6	6.217	5.9556		Aqua	5 l	6.0	5.9502	6.0			
4 20/02/2008	1	Aqua	5 l	6.0	5.990	5.988	245	Sugar	500 g	205	189.6	205	246	61	307
		Gluupy	5 l	0.55	0.561	0.558		Aqua	5 l	6.1	6.0776	6.1			
		Sugar	500 g	190	193.527	191.066		Gluupy	5 l	0.75	0.7264	0.75			
	2	Gluupy	5 l	0.65	0.649	0.649	249	Gluupy	5 l	0.65	0.6224	0.65	252	35	287
		Sugar	500 g	210	209.275	206.615		Sugar	500 g	210	198.2	210			
		Aqua	5 l	6.2	6.196	6.197		Aqua	5 l	6.2	6.1503	6.2			
	3	Sugar	500 g	205	205.894	205.403	250	Gluupy	5 l	0.5	0.4723	0.5	242	38	280
		Aqua	5 l	6.1	6.089	6.089		Sugar	500 g	185	162.8	185			
		Gluupy	5 l	0.75	0.737	0.738		Aqua	5 l	6.2	6.1402	6.2			
	4	Gluupy	5 l	0.5	0.497	0.497	254	Aqua	5 l	6.0	5.94	6.0	258	32	290
		Sugar	500 g	185	185.604	185.203		Gluupy	5 l	0.55	0.5105	0.55			
		Aqua	5 l	6.2	6.199	6.198		Sugar	500 g	190	165.6	190			
	5	Aqua	5 l	7.4	7.390	7.447	337	Aqua	5 l	7.4	7.2609	7.4	287	28	315
		Gluupy	5 l	0.6	0.604	0.606		Gluupy	5 l	0.6	0.5696	0.6			
		Sugar	500 g	195	198.261	196.598		Sugar	500 g	195	159.4	195			
	6	Sugar	500 g	200	201.836	198.888	236	Sugar	500 g	200	180.1	200	269	27	296
		Gluupy	5 l	0.7	0.701	0.702		Gluupy	5 l	0.7	0.6766	0.7			
		Aqua	5 l	6	5.996	5.998		Aqua	5 l	6.0	5.9446	6.0			

Table M-1 *Continues*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5 28/04/2008	1	Aqua	5 l	6.0	5.9822	6.017	250	Sugar	500 g	205	164.2	205	148	28	176
		Gluupy	5 l	0.55	0.5824	0.582		Aqua	5 l	6.1	6.0433	6.1			
		Sugar	500 g	190	197.5000	195.829		Gluupy	5 l	0.75	0.6958	0.75			
	2	Gluupy	5 l	0.65	0.6380	0.634	236	Gluupy	5 l	0.65	0.5886	0.65	145	30	175
		Sugar	500 g	210	206.4000	209.454		Sugar	500 g	210	199.2	210			
		Aqua	5 l	6.2	6.1676	6.208		Aqua	5 l	6.2	6.124	6.2			
	3	Sugar	500 g	205	199.6000	195.092	233	Gluupy	5 l	0.5	0.4593	0.5	145	21	166
		Aqua	5 l	6.1	6.0810	6.073		Sugar	500 g	185	85.6	185			
		Gluupy	5 l	0.75	0.7494	0.747		Aqua	5 l	6.2	6.1236	6.2			
	4	Gluupy	5 l	0.5	0.5735	0.570	222	Aqua	5 l	6.0	5.9179	6.0	142	23	165
		Sugar	500 g	185	177.1000	176.157		Gluupy	5 l	0.55	0.5047	0.55			
		Aqua	5 l	6.2	6.2238	6.220		Sugar	500 g	190	180.3	190			
	5	Aqua	5 l	7.4	7.4324	7.418	240	Aqua	5 l	7.4	7.2315	7.4	141	14	155
		Gluupy	5 l	0.6	0.6443	0.647		Gluupy	5 l	0.6	0.5339	0.6			
		Sugar	500 g	195	191.1000	189.427		Sugar	500 g	195	159.5	195			
	6	Sugar	500 g	200	183.0000	206.218	192	Sugar	500 g	200	161.7	200	130	16	146
		Gluupy	5 l	0.7	0.6885	0.691		Gluupy	5 l	0.7	0.6342	0.7			
		Aqua	5 l	6	5.9912	5.990		Aqua	5 l	6.0	5.9358	6.0			
6 29/04/2008	1	Aqua	5 l	6.0	6.2469	6.245376	404	Sugar	500 g	205	154.6	205	361	77	438
		Gluupy	5 l	0.55	0.5679	0.540854		Aqua	5 l	6.1	6.0188	6.1			
		Sugar	500 g	190	189.8000	189.3615		Gluupy	5 l	0.75	0.7187	0.75			
	2	Gluupy	5 l	0.65	0.6452	0.637616	377	Gluupy	5 l	0.65	0.6059	0.65	285	41	326
		Sugar	500 g	210	212.5000	210.5649		Sugar	500 g	210	210	210			
		Aqua	5 l	6.2	6.2044	6.207742		Aqua	5 l	6.2	6.1366	6.2			
	3	Sugar	500 g	205	207.1000	204.6487	326	Gluupy	5 l	0.5	0.4745	0.5	223	39	262
		Aqua	5 l	6.1	6.0898	6.087611		Sugar	500 g	185	190.5	185			
		Gluupy	5 l	0.75	0.7409	0.740229		Aqua	5 l	6.2	6.1327	6.2			
	4	Gluupy	5 l	0.5	0.4984	0.493706	286	Aqua	5 l	6.0	5.9104	6.0	227	35	262
		Sugar	500 g	185	190.0000	188.8698		Gluupy	5 l	0.55	0.4864	0.55			
		Aqua	5 l	6.2	6.1896	6.189238		Sugar	500 g	190	180.1	190			
	5	Aqua	5 l	7.4	7.3999	7.398233	345	Aqua	5 l	7.4	6.3142	7.4	211	44	255

