Traceability in Continuous Processes
Applied to Ore Refinement Processes

Björn Kvarnström
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- Applied to Ore Refinement Processes

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Doctoral Thesis number 19 in the subject
Quality Technology and Management
Division of Quality Technology, Environmental Management, and Social Informatics
Department of Business Administration and Social Sciences
Luleå University of Technology
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To my loving family
for their love and support!
ACKNOWLEDGEMENTS

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First of all, I would like to thank my supervisors, Professor Bjarne Bergquist and Professor Kerstin Vännman for their support, guidance, and collaboration during my research process.

Secondly, I am indebted to LKAB, VINNOVA’s mining research program, Electrotech, the County Administrative Board of Norrbotten (grant 303-02863-2008), and the Regional Development Fund of the European Union (grant 43206) for their financial support that made this research project possible.

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Sixthly, I want to thank all my former and present colleagues for all the laughs and discussions. You have all made my time as a PhD-student wonderful. Furthermore, I appreciate all your comments and improvement suggestions regarding my research. Special thanks to Erik Vanhatalo and Thomas Olsson for all the fun, the winter beers - and the summer beers! You have been true friends.

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Finally and most importantly, my dearest thanks go to my family and relatives for their support, love, and good cheer. I dedicate this thesis to my partner Linnea and my children Tim and Mio for always making me long to come home and for all your love. I also send special thanks to my father Jan, mother Helen, and sister Lisa, because without you I would not be where I am today.
ABSTRACT

Introduction and purpose: Traceability is central for the identification of the root cause(s) behind a product deviation and thus to achieve a product and process quality that is both high and even. Continuous processes contain several characteristics complicating traceability which are not usually discussed in the scientific literature. The overall purpose of this thesis is to provide a theoretical framework for traceability and to develop and test methods for traceability in continuous processes.

Design/methodology/approach: A literature review and interviews with engineers in continuous processes were performed in order to identify existing traceability theories and applications as well as characteristics complicating traceability in continuous processes. In addition, experiments evaluating traceability applications in three continuous processes were conducted at the Swedish iron ore refinement company Loussavaara Kiirunavaara AB (LKAB). Radio Frequency Identification (RFID), chemical tracer, and ideal flow simulations were, for example, used within the studied applications.

Findings: A theoretical framework for traceability in continuous processes is outlined based on existing scientific literature. Several traceability methods suitable for continuous processes are described and illustrated within the framework. Furthermore, the complicating characteristics in continuous processes that each method may deal with are described. This thesis also presents and illustrates how traceability may be achieved in three continuous processes operating within ore refinement industries.

Research limitations/implications: The presented research gives an insight into traceability theory and more specifically into traceability problems in continuous processes. However, the empirical results from the experiments are based on three specific processes, and research in other processes should be performed to validate the results.

Practical implications: The presented results illustrate how to increase the ability to trace, track, and predict the product location in processes where traceability previously has been difficult.

Originality/value: Prior traceability research has primarily focused on discontinuous processes. By contrast, this thesis presents traceability from a continuous process perspective as well as the design and development of traceability applications for three of these processes.

Keywords: Traceability methods; Process industry; Radio frequency identification; RFID; Granular flows; Iron ore pellets; Flow simulation model; Principal component analysis; Time series analysis; Continuous improvements; Quality Management.
Introduktion och syfte: Spårbarhet är centrat för identifiering av rotorsken(erna) bakom en produktavvikelse och därmed förmågan att uppnå en hög och jämn produkt- och processkvalitet. Kontinuerliga processer har ett flertal egenskaper som försvårar spårbarhet och som vanligtvis inte diskuteras i den vetenskapliga litteraturen. Det övergripande syftet med denna avhandling är att utveckla en teoretisk referensram för spårbarhet och att utveckla samt testa metoder för spårbarhet i kontinuerliga processer.

Design/metod/forskningsansats: En litteraturstudie samt intervjuer med ingenjörer i kontinuerliga processer genomfördes i syfte att kartlägga befintliga spårbarhetsteorier och tillämpningar samt egenskaper som komplicerar spårbarhet i kontinuerliga processer. Dessutom utfördes experiment för att utvärdera spårbarhetsapplikationer i tre kontinuerliga processer inom det svenska järmalsförädlingsföretaget Loussavaara Kiirunavaara AB (LKAB). Radio Frequency Identification (RFID), kemiska spårämne och ideal flödessimuleringar är exempel på metoder som användas inom de studerade applikationerna.

Resultat: En teoretisk referensram för spårbarhet i kontinuerliga processer baserad på befintlig forskningslitteratur har utvecklats. Flera spårbarhetsmetoder lämpliga för kontinuerliga processer beskrivs och illustreras inom den framtagna referensramen. Vidare beskrivs vilka komplicerande egenskaper i kontinuerliga processer som varje metod kan hantera. Denna avhandling presenterar och visar också hur spårbarhet kan uppnås i tre kontinuerliga processer som återfinns inom malmförädlingsindustrier.

Forskningsbegränsningar/konsekvenser: Den presenterade forskning ger en inblick i spårbarhetsteorier och mer specifikt den spårbarhetsproblematik som återfinns i kontinuerliga processer. De empiriska resultaten från experimenten bygger dock på tre specifika processer, och fortsatt forskning bör utföras i andra processer för att validera resultaten.

Praktiska konsekvenser: De presenterade resultaten visar hur man kan öka möjligheten att spåra, följa och prediktera en produkt’s position i processer där spårbarhet tidigare varit svårt att uppnå.

Originalitet/forskningsvärde: Tidigare spårbarhetsforskning har främst fokuserat på diskontinuerliga processer. Denna avhandling presenterar dock spårbarhet utifrån ett kontinuerligt processperspektiv samt utvecklar och skapar spårbarhetsapplikationer för tre kontinuerliga processer.

Nyckelord: Spårbarhetsmetoder; Processindustri; Radio frequency identification; RFID; Granulära flöden; Flödessimuleringsmodell; Principalkomponentanalys; Tidsserieanalys; Kontinuerliga förbättringar; Kvalitetsutveckling.
**APPENDED PAPERS**

<table>
<thead>
<tr>
<th>Paper</th>
<th>Authors</th>
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<th>Journal/Conference</th>
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</table>
RELATED PUBLICATIONS


List of Technical Terms and Abbreviations

<table>
<thead>
<tr>
<th>Technical term</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>Backward traceability</td>
<td>Identification of the lot history.</td>
</tr>
<tr>
<td>Forward traceability</td>
<td>Identification of the lots containing components from a certain batch.</td>
</tr>
<tr>
<td>Item</td>
<td>The smallest quantity of a product that is separated in the process which may for example be a car, a bottle of soda, or a flour bag.</td>
</tr>
<tr>
<td>Lot</td>
<td>A set of items’ of a product, which have been produced and/or processed or packaged under similar circumstances. Note 1: The lot is determined by parameters established beforehand by the organization. Note 2: A set of items may be reduced to a single item of product. (Agriculture and Agri-Food Canada, 2006, p. 12)</td>
</tr>
<tr>
<td>Passive traceability</td>
<td>Provides information concerning the location of were a specific lot is and has been and the components contained in the lot.</td>
</tr>
<tr>
<td>Perfectly mixed flow</td>
<td>A flow system where the incoming flow is assumed to instantaneously propagate through the whole system. Hence, in this type of flow each position in the system has the exact same constituents at any given time.</td>
</tr>
<tr>
<td>Plug flow</td>
<td>A flow system where no mixing of constituents is assumed to occur and the particles therefore enter and exit in the same order.</td>
</tr>
<tr>
<td>Predictive traceability</td>
<td>Allows prediction of the future location of a lot and provides information concerning the location of were a specific lot is and has been and the components contained in the lot.</td>
</tr>
<tr>
<td>Radio Frequency</td>
<td>A wireless and automatic identification technique.</td>
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<tr>
<td>Identification (RFID)</td>
<td></td>
</tr>
<tr>
<td>Residence time</td>
<td>The probability distribution function that describes the amount of time a particle or element resides within a process section.</td>
</tr>
<tr>
<td>Space time</td>
<td>The time necessary to process, for example, the volume of one reactor or silo.</td>
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<tr>
<td>Supply chain</td>
<td>The integrated process wherein a number of various business entities (i.e. suppliers, manufacturers, distributors, and retailers) work together in an effort to: (1) acquire raw materials, (2) convert these raw materials into specified final products, and (3) deliver these final products to retailers. (Beamon, 1998, p. 281)</td>
</tr>
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1 The term ‘unit’ has been replaced with ‘item’ according to the definition in the reference.
<table>
<thead>
<tr>
<th>Technical term</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>Traceability</td>
<td>The ability to track, trace, and predict the location of a lot, its sub-components, and raw materials through the supply chain.</td>
</tr>
<tr>
<td>Traceability method</td>
<td>Provides the mean for a traceability system to connect correct process data to a physical lot through the whole or part of the supply chain.</td>
</tr>
<tr>
<td>Traceability system</td>
<td>Provides an unambiguous and uninterrupted means of traceability for a physical lot, its sub-components, and raw materials throughout the supply chain.</td>
</tr>
<tr>
<td>Track</td>
<td>Following the location of a lot.</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full form</th>
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<tbody>
<tr>
<td>LKAB</td>
<td>The Swedish mining company Loussavaara Kiirunavaara AB</td>
</tr>
<tr>
<td>LTU</td>
<td>Luleå University of Technology</td>
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<tr>
<td>PCA</td>
<td>Principal component analysis</td>
</tr>
<tr>
<td>Pellets</td>
<td>Iron ore pellets</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio frequency identification</td>
</tr>
</tbody>
</table>
Part I
INTRODUCTION

It is often argued that product quality is determined by the customer. Customer comments therefore contain important information that may be used by companies to achieve a product and process quality that is both high and even. The ability to make use of customer comments partially depends on the product traceability, which is the ability to identify when a product was produced. In some cases, an assignable cause may occur in the process that affects the product quality and leads to the production of defective products. The production of defective products may not always be detected before the product is delivered to the customer. Therefore, a company may need to issue a product recall if the defect is serious. The recall cost can be astronomic and escalates dramatically (Jacobs, 1996). Jacobs and Mundel (1975) and Fisk and Chandran (1975) argue that, traceability is important to minimize the extent of product recalls.