Table M-1 *Continues*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Gluupy	5 l	0.6	0.5961	0.590867		Gluupy	5 l	0.6	0.5574	0.6			
		Sugar	500 g	195	196.2000	193.8066		Sugar	500 g	195	179.6	195			
	6	Sugar	500 g	200	203.6000	199.9904	260	Sugar	500 g	200	182.3	200	194	27	221
		Gluupy	5 l	0.7	0.6926	0.691942		Gluupy	5 l	0.7	0.6823	0.7			
		Aqua	5 l	6	6.0236	6.006193		Aqua	5 l	6.0	5.9375	6.0			
7 30/04/2008	1	Aqua	5 l	6.0	5.9975	6.000231	389	Sugar	500 g	205	191.5	205	214	48	262
		Gluupy	5 l	0.55	0.5468	0.547305		Aqua	5 l	6.1	5	6.1			
		Sugar	500 g	190	181.7000	191.0456		Gluupy	5 l	0.75	1.8024	0.75			
	2	Gluupy	5 l	0.65	0.6302	0.649898	298	Gluupy	5 l	0.65	0.6122	0.65	227	26	253
		Sugar	500 g	210	205.9000	211.0895		Sugar	500 g	210	191.9	210			
		Aqua	5 l	6.2	6.1894	6.19639		Aqua	5 l	6.2	6.1303	6.2			
	3	Sugar	500 g	205	200.6000	205.2326	251	Gluupy	5 l	0.5	0.4557	0.5	179	29	208
		Aqua	5 l	6.1	6.0925	6.103872		Sugar	500 g	185	169	185			
		Gluupy	5 l	0.75	0.7298	0.743158		Aqua	5 l	6.2	6.7515	6.2			
	4	Gluupy	5 l	0.5	0.4975	0.503502	217	Aqua	5 l	6.0	5.9512	6.0	185	24	209
		Sugar	500 g	185	174.5000	184.8199		Gluupy	5 l	0.55	0.4971	0.55			
		Aqua	5 l	6.2	6.1644	6.200878		Sugar	500 g	190	170.2	190			
	5	Aqua	5 l	7.4	7.4070	7.40427	236	Aqua	5 l	7.4	7.278	7.4	201	28	229
		Gluupy	5 l	0.6	0.6010	0.601771		Gluupy	5 l	0.6	0.5479	0.6			
		Sugar	500 g	195	193.2000	192.9762		Sugar	500 g	195	174.5	195			
	6	Sugar	500 g	200	200.5000	200.3347	224	Sugar	500 g	200	188.3	200	179	26	205
		Gluupy	5 l	0.7	0.6923	0.691258		Gluupy	5 l	0.7	0.6549	0.7			
		Aqua	5 l	6	5.9902	5.992205		Aqua	5 l	6.0	5.9744	6.0			
8 01/05/2008	1	Aqua	5 l	6.0	5.9795	5.977421	275	Sugar	500 g	205	179.2	205	260	25	285
		Gluupy	5 l	0.55	0.5464	0.543741		Aqua	5 l	6.1	5.9765	6.1			
		Sugar	500 g	190	194.3000	189.8154		Gluupy	5 l	0.75	0.7391	0.75			
	2	Gluupy	5 l	0.65	0.6390	0.636609	283	Gluupy	5 l	0.65	0.5891	0.65	245	23	268
		Sugar	500 g	210	208.1000	209.415		Sugar	500 g	210	178	210			
		Aqua	5 l	6.2	6.1865	6.184854		Aqua	5 l	6.2	6.1688	6.2			
	3	Sugar	500 g	205	207.2000	202.2588	267	Gluupy	5 l	0.5	0.4915	0.5	250	18	268
		Aqua	5 l	6.1	6.0330	6.076445		Sugar	500 g	185	172.3	185			

Table M-1 *Continues*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Gluupy	5 l	0.75	0.7345	0.732321		Aqua	5 l	6.2	6.163	6.2			
	4	Gluupy	5 l	0.5	0.4920	0.487566	266	Aqua	5 l	6.0	5.9517	6.0	246	21	267
		Sugar	500 g	185	188.4	185.3		Gluupy	5 l	0.55	0.5406	0.55			
		Aqua	5 l	6.2	6.1896	6.187324		Sugar	500 g	190	166.6	190			
	5	Aqua	5 l	7.4	7.3738	7.396503	511	Aqua	5 l	7.4	7.3275	7.4	290	18	308
		Gluupy	5 l	0.6	0.5883	0.586394		Gluupy	5 l	0.6	0.5915	0.6			
		Sugar	500 g	195	197.0	192.1		Sugar	500 g	195	183.8	195			
	6	Sugar	500 g	200	202.4	197.6	241	Sugar	500 g	200	181.9	200	258	16	274
		Gluupy	5 l	0.7	0.6869	0.681485		Gluupy	5 l	0.7	0.6742	0.7			
		Aqua	5 l	6	6.0024	6.000373		Aqua	5 l	6.0	5.958	6.0			
9 05/06/2008	1	Aqua	5 l	6.0	5.9859	5.990827	150	Sugar	500 g	205	190.2	205	118	39	157
		Gluupy	5 l	0.55	0.5489	0.556327		Aqua	5 l	6.1	5.9603	6.1			
		Sugar	500 g	190	194.3	191.9		Gluupy	5 l	0.75	0.695	0.75			
	2	Gluupy	5 l	0.65	0.6487	0.645993	129	Gluupy	5 l	0.65	0.6769	0.65	111	34	145
		Sugar	500 g	210	210.4	210.8		Sugar	500 g	210	191.9	210			
		Aqua	5 l	6.2	6.2252	6.23094		Aqua	5 l	6.2	6.192	6.2			
	3	Sugar	500 g	205	210.7	209.0	154	Gluupy	5 l	0.5	0.4834	0.5	99	24	123
		Aqua	5 l	6.1	6.0887	6.090956		Sugar	500 g	185	178.2	185			
		Gluupy	5 l	0.75	0.7440	0.748349		Aqua	5 l	6.2	6.1509	6.2			
	4	Gluupy	5 l	0.5	0.5445	0.499638	138	Aqua	5 l	6.0	5.9186	6.0	93	15	108
		Sugar	500 g	185	193.1	191.3		Gluupy	5 l	0.55	0.5053	0.55			
		Aqua	5 l	6.2	6.2099	6.211722		Sugar	500 g	190	85	190			
	5	Aqua	5 l	7.4	7.4319	7.440509	161	Aqua	5 l	7.4	7.2007	7.4	99	18	117
		Gluupy	5 l	0.6	0.6151	0.608612		Gluupy	5 l	0.6	0.53	0.6			
		Sugar	500 g	195	198.4	196.5		Sugar	500 g	195	163.8	195			
	6	Sugar	500 g	200	209.5	210.4	137	Sugar	500 g	200	188.5	200	102	16	118
		Gluupy	5 l	0.7	0.7057	0.70799		Gluupy	5 l	0.7	0.6571	0.7			
		Aqua	5 l	6	5.9951	5.99729		Aqua	5 l	6.0	5.9606	6.0			