Traceability is thus important for the work with continuous improvement (Mahoney and Thor, 1994). Furthermore, traceability is vital for identification of root-causes and to prevent their reoccurrence (Duffin, 1995), and essential if effective methods of process control are to be applied (Oakland, 1995). Continuous improvement and root-cause identification are two commonly mentioned core values in the quality management literature, see, for example, Hsu and Shen (2005), Hansson (2003), Dale et al. (2001), Hellsten and Klefsjö (2000), and Dean and Bowen (1994). Root-cause identification is also an essential principle within Lean Production (Liker, 2004). McInerney (2003) argues that with the introduction of Lean, traceability has never been more critical. Furthermore, many quality management systems require that organizations meet particular traceability demands. An organization must be able to show, for example, traceability when required internally or by a third party to be ISO 9001-2008 (2008, 7.5.3) certified. The ISO/TS 16949:2009 (2009, 7.5.3.1), the quality specification for the automotive industry supply chain, is even more strict since it demands traceability of all products. Hence, traceability is an important element in many quality technology
and management concepts. However, the importance of traceability is not limited to these areas. According to Fisk and Chandran (1975), traceability is an important ability for all manufacturers.

Rábade and Alfaro (2006) argue that, the first articles that deals with traceability in a scientific way appeared in the seventies, whilst the major interest in traceability in the scientific literature started in the early nineties. Traceability has, for example, become a focus in the food and the dairy sector after the outbreak of food crises, such as, BSE (mad-cow disease), foot-and-mouth disease, and the scandal of infant milk tainted with Melamine in China. Other reasons for the increased demand for traceability in these industries are the introduction of genetically modified organisms, plants and animals (Opara, 2003) and the increased possibility to market products with special raw material or product features (Moe, 1998). Traceability makes, for example, product authenticity and authentication possible. Karoui et al. (2004) argue that product authenticity and authentication are two emerging topics within the food sector, and that authenticity is a guarantee of eating quality and safety. Rábade and Alfaro (2006) conclude that firm specific variables (internationalization, size and characteristics of final product) and competitive environment variables (consumers' pressure and legal environment) affect the resources employed in traceability systems for the food and dairy industry. The lack of verifiable traceability in the event of a food crisis has shown to result in losses of, for example, market share, see Deasy (2002). Golan et al. (2004) found, in an empirical investigation, that the food and dairy industries tend to be motivated by economic incentives when constructing traceability systems and not by government traceability regulations. They therefore argue that government-mandated or -administered traceability is usually not the optimal response to solve potential traceability problems. Voluntary standards like, for example, “The Canadian Food Traceability Data Standard Version 2.0” (Agriculture and Agri-Food Canada, 2006) do however exist. Smith et al. (2005) describe several contexts in which traceability for livestock, poultry, and meat can, could or will eventually be used.

In addition, traceability has become important in the forestry sector to provide information about where the raw materials originate and to control illegal logging, see, for example, Dykstra et al. (2002) and Charpentier and Choffel (2003). Traceability is also a key component in the striving to achieve more efficient utilization of the raw materials, that is to produce the most suitable product from each log, see Flodin et al. (2007). Finally, traceability is an essential element in the control and efficiency in the supply chain logistics for the industry (Chiorescu, 2003). Traceability research within the forestry sector mainly focuses on traceability methods for the wood, see, for example, Uusijärvi (2003). Dykstra et al. (2002) give
an extensive list of methods suitable to use for achieving traceability in the forestry sector and describes the advantages and disadvantages of each method from a forestry perspective.

Both the food and dairy sector and the paper and pulp sector are examples of continuous process industries in which traceability has been in focus. The APICS dictionary defines continuous processes as:

“A production system in which the productive equipment is organized and sequenced according to the steps involved to produce the product. This term denotes that the material flow is continuous during the production process. The routing of the jobs is fixed and setups are seldom changed.” (Blackstone Jr and Cox III, 2008, p. 25)

Continuous processes are common in process industries, and the APICS dictionary defines a process industry as:

“The group of manufacturer that produce products by mixing, separating, forming and/or performing chemical reactions” (Blackstone Jr and Cox III, 2008, p. 104)

We may find continuous processes, for example, in the mining, dairy and food, pulp and paper, and steel industries.

1.1 Problem discussion

Much of the existing traceability literature, found in databases such as Scopus®, usually describes findings from specific applications in various production processes. No literature, found during the research project, attempts to present a traceability theory based on existing research. I would, therefore, argue that there is a lack of theoretical discussion concerning traceability within the scientific literature. Hence, to develop a theoretical framework for traceability by gathering and comparing existing research should provide valuable knowledge.

Secondly, most of the applications described in the literature are within discontinuous processes, with the exception of the food and dairy and forestry industries. Indeed, Flapper et al. (2002) argue that traceability is important in process industries where continuous processes are common. The characteristics of continuous processes differ in several ways from discontinuous processes. I would argue that some of these characteristic differences complicate the possibility to achieve traceability in a continuous process. Table 1.1 contains a summary of the characteristics of continuous process industries that may cause traceability problems and descriptions of why they are problematic.

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2 www.scopus.com
Table 1.1. Characteristics in continuous process industries that can complicate traceability. The table also contains references for description of the characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Problem</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Continuous flow</td>
<td>No natural batches</td>
<td>Skoglund and Demjak (2007)</td>
</tr>
<tr>
<td>Product may change state</td>
<td>No natural units</td>
<td>Fransoo and Rutten (1993) and Dennis and Meredith (2000)</td>
</tr>
<tr>
<td>Low value added to the products in the production process</td>
<td>Large sensitivity for cost addition</td>
<td>Fransoo and Rutten (1993)</td>
</tr>
<tr>
<td>Mixture of continuous flows and non continuous flows</td>
<td>Large variation in residence time</td>
<td>Lundqvist and Kubulnieks (1995)</td>
</tr>
<tr>
<td>Reflux of material</td>
<td>The material may enter and exit in different order</td>
<td>Fransoo and Rutten (1993) and Hild et al. (2000)</td>
</tr>
<tr>
<td>Extreme environment</td>
<td>Extreme endurance places</td>
<td>Demands on the traceability solution</td>
</tr>
<tr>
<td>Segregation</td>
<td>The flow depends on the physical characteristic of the product</td>
<td>Bergquist (1997) and Ottino and Khakar (2000)</td>
</tr>
</tbody>
</table>

The continuous flow of material, for example, causes problems as traceability solutions normally rely on the definition of a batch (Skoglund and Dejmek, 2007). Furthermore, the product in a continuous process may also be in a non-discrete-state and can undergo multiple changes of state before delivery (Fransoo and Rutten, 1993; Dennis and Meredith, 2000). The change of state implies that no naturally locatable unit exists in the process. A continuous production process may also contain sub processes that have continuous as well as batch-wise material flows (Lundqvist and Kubulnieks, 1995). The combination of the two material flows results in immense variation in the residence time of the process, the time a product stays within the process, thereby making it hard to model the material flow and attain traceability. Moreover, the raw materials used in continuous processes usually come directly from the natural world. Therefore, the raw material in a continuous process usually has a higher level of natural variation than the preprocessed raw materials commonly used in discrete production (Fransoo and Rutten, 1993). Continuous process industries commonly use various control systems and reflux of material to handle the increased natural variation in raw materials (Hild et al., 2000). The reflux of material complicates the material flow and thereby the possibility to achieve traceability. In addition, organizations with continuous processes often expose their products to extreme physical environments such as high temperatures, high pressures, and strong acids or bases during production. The extreme environment complicates traceability as it becomes difficult to find an application.
that both can handle the environment and can be used to achieve traceability. Granular materials, conglomerates of discrete macroscopic particles, are common in continuous processes. These materials usually come directly from the natural world, and the physical characteristics of the material, such as density, shape and size, therefore, tend to display variations. Studies have shown that granular materials segregate due to differences in physical characteristics when handled, see, for example, Ottino and Khaker (2000). Moreover, it is hard to model the segregation behavior of these materials, since no fundamental laws governing segregation have been formed (Duran, 2000). The segregation is a consequence of differences in product flow behavior, which implies that the physical characteristic of a product may affect its behavior in the material flow. Hence, the flow behavior may differ between the products in granular flows which further complicates traceability.

A process stage within a continuous process industry seldom includes all the described characteristics. Nevertheless, the characteristics present within each process stage in a continuous process may vary and each stage usually contains more than one characteristic. Therefore, the traceability problems vary between different flow systems in continuous process industries. The characteristics in Table 1.1 are usually not addressed in the traceability literature. However, they do certainly complicate traceability in continuous processes. Hence, further research about traceability in continuous process would be a valuable contribution to improving the understanding of traceability in these processes.

1.2 Research purpose, aims, and scope

The lack of a common traceability theory presented within the scientific literature and the traceability complications in continuous processes have been identified as two areas within the traceability research that need to be studied further. Therefore, the overall purpose of this thesis was to provide a theoretical framework for traceability and to develop methods for traceability in continuous processes. More specifically, the aims of this thesis were to:

Aim 1: explore and describe how different traceability concepts are related.

Aim 2: explore, describe, and explain how continuous process industries may achieve traceability in various flow systems.

In addition, a number of delimitations were made in the research. Firstly, the research was delimited to develop methods to achieve traceability in continuous processes. The main reason for making this delimitation was that I believed the differences between continuous and non continuous processes to primarily affect the
development of traceability methods and not, for example, the factors enabling traceability.