Table M-2 Total time of using the weighing system ($t_2 - t_1$)(seconds)

Operator	Task	Aqua	Gluupy	Sugar
1	**2**	**3**	**4**	**5**
1	1	13.3	29.3	8.9
	2	13.2	18.1	9.1
	3	13.0	27.4	11.6
	4	14.2	15.3	7.4
	5	10.7	19.4	7.0
	6	14.4	29.9	13.3
2	1	15.4	12.5	12.2
	2	8.9	14.8	19.4
	3	7.9	15.4	10.7
	4	7.4	20.3	9.3
	5	10.6	11.2	12.4
	5	9.5		
	6	10.4	10.0	17.7
3	1	7.5	7.7	2.5
	2	8.4	8.3	3.4
	3	11.8	13.3	5.2
	4	6.6	14.0	4.1
	5	8.7	9.9	3.2
	5	6.2		
	6	12.4	15.8	3.4
4	1	9.4	8.4	8.3
	2	10.9	7.8	9.3
	3	9.9	11.3	9.4
	4	12.5	23.6	4.4
	5	7.9	11.1	23.3
	5	18.6		
	6	6.1	6.5	8.0
5	1	7.8	10.7	9.5
	2	10.0	11.7	7.2
	3	10.5	10.1	7.9
	4	8.7	14.3	9.8
	5	8.0	10.2	7.7
	5	5.8		
	6	12.9	10.2	12.6
6	1	9.7	15.8	12.7
	2	11.6	10.8	13.6
	3	8.4	12.4	18.0
	4	9.1	13.5	15.2
	5	12.4	13.5	10.0
	5	15.3		
	6	11.9	16.9	8.9

Table M-2 *Continues*

1	**2**	**3**	**4**	**5**
7	1	8.1	3.5	4.8
	2	2.6	2.1	2.9
	3	4.1	2.7	4.9
	4	2.6	3.8	3.4
	5	8.1	3.3	4.2
	5	5.1		
	6	4.7	4.2	4.4
8	1	4.2	6.7	1.8
	2	5.9	9.1	7.6
	3	10.9	6.4	5.5
	4	8.6	12.0	6.7
	5	9.3	9.8	8.6
	5	12.7		
	6	9.3	18.3	4.6
9	1	7.9	11.0	7.6
	2	5.7	5.2	8.8
	3	6.9	7.2	10.0
	4	4.7	10.6	8.2
	5	12.8	7.1	9.4
	5	13.7		
	5	13.5		
	6	7.0	6.0	11.1
10	1	13.5	18.4	7.8
	2	13.6	16.6	10.2
	3	18.2	13.4	13.4
	4	12.4	16.9	10.3
	5	17.9	28.9	11.7
	5	18.6		
	6	18.7	15.8	10.1

Table M-3 Rate of weighing ($\%\cdot s^{-1}$), slope between 0.1 and 0.9 of maximum

Operator	Task	Aqua	Gluupy	Sugar
1	**2**	**3**	**4**	**5**
1	1	24.0	17.5	25.6
	2	85.3	21.3	24.5
	3	29.0	22.0	26.5
	4	23.1	18.7	25.3
	5	20.7	18.6	29.3
	6	19.1	15.2	20.7
2	1	26.6	27.7	20.6
	2	24.8	20.7	18.4
	3	27.9	18.8	23.8
	4	23.2	19.5	28.7
	5	23.6	21.7	19.7
	5	24.3		
	6	19.8	24.3	19.9
3	1	34.9	31.3	57.5
	2	25.4	31.1	46.5
	3	22.7	21.3	36.3
	4	33.7	21.6	38.4
	5	25.3	19.4	38.8
	5	34.2		
	6	28.1	17.5	36.2
4	1	27.8	28.4	36.4
	2	32.6	34.8	37.4
	3	27.4	32.8	31.7
	4	26.3	17.9	38.3
	5	24.2	23.3	16.0
	5	22.1		
	6	50.2	41.6	30.2
5	1	39.4	34.6	31.5
	2	37.8	32.9	41.1
	3	39.9	39.0	42.1
	4	38.7	32.3	47.0
	5	55.3	32.7	40.2
	5	37.5		
	6	34.7	36.0	30.2
6	1	35.2	21.0	24.0
	2	33.0	25.1	23.7
	3	35.2	25.6	20.1
	4	26.9	22.4	25.7
	5	19.5	20.0	22.0
	5	18.2		
	6	20.6	22.0	22.4

Table M-3 *Continues*

1	2	3	4	5
7	1	144.3	50.9	49.9
	2	60.5	67.6	57.7
	3	56.0	59.2	52.8
	4	59.5	47.0	49.6
	5	43.6	51.4	55.1
	5	36.2		
	6	45.8	44.9	46.0
8	1	56.7	40.3	126.2
	2	51.4	34.5	68.2
	3	30.0	26.4	74.1
	4	28.5	16.1	45.9
	5	19.5	24.0	37.9
	5	20.5		
	6	31.5	35.9	43.2
9	1	35.3	33.2	34.6
	2	51.0	36.3	41.8
	3	38.7	32.5	35.4
	4	48.2	27.1	43.3
	5	25.2	30.5	36.1
	5	17.2		
	5	29.3		
	6	35.2	36.3	36.6
10	1	20.1	16.3	29.6
	2	19.2	16.7	24.3
	3	21.2	25.8	22.6
	4	24.6	20.5	18.4
	5	17.8	14.6	21.1
	5	13.9		
	6	19.4	23.4	19.4

Appendix N. Statistical analysis report of the operator performance experiment

The data were analysed with GenStat v10.1.

N.1. Accuracy of dispensing and recording

Analysis of variance

Variate: Data

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Operator stratum	8		403.04	50.38	0.51	
Operator.*Units* stratum						
Material	2		671.85	335.92	3.42	0.034
Method	2		6315.93	3157.96	32.11	<.001
Task	5		105.47	21.09	0.21	0.956
Material.Method	4		1596.82	399.20	4.06	0.003
Material.Task	10		1553.03	155.30	1.58	0.110
Method.Task	10		463.14	46.31	0.47	0.909
Material.Method.Task	20		2927.36	146.37	1.49	0.081
Residual	421	(3)	41407.75	98.36		
Total	482	(3)	55380.40			

Tables of means

Variate: Data

Grand mean 97.71

Material	Aqua	Gluupy	Sugar
	97.79	99.11	96.23

Method	AD	AR	MD
	100.36	100.16	92.61

Task	1	2	3	4	5	6
	98.16	97.01	97.39	98.38	97.50	97.81

Material	Method	AD	AR	MD
Aqua		100.51	100.51	92.36
Gluupy		100.24	99.78	97.30
Sugar		100.33	100.19	88.18

Material	Task	1	2	3	4	5	6
Aqua		100.63	97.06	93.37	99.99	97.58	98.14

Gluupy		98.36	97.24	103.15	99.93	98.39	97.56
Sugar		95.50	96.72	95.66	95.22	96.54	97.73

Method	Task	1	2	3	4	5	6
AD		101.92	99.36	99.10	100.83	101.04	99.91
AR		101.65	99.31	99.07	100.43	100.62	99.87
MD		90.93	92.36	94.01	93.88	90.85	93.65

Material	Method	Task	1	2	3	4	5
Aqua	AD		103.94	100.48	98.97	99.45	100.30
	AR		104.52	100.07	99.34	99.40	100.48
	MD		93.41	90.64	81.81	101.10	91.95
Gluupy	AD		101.23	98.40	98.65	103.06	101.17
	AR		100.10	98.23	98.86	101.91	100.76
	MD		93.76	95.09	111.93	94.82	93.25
Sugar	AD		100.58	99.19	99.66	99.98	101.65
	AR		100.32	99.62	99.00	99.97	100.64
	MD		85.61	91.36	88.30	85.72	87.34

Material	Method	Task	6
Aqua	AD		99.91
	AR		99.24
	MD		95.28
Gluupy	AD		98.93
	AR		98.82
	MD		94.95
Sugar	AD		100.91
	AR		101.55
	MD		90.72

Standard errors of means

Table	Material	Method	Task	Material Method
rep.	162	162	81	54
d.f.	421	421	421	421
e.s.e.	0.779	0.779	1.102	1.350
Table	Material Task	Method Task	Material Method Task	
rep.	27	27	9	
d.f.	421	421	421	
e.s.e.	1.909	1.909	3.306	

(Not adjusted for missing values)

Standard errors of differences of means

Table	Material	Method	Task	Material Method
rep.	162	162	81	54
d.f.	421	421	421	421
s.e.d.	1.102	1.102	1.558	1.909
Table	Material Task	Method Task	Material Method	