Secondly, the examined scientific literature contained many description of traceability based on specific applications. However, no commonly accepted theoretical framework for traceability was found in the literature. Therefore, the research in this thesis was delimited to gather and develop existing traceability theories into a theoretical framework and not on developing new theories.

Thirdly, the research was delimited to traceability of goods and will not discuss, for example, requirement traceability. A wider definition of traceability would have demanded a more extensive literature examination and would have meant that fewer applications could be studied, due to time constraints. I judged it more interesting to study traceability applications than different types of traceability and, therefore, delimited the research to study traceability.

1.3 Organization of the thesis
The thesis includes two parts. Part I works as an introductory frame to the appended papers in Part II and it intends to relate each paper to existing literature. Part II contains the six appended research papers. Figure 1.1 gives an overview of the connection between the papers in Part II. This section summarizes the content of the two parts.

![Figure 1.1 An overview of the content in the appended papers.](image)

**Part I**
Part I contains five chapters. Chapter 1 introduces the research field, provides a problem discussion, and presents the research aims. Chapter 2 presents the applied research process and research strategy. Chapter 3 presents a traceability framework based on the existing literature and ends with a discussion of traceability in
continuous processes. Chapter 4 provides a description of traceability applications for three continuous flow systems in an ore refinement process. Chapter 5 discusses the contribution of the research, provides some major conclusions, and proposes ideas for future research.

Part II

Part II contains six appended papers and the content of each paper is summarized here.


Paper A identifies and describes different traceability methods useful to improve traceability in continuous processes. The paper builds on a literature study and interviews with various engineers from continuous process industries. Furthermore, the paper gives a theoretical example of how to use various traceability methods in a refinement process of iron ore to achieve traceability. Paper A also presents the advantages and disadvantages of each traceability method.

The paper was initiated by Björn Kvarnström. Data collection of the empirical material to identify suitable traceability methods through a literature study, interviews at Luossavaara-Kiirunavaara AB (LKAB), interviews at other process industries, and direct observations were mainly done by Björn Kvarnström. Pejman Oghazi took an active part in exemplifying the use of the traceability methods to achieve traceability in the refinement process of iron ore to iron ore pellets. Björn Kvarnström mainly wrote the paper with contributions from Pejman Oghazi.


Paper B presents and discusses how to achieve traceability in a continuous iron ore pelletizing process. The method presented in the paper uses a flow simulation model based on ideal flow assumptions. The ideal flow assumptions are based on interviews with process engineers within the process, process data, and chemical tracer experiments. The paper then exemplifies various disturbances that may arise in the process and uses the flow simulation model to test the effects of these disturbances in the process. Finally, the paper presents and discusses various application fields in continuous processes for the presented model.

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1 LKAB is a Swedish mining company that produces iron ore products for the steel industry. The research presented in this thesis used various processes at LKAB as study objects.

2 Pejman Oghazi worked as PhD candidate in Mineral Processing at Luleå University of Technology (LTU).
The paper was initiated by Björn Kvarnström who also carried out the data collection, the data analysis, the construction of the flow simulation model, and the simulations. He mainly wrote the paper with contributions from Bjarne Bergquist.


Paper C is a continuation of Paper B and gives further details concerning the construction of the flow simulation model. The paper then demonstrates the use of the developed model in a field trial that involved a change in the raw material for production of a special product. The use of the simulation model implied that the engineers could visualize and predict the effect of the raw material change in the output at different times. Paper C also compares the simulation model output against the actual output. The comparison showed that the presented model, after some modifications, gave a result similar to the analysis results of the collected samples during the field trial. Moreover, the paper discusses the possibility to use the constructed model for identification of cause and effect relations and as a decision support regarding the necessity for control measures in case of process deviations.

The paper was initiated by Björn Kvarnström who also carried out the simulation model, the simulations, and the modifications of the model. He and Bjarne Bergquist wrote the paper together.


Paper D explores how to achieve traceability in continuous granular flows. The paper proposes and tests the use of Radio Frequency Identification (RFID) to improve traceability in a flow of granular products. The tests are made in a distribution chain of iron ore pellets and the results show how RFID can be used to improve traceability in the flow. Furthermore, the paper describes and discusses different problems concerning the use of RFID in continuous processes.

The paper was initiated by Björn Kvarnström who also performed the experiments, data collection and analysis. Furthermore, he was the primary writer of the paper with contributions from Erik Vanhatalo.

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5 Bjarne Bergquist has been the supervisor for the author and is a professor in Quality Technology and Management at LTU.
6 Erik Vanhatalo worked as a Ph.D. candidate in Quality Technology and Management at LTU.
-INTRODUCTION-  

**Paper E: RFID to Improve Traceability in Continuous Granular Flows - An Experimental Case Study**

Paper E is a continuation of Paper D and it investigates various methods to improve the performance of RFID applications in continuous granular flows. The results of the paper build on experimental data collected in a distribution chain of iron ore pellets. The paper identified several ways to improve the performance of the studied RFID application. Moreover, the paper gives recommendations about the use of RFID in continuous granular flows.

The paper was initiated by Björn Kvarnström. The experiments and the data collection were done by Björn Kvarnström. He also performed the analysis with contributions from Bjarne Bergquist and Kerstin Vännman. All three authors took part in the writing process of the paper.

**Paper F: A Method to Determine Transition Time for Experiments in Dynamic Processes.**

Paper F explores the use of historical data to understand the transition time in continuous processes. The paper combines principal component analysis (PCA) and time series analysis methods to determine and model the transition time in a process using historical data. The paper demonstrates the methods by determining the transition time and the transition time model for two changes in an experimental blast furnace.

The ideas to the paper were sparked during a course in time series analysis and all authors helped develop the analysis method. Erik Vanhatalo and Björn Kvarnström jointly performed the data analysis. Erik Vanhatalo was the principal author of the paper with contributions by the other authors.

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7 Kerstin Vännman has been the supervisor for the author and is a Professor in Mathematical Statistics at LTU, at Umeå University, and at University West.
The research presented in this thesis is a result of a collaboration project between LTU (Luleå University of Technology) and LKAB (Luossavaara-Kiirunavaara AB). In 2005, LKAB expressed an interest in improving traceability in their refinement process of iron ore into iron ore pellets (henceforth pellets), which is a process with continuous production. The interest resulted in the start of two research projects, which later became three. Three different research subjects (Quality Technology and Management, Mineral Processing, and Ore Geology) were responsible for one project each, and each subject recruited a PhD-student. Each project had responsibility for a specific part of the production chain at LKAB, but also an overarching aim to study traceability problems in continuous processes. The research project presented in this thesis focuses on the iron ore pelleting plants and the distribution chain of iron ore pellets. For a closer description of the process see the appended papers. Oghazi (2008) and Lund (2009) describe the other two projects in detail. Kent Tano and Sofia Nordqvist at LKAB acted as the link between the overall project and the project presented in this thesis. Figure 2.1 gives an overview of the project structure.

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Figure 2.1. The relation between the three research projects and the process stages at LKAB. This thesis presents the grey marked project.

2.1 Research approach and strategy

Zikmund (2000) and Marshall and Rossman (2006) argue that there are three types of research aims: descriptive, explorative, and explanatory. A research project may combine more than one of the three, see, for example, Saunders et al. (2000). The research in this thesis makes use of all three, and Table 2.1 gives an overview of the connection between the aims of the presented research and the different types of research aims.

Table 2.1. An overview of the connection between the aims of the presented research and the different research aims. X indicates a strong connection, (X) describes a weaker connection, and a blank field indicates no connection.

<table>
<thead>
<tr>
<th>Research aims</th>
<th>Exploratory</th>
<th>Descriptive</th>
<th>Explanatory/Causal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. To explore and describe how different traceability concepts are related.</td>
<td>(X)</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2. To explore, describe, and explain how continuous process industries may achieve traceability in various flow systems</td>
<td>(X)</td>
<td>X</td>
<td>(X)</td>
</tr>
</tbody>
</table>

The research approach describes the realization of the research, and the research approach differs between various studies. The research in this thesis started with an idea that traceability could be achieved in continuous processes. This idea was then tested in various processes and the result of these tests was then analyzed. Based on the result of the analysis new ideas were developed and tested. The research approach was used since some previous traceability applications in continuous processes existed, but not for the studied processes. Therefore, theories from existing research could be used to form initial ideas that later on could be modified based on empirical findings. Box et al. (2005) describe this research approach as an iterative deductive-inductive process. Figure 2.2 illustrates the approach.
A research project may be conducted following different general directions, that is, different research strategies (Bryman, 2001). The research in this thesis took place in three phases. Phase 1 had an exploratory aim that focused on exploring existing research on traceability in continuous processes. Phase 2 had a descriptive aim that focused on identifying and describing traceability methods for continuous processes. Phase 3 had an explanatory aim that focused on the developing, testing, and explaining of traceability applications useful for achieving traceability in various continuous flows. Figure 2.3 gives an overview of the research presented in this thesis.

Figure 2.2. The iterative deductive-inductive process from Box et al. (2005, p. 2).

Figure 2.3. An overview of the research process, the research activities, the focus of each research activity, type of research aim, and the connection between the research activities and the appended papers.
According to Yin (2003), the collection and analysis of data within the social science paradigm may be done according to five strategies. Phases 1 and 2 may be classed as an archival analysis according to these strategies, since the phases aim to determine, for example, which traceability methods that may be used in continuous processes. An archival analysis strategy was used as the research in the two phases did not require control over events and focused on both historical and contemporary applications. Phase 3 can be seen as part of an experimentation strategy according to the strategies presented by Yin (2003), since it aims to answer, for example, how traceability can be achieved in a particular process. The third phase demanded control over events and focused on a contemporary event. The research activities in the three phases will be briefly described in the next section. The three phases had a certain time overlap, and thus previous research results were reexamined and analyzed in the light of later findings.

2.2 Research activities in phase 1

Four data collection methods, a literature search, direct observations, interviews with engineers/managers at LKAB and interviews with engineers at various process industries, were used in Phase 1.

The literature search: A literature search was made to explore the existing scientific literature regarding traceability in continuous processes. The collection activity was selected as it provided an overview of previous research and therefore contributed to fulfilling the exploratory aim. Keywords and search strings for the literature search were generated through reading and discussions with Pejman Oghazi. The generated search strings were used to identify literature of interest within the scientific databases Compendex®10, Emerald11, and ScienceDirect®12. The three databases were selected to cover a wide range of scientific literature, including both engineering and management research. Pejman and I then read all the article abstracts to decide if the article was relevant for the research project. An article was judged as relevant if at least one of us classed it as relevant. However, no record regarding the concordance of the article classification between us was kept. After the classification, we read the relevant articles, highlighted key sections, and wrote down new keywords and references. This approach was used for all literature searches within the thesis. However, the researchers that participated in the different literature searches depended on to the scope of the search. For an overview of the literature search, see Table 2.3

10 Now part of engineering village found at www.engineeringvillage.org
11 www.emeraldinsight.com
12 http://www.sciencedirect.com/
Table 2.3. Result of initial literature search. The literature search was performed in August 2007. All fields were used in the search unless otherwise stated.

<table>
<thead>
<tr>
<th>Database</th>
<th>Combination of search strings</th>
<th>Articles found</th>
<th>Relevant to research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compendex®</td>
<td>Traceability and “continuous process”</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td>Emerald</td>
<td>Traceability (Title) and “process industry”</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>ScienceDirect®</td>
<td>“Traceability technique” and “process industry”</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Compendex®</td>
<td>“Traceability method” and “process industry”</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Emerald</td>
<td>Traceability method and “process industry”</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>ScienceDirect®</td>
<td>“Traceability method” and “process industry”</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Compendex®</td>
<td>“Traceability method” and “process industry”</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td>Emerald</td>
<td>Traceability method and “process industry”</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ScienceDirect®</td>
<td>“Traceability method” and “process industry”</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Grand total</td>
<td></td>
<td>123</td>
<td>32</td>
</tr>
</tbody>
</table>

Direct observations during guided tours: Observations were made to get a better knowledge of the characteristics in continuous processes that complicate traceability. The activity was chosen as it was expected to provide the best opportunity for a deep understanding of these characteristics. Process engineers at LKAB acted as guides, and they gave detailed explanations of each process step. I also made a guided tour at a pulp and paper mill to get an understanding of similarities and differences between some major industries with continuous processes. The two industries were selected to give an understanding of two different process branches, and because they were positive regarding access to their processes.

Interviews with thirteen engineers/managers at LKAB: A prerequisite for the research project was that the research would focus on processes that could be found at LKAB. Interviews were made at LKAB to improve my knowledge of their processes, characteristics that complicated traceability in these processes, and any previous work with traceability at the company. I selected the interview respondents together with Sofia Nordqvist, a research engineer at LKAB. The selection intended to cover all parts in the production process at LKAB to get an understanding of all their existing processes and traceability initiatives. Most of the respondents were middle managers and process engineers from the production process. Sofia and I primarily selected respondents from these two groups, as they would have a deep knowledge of various traceability initiatives within the process and the actual production process. A semi-structured interview approach with open-ended
question was used for the interviews as the focus areas of the interviews were known beforehand. Merriam (1998, pp. 72-75) gives a further discussion of semi-structured interviews. Kvarnström (2008, Appendix 1) lists all the questions used for the interviews with the LKAB engineers/managers in Swedish. Each interview was summarized and sent to the respondent for approval. The summary and approval procedure should have a positive effect on the reliability, as the respondents were given the possibility to correct erroneous interpretations of their answers and add information to their responses. After approval, the summary was used to generate key words for the literature study, to get a better understanding of the specific process, and to achieve a better understanding of the characteristics of continuous processes that complicate traceability.

Interviews with four engineers at four process companies in Sweden:
I made these interviews to scan the field for unpublished traceability applications and projects within continuous processes. The interviews were made at two food companies, a paper and pulp mill, and at a pharmaceutical company. The organizations and engineers interviewed were selected based on recommendations from other respondents, except for the first respondent who was selected together with Bjarne Bergquist.

2.3 Research activities in Phase 2
The focus in Phase 2 was on exploring and describing traceability methods suitable for continuous processes. A secondary literature search was made to explore and describe these methods. I made use of input from Phase 1 to define the key words and the search strings used for this search. Radio frequency identification (RFID), fingerprint, and residence time distribution (RTD) are examples of keywords and search strings used in the search. The same databases (Compendex®, Emerald, and ScienceDirect®) were used as in the first search. The results of the research activities in Phases 1 and 2 are presented in Paper A. The literature search has been an ongoing data collection activity within the research project focusing on various key words. The ongoing search has however been less systematic than the initial and secondary search, and its intensity has shifted over time.

2.4 Research activities in Phase 3
The research in Phase 3 shifted to an applied focus as the phase explored, described, and explained how to achieve traceability in various continuous flows. Traceability strategies were developed and tested for three different continuous flow systems within the ore refinement process at LKAB. Hence, the LKAB ore refinement process and the flows within the process played a central role for the continuation of
the research project. Table 2.4 gives an overview of the characteristics for the studied flow systems.

**Table 2.4. Characteristics for the studied flow systems.**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Flow 1: Pelletizing of iron ore</th>
<th>Flow 2: Distribution of pellets</th>
<th>Flow 3: Blast furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full continuous flow</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Product change state</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Low added value</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Reflux</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extreme environment</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Segregation</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mixture of continuous and non-continuous flows</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

The first flow system investigated was the pelletizing plant. Papers B and C give a closer description of the system. It was decided to use a flow simulation model to achieve traceability in the first flow system. The construction of this flow model may be described using the approach presented by Refsgaard and Henriksen (2004). Their approach was selected as it provided a structured way to construct a model for a flow system based on previous literature. Figure 2.4 illustrates the approach used for the construction of the flow model. In the first step, a conceptual model was constructed based on data from the process and from tracer experiments. The conceptual model was discussed with engineers at LKAB and modified until they considered that it gave a correct description of the flow system. Secondly, the conceptual model was translated into a model code for MATLAB® using the SIMULINK® toolbox. The function of the model code was then step-wise tested and verified. Thirdly, the model code made it possible to set up a flow simulation model of the process. Simulations were then made with the model and the credibility of the simulation outcomes were discussed with engineers at LKAB. The discussion resulted in some changes being made to the model setup. Finally, LKAB and I tested and modified the model during production of a special product for confirmation purposes. Papers B and C give a closer description of the development and construction of the flow simulation model.
The second flow system studied was the distribution chain of pellets. Table 2.4 gives an overview of the characteristics for this flow system, while Papers D and E give a detailed description. My supervisors and I decided to investigate the possibility to use RFID to create traceability within the granular flow. RFID was chosen as it tentatively offered an opportunity to divide a granular continuous flow into batches and automatically monitor the batch location. All RFID readers used in the experiments were manufactured and mounted by Electrotech and calibrated after installation. Three different types of passive low frequency (125 kHz) transponders were used in the experiments. All transponders were encapsulated with different casings to reduce the risk that the transponder would be physically damaged in the flow system. The maximum pressure that the transponder casings could endure before breaking was tested and found to be higher than the pressure the pellets could undergo without breaking. All transponder identification numbers were recorded and stored together with information of their size and casing design before each experiment. Hence, from an identification number all the transponder design information was accessible. The performed experiments aimed to evaluate the possibility to use an RFID system to achieve traceability in the distribution chain, and to evaluate approaches to improve the performance of the system. The experimental results were analyzed using statistical methods. Papers D and E give a more detailed description of the experimental equipment, the transponders used, the transponder design, how the experiments were performed, and the analysis of the results.
The third flow system studied was the experimental blast furnace at LKAB. Vanhatalo (2009) gives a detailed description of the system. The approach was to analyze previous process data from experiments to estimate the transfer function model, that is the transition pattern in a process to a known change. By knowing the transfer function model, the cumulative percent of change may be calculated which is equivalent to an estimation of the residence time distribution. Hence, the transfer function model may be used to create traceability. Erik Vanhatalo, my supervisors, and I developed a method that combined principal component analysis and time series analysis methods to estimate the transfer function model. We used historical data to investigate the appropriateness of the developed method. Paper F presents the method and describes the tests of the method on historical data.

2.5 Research quality
The quality of research is often evaluated based on its validity and reliability. Validity is concerned with whether the research measures what it intends to measure (Bryman, 2001). Reliability is the extent to which an experiment, test, or measure yields the same results on repeated trials (Carmines and Zeller, 1979). Within the literature about scientific methods, there are several authors that describe different tactics to improve these measures, see, for example, Yin (2003), Riege (2003), and Newman and Benz (1998). However, the nature of the research in this thesis is more technical and it, therefore, differs from the research that these tactics are developed for. Nevertheless, I believe that some of these tactics are still relevant for use in order to strengthen the research quality.

One way to improve the validity of a study is triangulation. Triangulation implies the use of multiple sources such as data, investigators, theories, or methods, see, for example, Yin (2003). The rationale behind triangulation is that results and conclusions should be more trustworthy if they rely on multiple sources. Different types of triangulation have been used during the research project. For example, multiple data collection methods have been used to identify traceability methods and several researchers participated in the analysis of data from the experiments. According to Yin (2003), another way to improve research validity is to have key informants review the research. Letting key informants review and comment on the research should increase the accuracy of event descriptions and reduce the risk that the researcher misinterprets an event. In this study, key informants have reviewed the research at several occasions during, for example, quarterly project meetings and the development of the flow simulation model. Validity may also be strengthened by addressing rival theories, as it forces the researcher to study the problem using different theoretical standpoints. Rival theories were, for example, addressed during
the identification and development of traceability definitions. Moreover, when analyzing the experimental data different hypotheses were tested. The use of all these tactics should have strengthened the validity of the research presented in this thesis.