			Task
rep.	27	27	9
d.f.	421	421	421
s.e.d.	2.699	2.699	4.675

(Not adjusted for missing values)

Least significant differences of means (5% level)

Table	Material	Method	Task	Material Method
rep.	162	162	81	54
d.f.	421	421	421	421
l.s.d.	2.166	2.166	3.063	3.752
Table	Material Task	Method Task	Material Method Task	
rep.	27	27	9	
d.f.	421	421	421	
l.s.d.	5.306	5.306	9.190	

(Not adjusted for missing values)

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Operator	8	0.966	1.0
Operator.*Units*	421	9.917	10.1

N.2. Speed of operation Auto vs Manual total

N.2.1. Tasks 1–6

Analysis of variance

Variate: Data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Operator stratum	8	305336.	38167.	27.66	
Operator.*Units* stratum					
Method	1	16305.	16305.	11.82	<.001
Task	5	41309.	8262.	5.99	<.001
Method.Task	5	7994.	1599.	1.16	0.336
Residual	88	121434.	1380.		
Total	107	492378.			

Tables of means

Variate: Data

Grand mean 231.2

Method	Auto	Manual Total
	243.5	218.9

Task	1	2	3	4	5	6
	261.2	237.3	220.8	212.7	248.5	206.6

Method	Task	1	2	3	4	5	6
Auto		269.2	249.0	231.2	220.1	279.4	211.8
Manual Total		253.2	225.6	210.3	205.3	217.6	201.3

Standard errors of means

Table	Method	Task	Method Task
rep.	54	18	9
d.f.	88	88	88
e.s.e.	5.06	8.76	12.38

Standard errors of differences of means

Table	Method	Task	Method Task
rep.	54	18	9
d.f.	88	88	88
s.e.d.	7.15	12.38	17.51

Least significant differences of means (5% level)

Table	Method	Task	Method Task
rep.	54	18	9
d.f.	88	88	88
l.s.d.	14.21	24.61	34.80

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Operator	8	56.40	24.4
Operator.*Units*	88	37.15	16.1

N.2.2. Tasks 1–4 and 6

Analysis of variance

Variate: Data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Operator stratum	8	230945.	28868.	28.22	
Operator.*Units* stratum					
Method	1	6588.	6588.	6.44	0.013
Task	4	34827.	8707.	8.51	<.001
Method.Task	4	475.	119.	0.12	0.976
Residual	72	73650.	1023.		
Total	89	346484.			

Tables of means

Variate: Data

Grand mean 227.7

Method	Auto	Manual Total
	236.3	219.2

Task	1	2	3	4	6
	261.2	237.3	220.8	212.7	206.6

Method	Task	1	2	3	4	6
Auto		269.2	249.0	231.2	220.1	211.8
Manual Total		253.2	225.6	210.3	205.3	201.3

Standard errors of means

Table	Method	Task	Method Task
rep.	45	18	9
d.f.	72	72	72
e.s.e.	4.77	7.54	10.66

Standard errors of differences of means

Table	Method	Task	Method Task
rep.	45	18	9
d.f.	72	72	72
s.e.d.	6.74	10.66	15.08

Least significant differences of means (5% level)

Table	Method	Task	Method Task
rep.	45	18	9
d.f.	72	72	72
l.s.d.	13.44	21.25	30.06

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Operator	8	53.73	23.6
Operator.*Units*	72	31.98	14.0

N.3. Speed of operation Auto vs Manual loading

N.3.1. Tasks 1–6

Analysis of variance

Variate: Data

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Operator stratum	8		280482.	35060.	27.44	
Operator.*Units* stratum						
Method	1		73396.	73396.	57.44	<.001
Task	5		30260.	6052.	4.74	<.001
Method.Task	5		8226.	1645.	1.29	0.277
Residual	87	(1)	111164.	1278.		
Total	106	(1)	502231.			