A weakness in the presented research project is that much of the research has focused on a single company (LKAB). I, therefore, view the external validity (generalizability) as a potential weakness. Likewise as in a single case study, the external validity for my research relies on analytical generalization. Yin (2003) explains analytical generalization as research that tries to generalize the findings to some broader theory. Here I try to relate the findings to theory about continuous processes and traceability to make generalization of the findings possible. This theory also worked as a guide for decisions concerning the research activities in the data collection process. However, the lack of theory made it difficult to relate all the research findings to the existing theory. For example, it was difficult to find relevant theory to relate the findings regarding the use of RFID in an ore refinement process.

According to Yin (2003), the reliability of research may be improved by carefully documenting all research activities. By documenting the research, it becomes possible for an outsider to follow the research process and in principle repeat the activities. In this research project, the activities and decisions have been documented and described in protocols, different reports, and in the appended papers. Hence, I have used documentation of various activities to improve the reliability of the research. However, replication of the research is difficult as much of the data collection took place in a unique and hard-to-control process. All data used in the analyses was stored, and other researchers can consequently repeat the analysis. The preservation of the data is a prerequisite for reliability and replication.
Chapter 3 summarizes the research findings from the exploratory and descriptive study of traceability conducted in this research project. In this thesis, three traceability concepts are used: traceability, traceability system, and traceability methods. Figure 3.1 gives an initial illustration of the relation between the three concepts. This chapter discusses these concepts and other related traceability concepts based on existing literature and develops a theoretical framework for traceability. The discussion of the concepts is mainly done from a continuous process context.

Figure 3.1 The three concepts of traceability used in this thesis and the relation between them.

3.1 Traceability and traceability systems
The scientific literature contains several definitions of traceability. Table 3.1 summarizes the definitions found within the literature during the presented research project. Comparing the definitions, similarities as well as differences can be seen between them. Most definitions agree that traceability is an ability, that it is possible to describe it with different verbs, for example track and trace, and that the ability is connected to physical objects. Furthermore, many of the definitions are in
agreement that the ability is not restricted to a single company. The definitions do not agree regarding the exact verbs to include, what the physical object is, and the exact extent of the ability. A closer discussion of the notions connected to traceability will therefore be given here. Note that the APICS (Blackstone and Cox, 2008) dictionary definition is the only one that mentions how traceability should be realized. Therefore, the APICS definition may be seen as a more applied definition than the others.

Table 3.1 Definitions of traceability found in the examined literature.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moe (1998, p. 211)</td>
<td>Traceability is the ability to track a product batch and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales or internally in one of the steps in the chain.</td>
</tr>
<tr>
<td>Töyrylä (1999, p. 38)</td>
<td>Traceability is the ability to preserve and access the identity and attributes of a physical supply chain’s object.</td>
</tr>
<tr>
<td>McKean (2001, p. 363)</td>
<td>Traceability is the ability to maintain a credible custody of identification for animals or animal products through various steps within the food chain from the farm to the retailer.</td>
</tr>
<tr>
<td>The European Parliament and of the Council (2002, p. L31/8)</td>
<td>Traceability means the ability to trace and follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing and distribution.</td>
</tr>
<tr>
<td>ISO 9000 (2005, p. 12)</td>
<td>Traceability is the ability to trace the history, application or location of that which is under consideration.</td>
</tr>
<tr>
<td>Van der Vorst (2006, p. 33)</td>
<td>Traceability is the ability to document and trace a product (lot) forward and backward and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales.</td>
</tr>
<tr>
<td>APICS dictionary (Blackstone and Cox, 2008, p. 140)</td>
<td>Traceability is (1) the attribute that allows the ongoing location of a shipment to be determined, and (2) the registering and tracking of parts, processes and materials used in production, by lot or serial number.</td>
</tr>
<tr>
<td>Van Rijswijk and Frewer (2008, p. 455)</td>
<td>Traceability is the ability to trace and track food and food ingredients through the supply chain; thus all stages of production, processing and distribution.</td>
</tr>
</tbody>
</table>

Examining the definitions in Table 3.1, we see that there are differences in how they define the physical item. According to the definitions, the physical item may be either a single item (an animal) or a group of items (animals). An item is here defined as:
“the smallest quantity of a product an organization separates in the process which may for
example be a pencil, a vehicle, a can of soda, or a bag of flour.”

The term lot is often used in the literature discussing traceability to denote various numbers of items, see for example Petroff and Hill (1991) and Steele (1995). I, therefore, propose that the term lot is suitable for use to define the physical unit in the definition of traceability, since a lot can denote either a single item or several items. The following definition of a lot is used here:

“A set of items of a product, which have been produced and/or processed or packaged under similar circumstances. Note 1: The lot is determined by parameters established beforehand by the organization. Note 2: A set of items may be reduced to a single item of product.” (Agriculture and Agri-Food Canada, 2006, p. 12)

In some industries, for example the automotive industries, the processes produce few items from many sub-components and/or raw materials. In other industries, for example the forestry industry, the processes produce many items from a few sub-components and/or raw materials. If the traceability definition is to be general, it needs to be suitable for both types of industries, and it should emphasize the importance of maintaining the link from the sub-components and/or raw materials to the lots.

The next step is to discuss the extent of the traceability and define the term to denote the extent. Most definitions in Table 3.1 define the extent of traceability from the acquisition of the raw material to the point of sale. In the scientific literature, researchers often use the term supply chain to denote the whole production chain from the raw materials to the final product. I, therefore, suggest the use of the term supply chain to describe the extent of traceability and use the following definition of the term:

“A supply chain may be defined as an integrated process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together in an effort to: (1) acquire raw materials, (2) convert these raw materials into specified final products, and (3) deliver these final products to retailers.” (Beamon, 1998, p. 281)

After defining the physical item and the extent of traceability, it remains to define the actual ability. Several definitions in Table 3.1 use the terms track and/or trace. According to Stefansson and Tilanus (2000) there is no precise definition of tracking and tracing in the literature, but tracking usually implies following the location of a lot whereas tracing refers to locating the position of a lot. I agree with

13 The term unit has been replaced with item compared to the definition in the reference.
Stefansson and Tilanus’s (2000) interpretation of tracking and tracing, and, therefore, use their view of the terms in the thesis.

Backward and forward traceability are two other terms mentioned within the literature. Jansen-Vullers et al. (2003) describe forward traceability as the ability to explore the where-used relations between lots and backward traceability as the ability to explore where-from. Backward traceability is necessary for identifying the history of a lot and makes root-cause identification of customer complaints easier. Forward traceability is required for identification of lots containing items from a certain batch. Moreover, it is necessary to allow selective product recalls. In this thesis backward traceability and trace are seen as synonyms and forward traceability and tracking are also seen as synonyms. Therefore, the traceability definition needs to contain both tracing and tracking to incorporate both backward and forward traceability.

We can view traceability as a passive or a predictive ability. In a passive view, traceability provides information concerning the location of a special lot at present and in the past and information of the sub-components that each lot contains. The predictive view encompasses the passive view, but also includes the view of traceability as a tool to predict the future location of a lot. Hence, the predictive ability implies the possibility to use traceability to change individual process settings to fit a specific lot, and it thus allows the use of traceability for process optimization and control. The passive view does not allow optimization of the process as knowledge of a lot’s location is only available retrospectively. With a predictive view, the organization may more easily use traceability to decrease failure costs, increase productivity, and/or guarantee better quality (Jansen-Vullers et al., 2003).

Figure 3.2 illustrates the differences between passive and predictive views of traceability.

![Figure 3.2](image_url)  
*Figure 3.2 A graphical illustration of the difference between the passive and the predictive view of traceability.*

All the definitions in Table 3.1 have a more or less passive view of traceability and none of them explicitly mentions the predictive ability. I take a predictive view on traceability in this thesis, since such a view provides additional benefits compared to the passive view. Therefore, in addition to trace and track the traceability

---

14 Jansen-Vullers et al. (2003) use the term active instead of predictive (used throughout this thesis).
definition should include the ability to predict the location of a lot in the future. Figure 3.3 illustrates the meaning of trace, track, and predict.

Figure 3.3 A graphical illustration describing the use of trace, track, and predict in the thesis. Trace makes it possible to connect events in a distribution chain to particular lots. Track enables the organization to follow the location of a lot in a distribution chain. Predict is the ability to predict the future location of a lot in the distribution chain at a certain time.

None of the definitions in Table 3.1 cover all of the presented aspects of traceability. Table 3.2 summarizes my opinion regarding the limitations of each definition. In an attempt to cover all the aspects, the following definition is formulated and used:

“Traceability is the ability to track, trace, and predict the location of a lot, its sub-components, and raw materials through the supply chain.”

The proposed definition covers all of the discussed aspects of traceability, as well as most of the studied definitions in the literature.
Table 3.2 The limitations in my opinion of the existing traceability definitions in the literature compared to the proposed definition.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Limitations with definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Töyrylä (1999, p. 38)</td>
<td>Lacks the predictive ability and does not make use of the verbs trace and track to describe the ability.</td>
</tr>
<tr>
<td>McKean (2001, p. 363)</td>
<td>Lacks the trace and predictive ability, and is limited to the food industry.</td>
</tr>
<tr>
<td>ISO 9000 (2005, p. 12)</td>
<td>Lacks the predictive ability and the extent is not given.</td>
</tr>
<tr>
<td>Van der Vorst (2006, p. 33)</td>
<td>Lacks the predictive ability.</td>
</tr>
<tr>
<td>APICS dictionary (Blackstone and Cox, 2008, p. 140)</td>
<td>Lacks the trace and predictive ability, and the extent is not given.</td>
</tr>
<tr>
<td>Van Rijswijk and Frewer (2008, p. 455)</td>
<td>Lacks the predictive ability and is limited to the food industry.</td>
</tr>
</tbody>
</table>

Traceability can vary in importance in various processes and the target level of traceability, the minimum number of items an organization wants to be able to uniquely separate in the process (namely the lot size), may differ between products. Töyrylä (1999) has identified, through a literature review, five factors that affect the importance of traceability for an item and, consequently, the target level:

1. **Item value**— the value of each item, for higher value items a higher traceability cost may be accepted.

2. **Item criticality**— the probability of an item failure and the consequences that it will have on the system, workforce safety, economics, and the environment. Items with high probability of failure and where the consequences are serious require a higher level of traceability, see Figure 3.4.

3. **Length of item’s life**— a longer item life will imply that more items will be circulating in the system. Longer life length normally results in higher requirements for traceability as the items in use usually have been produced during longer production periods.

4. **Replacement cost**\(^{15}\) — the replacement cost of an item in time, money, and goodwill. Higher replacements costs require a stricter traceability target level.

\(^{15}\) Töyrylä denotes this factor as complexity of the system.
5. External environment— consumer concerns and the legal environment for the item. A high level of consumer concern and/or a strict legal environment require a more exact traceability. One example can be the food industry where consumer may be highly concerned regarding the country of origin for the product or if it contains genetically modified organisms.

Figure 3.4 An illustration of the correlation between the need for traceability and the probability and the consequences of an item failure.

An organization may use these five factors to determine a suitable target level of traceability for a product. After selecting target level, the organization needs to create the possibilities to reach the required traceability level for the item within the process. According to Moe (1998) and Furness and Osman (2003), a traceability system is required to manage traceability. I share their view, since such a system provides the possibility to store and manage the data required for traceability. Furness and Osman (2003, p. 476) define a traceability system as follows:

“A traceability system is required to provide an unambiguous, uninterrupted means of physically tracing and tracking an item, and/or its constituent components, through and between the inter-linking nodes of a supply chain. A node is distinguished as a point in the chain in which the item is handled or processed in some way”

According to this definition, the system is required to provide the means of traceability. Hence, the traceability system is the infrastructure that provides traceability within a supply chain. Similar to traceability, the system is not limited to an organization but to the whole supply chain, for the reason that it needs to provide an uninterrupted linking. To achieve consistent terminology for the definition of traceability system and traceability, the definition is modified as follows in this thesis:
“A traceability system is required to provide an unambiguous, uninterrupted means of traceability for a physical lot, its sub-components, and raw materials within the supply chain.”

The scientific literature mentions several benefits from traceability systems. Table 3.3 specifies some of the benefits that are connected to the use of a traceability system in continuous processes.

**Table 3.3.** Different benefits that may be achieved from traceability systems in continuous processes. The benefits were identified from existing traceability literature.

<table>
<thead>
<tr>
<th>Area of benefits</th>
<th>Benefits from a traceability system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Locates products on the market (Jönson, 1985).</td>
</tr>
<tr>
<td></td>
<td>- Reduces negative impacts of undesired events (Töyrylä, 1999).</td>
</tr>
<tr>
<td>Product-liability-prevention</td>
<td>- Provides logs that can be used as evidence in the event of a product liability claim (Caplan, 1990; Feigenbaum, 1991).</td>
</tr>
<tr>
<td>Quality- and process-</td>
<td>- Offers tools for identifying problems (Kendrick, 1994).</td>
</tr>
<tr>
<td>improvement</td>
<td>- Provides the possibility to trace defective products back to the prevailing conditions during manufacturing (Jönson, 1985).</td>
</tr>
<tr>
<td></td>
<td>- Makes it easier to distinguish effects of product changes (Kendrick, 1994).</td>
</tr>
<tr>
<td></td>
<td>- Enables creation of customized products and services (Töyrylä, 1999).</td>
</tr>
<tr>
<td></td>
<td>- Reduces and prevents future problems (Töyrylä, 1999).</td>
</tr>
<tr>
<td>Proof of quality and</td>
<td>- Provides product records that can be used to attain premiums or higher price, in some industries, (Jack et al., 1998).</td>
</tr>
<tr>
<td>origin</td>
<td>- Offers information showing that contractual requirements have been met (Kendrick, 1994).</td>
</tr>
<tr>
<td>Logistics</td>
<td>- Enables real time monitoring of shipments and estimations of arrival times (Ballou, 2004).</td>
</tr>
<tr>
<td></td>
<td>- Ensures that a product has gone through all the necessary manufacturing steps (Parker, 1992).</td>
</tr>
<tr>
<td></td>
<td>- Enables identification of counterfeit and illegal items (Armstrong-Smith, 1997).</td>
</tr>
<tr>
<td></td>
<td>- Prevents or reduces the number of undesired events (Töyrylä, 1999).</td>
</tr>
<tr>
<td>After-sales</td>
<td>- Provides warranty status verification (Jacobs and Mundel, 1975)</td>
</tr>
<tr>
<td></td>
<td>- Enables customized services, including additions of options and modifications (Caplan, 1990).</td>
</tr>
<tr>
<td>Accounting</td>
<td>- Assists in measuring where costs are incurred (Florence and Queree, 1993).</td>
</tr>
</tbody>
</table>

The benefits achieved from a traceability system will however depend on the design and the use of the system. According to Golan et al. (2004), the design of a traceability system can be described based on three characteristics:

1. The breadth— the amount of information about the lot the traceability system records.
2. The depth—how far up and down in the supply chain the traceability system tracks or traces the lot. The depth of the system is often determined by the breadth of the system or by the quality and safety control points in the supply chain.

3. The precision—how exactly we can track and trace a lot regarding its location and characteristics. The unit of analysis and the acceptable error rate determines the precision. The more homogenous the lot, the more precisely the traceability system can separate the deviating items (Agriculture and Agri-Food Canada, 2006).

Traceability systems are found in both part and batch production. Part production industries usually base the traceability system on item level whereas batch production industries base traceability on lot level. Steele (1995), Töyrylä (1999), and Caplan (1990) state that the design of a traceability system is determined by four elements and their view assumes that the organization already knows the required target level of traceability. Pyzdek (2003, p. 237-238) on the other hand takes a wider approach to the traceability system and includes the identification of the required traceability target level in the design step of the system. Taking this approach, Pyzdek identifies and describes ten factors that should be considered when setting up the traceability system, for example item category, item life, item cost, and the cost for a recall or a modification in the field. I prefer the former approach over Pyzdek’s, because I believe it advantageous to know the required target level of traceability for a product before considering the traceability system. The research presented in this thesis, therefore, takes the view that an organization first decides on the traceability target level and after that considers the design of the traceability system.

Steele (1995), Töyrylä (1999), and Jansen-Vullers et al. (2003) describe the four pillars connected to the design of a lot-traceability system as follows:

A. Physical lot-integrity—How large a lot of raw material is and how well the integrity of the lot is maintained will determine the resolution or precision of the traceability system. The resolution of a system is the minimum number of items that can be individually separated during the process, for example emanate from the same delivery lot.

B. Data collection—A system requires two types of data: process data that records process information, and lot-traceability data that keeps a record of the location and the merging of lots.

C. Product identification—The linking of product and process data.
D. Reporting— Retrieval of data from the system: the use of the system.

Regattieri et al. (2007) present another traceability system framework also based on four pillars: product identification; data to trace; product routing; and traceability method\(^\text{16}\). The product identification pillar contains information regarding the product, for example physical and mechanical characteristics. The data to trace pillar contain characteristics of the information that the system must handle and the required system abilities. The product routing pillar describes production activities within the supply chain, such as lead times, activities, and operations. The traceability methods pillar describes the methods that the system uses to link the correct product and process data. (Regattieri et al., 2007)

The two traceability system frameworks have much in common, but at the same time differ. Regattieri et al. (2007) have a more applied view while the other authors’ view is more theoretical. The more applied view may be easier to implement, while the other view may be more general. Hence, there are advantages and disadvantages with both views. I, therefore, have tried to combine the strengths of both views into a new and more extensive view in this thesis. A traceability system is here believed to need the following three pillars: data collection; reporting and display; and traceability methods. The data collection pillar contains information regarding the lot and process data that needs to be collected and stored by the different parties in the supply chain. The reporting and display pillar provides information on how the parties should manage data and information within the supply chain. The traceability method pillar provides information on the requirements for the traceability and can assist in the selection of the method to use for the linking of lot and process data. Figure 3.5 shows the framework and exemplifies the different components within the various blocks. The presented research focuses on traceability methods and the different traceability methods possible to use in continuous processes. Consequently, the rest of the thesis will focus on the traceability method block.

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\(^{16}\) Regattieri et al. (2007) denote this pillar as tractability’s tool.
3.2 Traceability methods

Traceability methods make it possible to keep track of a lot’s location in the process and therefore enable the correct linkage between process data and the lot data in a traceability system. Paper A and Regattieri et al. (2007) argue that a process may need to use several traceability methods to keep track of the lot’s location. The selection of method or methods suitable for use in a process demands consideration of parameters like product type, process operations, and target level of traceability. Within the examined scientific literature, no definition of traceability method or traceability tool was found. I, therefore, define a traceability method as follows:

“the method that provides the means for a traceability system to connect the correct process data to a physical lot through the whole or part of the supply chain.”

Paper A identified four traceability methods useful to achieve traceability in continuous processes.

**Off-line tracer methods:** The method implies the creation of a mathematical flow model for traceability based on residence time estimations for lots in a process section. The creation of the model often implies that chemical or radioactive tracer experiments are performed to estimate the residence time distribution in a process for various process conditions. A tracer experiment is often performed as follows: a temporary modification is made to the input of a process section and the effect of the modification is then studied in the output. For example, a researcher adds a chemical tracer momentarily to the input of a process section and

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17 Paper A originally identified five methods. These methods were later reduced to four methods by combining the chemical and radioactive tracer methods into one group: the off-line tracer methods.
then measures the concentration of the tracer in the output at various times to estimate the residence time distribution of the tracer. Paper A gives a more detailed description of the off-line tracer methods. The method has, for example, been used by Yianatos et al. (2001), Lelinski et al. (2002), Choi et al. (2004), De Andrade Lima and Hodouin (2005), and Paper B to estimate the residence time distribution in a process.