Tables of means

Variate: Data

Grand mean 217.4

Method	Auto	Manual Load
	243.5	191.3

Task	1	2	3	4	5	6
	238.8	223.4	207.8	200.8	237.0	196.5

Method	Task	1	2	3	4	5	6

Auto	269.2	249.0	231.2	220.1	279.4	211.8
Manual Load	208.4	197.8	184.4	181.6	194.6	181.2

Standard errors of means

Table	Method	Task	Method Task
rep.	54	18	9
d.f.	87	87	87
e.s.e.	4.86	8.43	11.92

(Not adjusted for missing values)

Standard errors of differences of means

Table	Method	Task	Method Task
rep.	54	18	9
d.f.	87	87	87
s.e.d.	6.88	11.92	16.85

(Not adjusted for missing values)

Least significant differences of means (5% level)

Table	Method	Task	Method Task
rep.	54	18	9
d.f.	87	87	87
l.s.d.	13.67	23.68	33.49

(Not adjusted for missing values)

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Operator	8	54.05	24.9
Operator.*Units*	87	35.75	16.4

Missing values

Variate: Data

Unit	estimate
2	181.5

Max. no. iterations 2

N.3.2. Tasks 1–4 and 6

Analysis of variance

Variate: Data

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Operator stratum	8		209492.7	26186.6	29.20	
Operator.*Units* stratum						
Method	1		46576.8	46576.8	51.94	<.001
Task	4		22162.5	5540.6	6.18	<.001
Method.Task	4		2373.0	593.3	0.66	0.621
Residual	71	(1)	63668.5	896.7		
Total	88	(1)	343484.5			

Tables of means

Variate: Data

Grand mean 213.5

Method	Auto	Manual Load
	236.3	190.8

Task	1	2	3	4	6
	239.0	223.4	207.8	200.8	196.5

Method	Task	1	2	3	4	6
Auto		269.2	249.0	231.2	220.1	211.8
Manual Load		208.8	197.8	184.4	181.6	181.2

Standard errors of means

Table	Method	Task	Method Task
rep.	45	18	9
d.f.	71	71	71
e.s.e.	4.46	7.06	9.98

(Not adjusted for missing values)

Standard errors of differences of means

Table	Method	Task	Method Task
rep.	45	18	9
d.f.	71	71	71
s.e.d.	6.31	9.98	14.12

(Not adjusted for missing values)

Least significant differences of means (5% level)

Table	Method	Task	Method Task
rep.	45	18	9
d.f.	71	71	71
l.s.d.	12.59	19.90	28.15

(Not adjusted for missing values)

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Operator	8	51.17	24.0
Operator.*Units*	71	29.95	14.0

N.4. Duration of weighing with AACTS

N.4.1. Block by operators

Analysis of variance

Variate: Data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Operator stratum	8	19480.5	2435.1	16.82	
Operator.*Units* stratum					
Material	2	1604.2	802.1	5.54	0.005
Task	5	2753.5	550.7	3.81	0.003
Material.Task	10	986.8	98.7	0.68	0.740
Residual	136	19683.3	144.7		
Total	161	44508.3			

Tables of means

Variate: Data

Grand mean 34.04

Material	Aqua	Gluupy	Sugar
	35.03	29.79	37.31

Task	1	2	3	4	5	6
	41.28	36.84	34.05	32.20	28.37	31.53

Material	Task	1	2	3	4	5	6
Aqua		46.69	37.30	33.22	34.41	26.86	31.71
Gluupy		31.54	33.29	31.28	24.94	26.40	31.31
Sugar		45.60	39.92	37.65	37.25	31.86	31.57

Standard errors of means

Table	Material	Task	Material Task
rep.	54	27	9
d.f.	136	136	136
e.s.e.	1.637	2.315	4.010

Standard errors of differences of means

Table	Material	Task	Material Task
rep.	54	27	9
d.f.	136	136	136
s.e.d.	2.315	3.274	5.671

Least significant differences of means (5% level)

Table	Material	Task	Material Task
rep.	54	27	9
d.f.	136	136	136
l.s.d.	4.579	6.475	11.215

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Operator	8	11.631	34.2
Operator.*Units*	136	12.030	35.3

N.4.2. Block by tasks

Analysis of variance

Variate: Data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Task stratum	5	2753.5	550.7	4.65	

Task.*Units* stratum					
Material	2	1604.2	802.1	6.78	0.002
Operator	8	19480.5	2435.1	20.58	<.001
Material.Operator	16	5284.6	330.3	2.79	<.001
Residual	130	15385.5	118.3		
Total	161	44508.3			