**Process data:** For some continuous processes there may exist known and repeatable changes in the raw material properties. Effects of the changes may often be visible at different positions in the process. Hence, an organization may use these changes to identify the residence time distribution in the process. Knowledge about this distribution allows the organization to keep track of the product location either continuously or through a mathematical flow model. Lundqvist and Kubulnieks (1995) and Skoglund and Denjak (2007) used process data to create traceability in a paper and pulp production plant and in a food processing plant. Paper C and Section 4.1 describe a similar approach using a flow simulation model based on ideal flows and existing process knowledge to improve traceability in an iron ore pelletizing process. Moreover, we may use data from existing product changes to determine the transition time (the time it takes for a process to react to a change) in a process. We can then use the transition time to estimate the residence time distribution. Paper F and section 4.3 describe and exemplify a method where principal component analysis and time series analysis methods are combined to estimate the transition time in a continuous process based on existing process data.

**Material signature (fingerprint):** Instead of process data, knowledge of natural variations in the material may be used. Just as all humans have unique DNA and fingerprints, other materials such as meat, grain, wood, and ore may contain unique structures. For example, in a pork chop, the exact amount and combination of chemical elements may depend on the origin, nourishment, soil, birth date, and other variables. Oghazi et al. (2009) attempt to identify and follow the material signature of iron ore by combining particle texture analysis and multivariate data analysis. Furthermore, Flodin et al. (2008) used 3-D data, x-ray data, and discriminant analysis to match planks to logs based on, for example, knot structures in a sawmill. In the food industry, a number of analytical methods have been tested for classification of food based on material signature, for a review of different incentives and analytical methods see Karoui and De Baerdemaeker (2006).

**Traceable marker (or unit):** Discontinuous processes commonly use different types of markers to mark either individual items or lots. Examples of marking techniques are paint label, stamped codes, paper or plastic label, magnetic stripe card or smart card, RFID, and microtaggant paint. Dykstra et al. (2002) give
an extensive list and description of marking techniques. Continuous processes may also use markers to create traceability. However, to equip all individual items in continuous flows is often too expensive, since the process often deals with large amounts of items and the value of each item is usually low compared to the marking cost. Furthermore, it is not possible to mark lots in continuous flows, since the continuous flow implies that there are no batches to mark. A solution is to create virtual batches, with markers acting as batch borders, so that the location of these batches may be monitored. The markers then need to behave in the same way as the product in the process flow and to be identifiable within the flow. Papers D and E describe how RFID may be used to create traceability in continuous granular flows. Kvarnström and Oja (2010) describe various RFID applications in continuous processes used to create traceability.

Paper A gives a more extensive description of the presented traceability methods and highlights the advantages and disadvantages of each method. Table 3.4 summarizes the findings presented in Paper A.

Table 3.4. A list of identified and described traceability methods with their respective advantages and disadvantages.

<table>
<thead>
<tr>
<th>Traceability method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical tracer</td>
<td>• Flexible</td>
<td>• Dilutes</td>
</tr>
<tr>
<td></td>
<td>• Easy to use</td>
<td>• Needs sampling</td>
</tr>
<tr>
<td></td>
<td>• Low-cost</td>
<td>• Based on historical data</td>
</tr>
<tr>
<td>Radioactive tracer</td>
<td>• Flexible</td>
<td>• Health hazards</td>
</tr>
<tr>
<td></td>
<td>• No sampling needed</td>
<td>• Permits required</td>
</tr>
<tr>
<td></td>
<td>• Interior flows can be measured</td>
<td>• Based on historical data</td>
</tr>
<tr>
<td>On-line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process data</td>
<td>• Easy to use</td>
<td>• Hard to find</td>
</tr>
<tr>
<td></td>
<td>• Low-cost</td>
<td>• Low precision</td>
</tr>
<tr>
<td></td>
<td>• Based on real time data</td>
<td>• Initial sampling needed</td>
</tr>
<tr>
<td>Traceable unit</td>
<td>• High precision</td>
<td>• Lower flexibility</td>
</tr>
<tr>
<td></td>
<td>• No sampling needed</td>
<td>• Cannot be used for fluids</td>
</tr>
<tr>
<td></td>
<td>• Could be used in process sections</td>
<td>• Can only be used at shorter distance</td>
</tr>
<tr>
<td></td>
<td>with both batch and continuous flows</td>
<td>• Costly to implement</td>
</tr>
<tr>
<td>Material signature</td>
<td>• Flexible</td>
<td>• Large amount of data handling</td>
</tr>
<tr>
<td></td>
<td>• Informative</td>
<td>• Time demanding</td>
</tr>
<tr>
<td></td>
<td>• High analysis precision</td>
<td>• Costly</td>
</tr>
</tbody>
</table>

3.3 Improving traceability in existing applications

The traceability target level may change for a product over time resulting in a need for the existing traceability application to be improved. Paper A presents a step-wise
model of how a new traceability target level may be reached, see Figure 3.6. The stepwise procedure includes three levels: traceability; traceability system; and traceability method. In the procedure, actions are first carried out on the system level to improve traceability and modifications are only made on the method level if these actions are insufficient. The presented model may also be used together with Figure 3.5 when designing an initial traceability application for a process.

Figure 3.6. A step-wise model of how to achieve a certain traceability target level. The figure is adapted from Paper A.
This chapter presents the development and application of traceability methods for three flow systems. Table 2.4 provides an overview of the flow systems and their characteristics. The chapter focuses on Research Aim 2.

4.1 Flow system 1: a pelletizing plant

The first investigated flow system is an iron ore pelletizing process. The flow system has the following characteristics:
- the flow of items is continuous,
- the items change state,
- the operations in the flow add a low value to the items,
- the items are subjected to reflux, and
- the flow exposes the items to an extreme environment.

Papers B and C give a more detailed description of this system. Similar flow systems are common in, for example, refinement processes of mineral ores that contains operations like crushing, grinding, flotation, magnetic separation, and gravity concentration.

4.1.1 Description of traceability application

In the research project, it was decided to investigate the possibility to use an application that combined the two traceability methods off-line tracers and process data to achieve traceability in Flow system 1. The combination of the two methods made it possible to create a flow simulation model for the studied system. Figure 4.1 describes the stepwise approach used for the creation of the flow simulation model.
within the research project. Skoglund and Demjak (2007) have used a similar approach to create traceability in a continuous process at a food processing plant.

![Diagram](image)

**Figure 4.1.** The stepwise approach used to create a simulation model for Flow 1.

The flow simulation model was based on an ideal flow assumption. The assumption implies that any material flow will range between the ideal states of perfectly mixed flow to plug flow. The one extreme, perfectly mixed flow suggests that the incoming flow to a process section propagates instantaneously through the process section. Hence, each position has exactly the same physical properties (chemistry, temperature, microstructure, particle size etc.) at any given time. The assumption of a perfectly mixed flow is often used for continuously-stirred containers. The other extreme, the plug flow state, implies that the material entering a section will maintain its properties, that no mixing will occur throughout the section, and that there is a fixed residence time for each particle in the section. The flow in tubular reactors is often approximated by assuming plug flow. For a closer description on ideal flows see Fogler (2005).

### 4.1.2 Test of application

LKAB engineers and I tested the constructed flow simulation model experimentally during a production run of a special product. The test aimed to verify the performance of the model and investigate the possibility to use the model as a decision support. Paper C gives a detailed description of the test.
4.1.3 Findings, conclusions, and discussion

The LKAB engineers argued that the flow simulation model performed satisfactorily during the test. Moreover, they experienced that the model could provide quick and accurate information and as such that it may be used as decision support.

The simulation model was originally designed to simulate a process where the process variables were constant during the simulation period. However, the process variables varied during the experimental test, and assuming constant variables resulted in an unnecessarily large simulation error. Therefore, the simulation model was modified to include logged process data in addition to the laboratory results. The model change improved the fit between the simulation output and the analysis data, see Figure 4.2 for a comparison of simulation results.

![Figure 4.2. Comparison of the fit between the analysis data of chemical content in pellets after the sintering furnace, simulation output for the initial simulation model, and simulation output for the modified simulation model. The modified simulation model was fitted to the actual buffer levels and flows in various process sections at different times, whereas the initial simulation model was based on static estimations of flows and contents using initial measurements.](image)

The flow simulation model may also be used to predict, for example, the amplitude, longevity, and whereabouts of process shifts, which is illustrated in Paper B. Furthermore, the model can be used for many different production speeds as it contains the opportunity to specify production parameters. However, several obstacles remain and need to be handled before the possibility to use the model can be fully evaluated. Firstly, the performance of the model needs to be verified for additional process settings, since it has only been tested for one setting. Secondly, the model needs to be implemented in the process and customized to fit the user...
demands. There is no doubt that more obstacles than these will be found to exist before the model may be brought into operation. However, the performed tests of the model indicate that it may be useful for creating traceability in the studied flow system. The approach may also be suitable to use in other flow systems with similar characteristics as the studied system.

4.2 Flow system 2: a distribution chain for pellets
The second flow system investigated is a distribution chain of pellets. The pellet in the distribution chain is a granular spherical product that has a diameter ranging from nine to fifteen millimeters. Moreover, the flow system has the following characteristics:

- the flow of items is both continuous and discontinuous,
- the operations in the flow add low value to the items, and
- the items in the flow are in a granular state.

Paper D and E give a more detailed description of the studied system. This type of flow system often exists in, for example, the interface between two industries. Granular products occur in industries such as the pulp and paper industry, the mining industry, and the food and dairy industry.