Tables of means

Variate: Data

Grand mean 34.04

Material	Aqua	Gluupy	Sugar
	35.03	29.79	37.31

Operator	1	2	3	4	5	6	7
	22.78	31.70	30.90	37.59	24.65	57.67	43.94

Operator	8	9
	36.45	20.72

Material	Operator	1	2	3	4	5	6
Aqua		24.38	29.11	31.24	39.49	28.27	67.67
Gluupy		22.12	23.69	29.79	34.59	22.68	53.50
Sugar		21.86	42.29	31.66	38.68	23.01	51.84

Material	Operator	7	8	9
Aqua		36.36	38.70	20.06
Gluupy		29.54	32.67	19.55
Sugar		65.91	37.97	22.56

Standard errors of means

Table	Material	Operator	Material Operator
rep.	54	18	6
d.f.	130	130	130
e.s.e.	1.480	2.564	4.441

Standard errors of differences of means

Table	Material	Operator	Material Operator
rep.	54	18	6
d.f.	130	130	130
s.e.d.	2.094	3.626	6.281

Least significant differences of means (5% level)

Table	Material	Operator	Material

			Operator
rep.	54	18	6
d.f.	130	130	130
l.s.d.	4.142	7.174	12.426

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Task	5	4.516	13.3
Task.*Units*	130	10.879	32.0

N.5. Rate of weighing with AACTS

N.5.1. Block by operators

Analysis of variance

Variate: Data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Operator stratum	8	1457.04	182.13	16.83	
Operator.*Units* stratum					
Material	2	165.05	82.52	7.63	<.001
Task	5	67.05	13.41	1.24	0.294
Material.Task	10	153.86	15.39	1.42	0.177
Residual	136	1471.64	10.82		
Total	161	3314.64			

Tables of means

Variate: Data

Grand mean 9.88

Material	Aqua	Gluupy	Sugar
	9.53	11.26	8.86

Task	1	2	3	4	5	6
	9.04	9.12	9.81	10.19	10.84	10.30

Material	Task	1	2	3	4	5	6
Aqua		9.17	8.62	9.84	8.06	11.10	10.38
Gluupy		10.51	9.58	10.26	14.33	11.35	11.52
Sugar		7.44	9.17	9.31	8.19	10.07	9.01

Standard errors of means

Table	Material	Task	Material Task
rep.	54	27	9
d.f.	136	136	136
e.s.e.	0.448	0.633	1.097

Standard errors of differences of means

Table	Material	Task	Material Task
rep.	54	27	9
d.f.	136	136	136
s.e.d.	0.633	0.895	1.551

Least significant differences of means (5% level)

Table	Material	Task	Material Task
rep.	54	27	9
d.f.	136	136	136
l.s.d.	1.252	1.770	3.067

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Operator	8	3.181	32.2
Operator.*Units*	136	3.290	33.3

N.5.2. Block by tasks

Analysis of variance

Variate: Data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Task stratum	5	67.045	13.409	1.40	
Task.*Units* stratum					
Material	2	165.047	82.523	8.63	<.001
Operator	8	1457.038	182.130	19.05	<.001
Material.Operator	16	382.871	23.929	2.50	0.002
Residual	130	1242.638	9.559		
Total	161	3314.639			

Tables of means

Variate: Data

Grand mean 9.88

Material	Aqua	Gluupy	Sugar
	9.53	11.26	8.86

Operator	1	2	3	4	5	6	7
	12.50	8.05	10.75	9.95	12.56	4.04	8.20

Operator	8	9
	8.21	14.69

Material	Operator	1	2	3	4	5	6
Aqua		9.84	9.03	10.36	9.46	10.79	4.80
Gluupy		14.05	11.50	11.43	11.22	13.81	3.25
Sugar		13.61	3.62	10.46	9.19	13.08	4.08

Material	Operator	7	8	9
Aqua		8.27	7.58	15.64
Gluupy		10.34	7.87	17.85
Sugar		6.00	9.19	10.57

Standard errors of means

Table	Material	Operator	Material Operator
rep.	54	18	6
d.f.	130	130	130
e.s.e.	0.421	0.729	1.262

Standard errors of differences of means

Table	Material	Operator	Material Operator
rep.	54	18	6
d.f.	130	130	130
s.e.d.	0.595	1.031	1.785

Least significant differences of means (5% level)

Table	Material	Operator	Material Operator
rep.	54	18	6
d.f.	130	130	130
l.s.d.	1.177	2.039	3.531

Stratum standard errors and coefficients of variation

Variate: Data

Stratum	d.f.	s.e.	cv%
Task	5	0.705	7.1
Task.*Units*	130	3.092	31.3