4.2.1 The application
In the research project it was decided to test the possibility to use the RFID method to achieve traceability in Flow system 2. RFID may be suitable for tracing granular material flows as it is durable, offers automatic identification that does not require line of sight, and provides a unique identification. For an extensive description of RFID see Finkenzeller (2003), Shepard (2005), or Lehpamer (2008). The application presented in this thesis made use of low frequency passive transponders as this transponder type offers a small transponder size with a high penetration ability. All transponders used during the research project were encapsulated within various protective casings. RFID antennas were mounted at various conveyors used to transport pellets in the distribution chain. Figure 2 illustrates how two reader antennas were mounted. The idea behind using RFID to create traceability is to use the transponders as batch markers and thereby create lots that may be tracked throughout the distribution chain.
Figure 4.3. Left: Reader 1 and 2 mounted at a conveyor used to transport pellets in the distribution chain. Right: The two reader antenna shapes and their location compared to the conveyor.

4.2.2 Test of application

Different experiments were performed to test the possibility of using the RFID method to achieve traceability in the distribution chain. The first experiments focused on a stepwise implementation and testing of an RFID system and Paper D describes these experiments in detail. Various methods to improve the performance of an RFID system were then experimentally tested and these experiments are thoroughly described in Paper E.

4.2.3 Findings, conclusions, and discussion

The performed experiments showed that it was possible to detect transponders encapsulated in casings with similar physical characteristics to the pellets in the distribution chain. However, these transponders had a low read rate (rate of transponders read by a reader) and consequently gave a low performance for the RFID system. The experiments presented in Paper E showed that the read rate may be significantly increased by using larger transponder size. Moreover, based on the experimental results, it was concluded that larger transponders could be encapsulated so they exhibited similar residence times as the pellet-like transponders’ encapsulation. The read rate for the larger transponder sizes was further increased by using two reader antennas with different locations against the material flow in the distribution chain.

RFID is a passive traceability method as it uses readings from the transponders to create traceability. Hence, the use of RFID should give a good track and trace ability or in other words a good passive traceability. However, a drawback with the use of RFID to create traceability in continuous processes is the lack of predictive ability. To achieve a high level of traceability in all three aspects of the definition, we need to complement RFID with a predictive tool, for example a mathematical
flow model. Moreover, the performed experiments highlighted some possible limitations with the use of RFID within continuous processes.

One limitation is the read range (the maximum distance at which a reader can detect a transponder). Kitayosi and Saway (2005) argue that the read range in most RFID systems ranges from three to ten meters. The read range for the RFID system used in this thesis was around three meters, and it implied that reader installations were only possible at conveyor belts in the distribution chain. Installation of readers at other positions in the distribution chain would have demanded longer read ranges. Hence, the read range limitation may hold back widespread use of RFID in continuous processes because they frequently include material flows through large production units and storage systems. Lindgren et al. (2010) describe how simulations can be used to predict read ranges for various installation positions. The results of such read range predictions can be used to determine if an installation position is suitable.

A second limitation for the use of RFID in continuous processes is the transponder sensitivity to potential environmental stresses, for example, mechanical and thermal stresses that occur within the material flow. However, the sensitivity may be reduced by encapsulating the transponder. La Rosa et al. (2007), for example, describe an application in which encapsulated transponders survived blasting and crushing. Hence, to design transponders that survive large physical stresses is already possible. I have, however, not identified any examples of RFID use in high temperature processes. Therefore, the transponder sensitivity to high temperatures may be a potential barrier to the use of RFID in continuous processes.

A third potential limitation is that the transponders may act as a contaminating factor in later process stages if not removed from the process. Therefore, when choosing and developing the transponder it is necessary to keep the whole process in mind. Kvarnström and Oja (2010) describe an example from the forestry industry in which logs were to be marked with transponders, but due to later restrictions in the supply chain the transponders were not allowed to contain plastics. However, the prior knowledge of the plastic restriction in the forestry application made it possible to design and use plastic free transponders in the application instead of the more common transponders containing plastics.

A fourth potential limitation is that there is a risk that the RFID system will affect existing process instrumentation. This problem occurred for an RFID application in a saw mill where the metal content in the transponder resulted in logs marked with a transponder being sorted out from the regular production process by the metal detector used to locate logs with high metal contents (nails). For a closer description of the problem see Kvarnström and Oja (2010). The sensitivity to the
metal in the described application shows the importance of considering all operations within a process before an RFID system is installed. Therefore, to make an RFID installation stepwise may be advisable. A stepwise installation would allow the organization to identify and solve potential problems with the RFID application as they occur, instead of having to deal with all problems at once as in the case of a full-scale installation.

A fifth limitation that may hamper the use of RFID is the transponder size. The physical size of the transponders makes it difficult to use RFID for traceability applications in processes with items in gaseous or liquid form. However, the experimental investigation in Paper E shows that transponders do not necessarily need to have the exact same physical characteristics as the item to behave similarly within the material flow. Hence, it may even be possible to use RFID transponders to achieve traceability in some processes with liquid or gaseous items.

We see that there are limitations and potential problems with the use of RFID. However, there are several examples in the literature, such as Papers A and D, that show how careful planning has made it possible to avoid these potential problems and reduce the limitations. The RFID method is still under rapid development, which is seen, for example, in the increase in research interest during recent years, see Figure 4.4. This interest should imply a continued development of the RFID method that leads to improvements in existing applications and will allow new areas of use.

![Figure 4.4.](image)

**Figure 4.4.** The number of research articles published in Scopus® containing RFID or Radio frequency identification in the title, abstract, or keyword each year during the period 1993-2009. Before 1993 only two articles containing the terms was found in Scopus®. The search in Scopus® was made on 14 October 2010.
4.3 Flow system 3: a blast furnace process

The third flow system investigated is a blast furnace process. The studied system has the following characteristics: the flow of items is continuous, the items change state, and the flow system exposes the items to an extreme environment, in this case a high temperature. Paper F and Vanhatalo (2009) give a more detailed description of the studied blast furnace. This type of flow systems often exists in, for example, paper and pulp mills and smelting plants.

4.3.1 The application

In the research project it was decided to test if the transition time in the blast furnace process could be decided by combining multivariate data analysis and time series analysis methods. It is then possible to use the resulting transition time model to create a mathematical model for the material flow, which may be used to achieve traceability. Figure 4.3 illustrates the framework for the combination of the two methods. Appendix A and Paper F provide a description of the multivariate data and times series analysis methods used.

![Figure 4.5](image)

**Figure 4.5.** The framework presented in Paper F to identify the transition time for a process.

4.3.2 Test of application

Two historical data sets from the blast furnace were used to test the appropriateness of combining multivariate data and time series analysis methods to determine the transition time. The first data set was taken from an experiment in which the oxygen content in the blast air was changed, and the second data set was taken from an experiment in which the incoming raw material to the blast furnace was changed.
4.3.3 Findings, conclusions, and discussion

Paper F showed that the multivariate data analysis and times series analysis methods may be combined to determine the transition time for changes in a blast furnace. At first, we reduced the number of response variables in the output data with principal component analysis (a multivariate data analysis method). The principal components extracted from the original response variables were then compared to the input data to identify potential correlation between the input and the output. Finally, we modeled the dependency between the input and the output signal using either a transfer function-noise model or intervention model (two time series analysis methods) depending on the type of input signal. The procedure resulted in a mathematical model for the transition in the process. The transition model may now be used to estimate the residence time distribution of material within the blast furnace. Knowing this distribution, a material flow model may be created and this model can be used to achieve traceability. A complete description of the procedure is presented in Paper F.

One advantage with the procedure in Paper F is the predictive ability of the resulting model. There are also drawbacks with the procedure. For example, the developed model is restricted to the studied input variable and to the production conditions under which the model was developed. Hence, the model input needs to be selected carefully. Several different production conditions should preferably be used to develop a model for the transition time.

Paper F analyzed two different types of inputs from a single process for similar production conditions, and found completely different transition times and patterns for the two inputs. Hence, for the model to be useful the correct type of variable needs to be studied. For example, if a direct change in a process variable, like the change of oxygen level in Paper F, is studied instead of a product variable the resulting transition model will probably not be useful as a traceability tool. Instead, the model may be useful for process control purposes.

The paper also examined if we can assume the transition time to be stable over time for an input during similar production conditions. This study showed that the transition time may be comparable over time.

In summary, the presented procedure may be useful to create transition time models that can be used to achieve traceability in continuous processes. However, the production setting during which the data is collected and the variable to use in the analysis when constructing the model need to be selected carefully.
CONCLUSIONS, DISCUSSION, AND FUTURE RESEARCH

This chapter discusses the research findings. The chapter also discusses the theoretical and the practical contribution of the research. Some reflections on the research process are then given and the chapter ends with proposals for future research.

5.1 Conclusions and recommendations

The first aim of the research presented in this thesis was to explore and describe how different traceability concepts are related. The research showed that several definitions of traceability exist in the scientific literature as well as various traceability concepts. However, no literature that discusses these definitions and the relation between the concepts was found during the research project. The research, therefore, explores the existing scientific literature and presents a theoretical framework for traceability based on that literature. This framework discusses and defines the concepts traceability, traceability system, and traceability methods based on previous definitions. Furthermore, Paper A and Chapter 3 describe and discuss suitable traceability methods to use in continuous processes as well as the advantages and disadvantages of each method. The research also illustrates how process characteristics differ between continuous processes and between process sections. Therefore, the preferable traceability method to use varies between processes, and more than one method may be needed in a process.

The second aim of the presented research was to explore, describe, and explain how continuous process industries may achieve traceability in various flow systems. The research investigated the possibility to achieve traceability in three flow systems. The three systems differ regarding the characteristics complicating traceability (see Table 2.4). However, together the three studied flow systems cover all the characteristics given in Table 1.1.
An ideal flow simulation model based on input from chemical tracer and process data may be used to achieve traceability within flow systems similar to the pelletizing process. The flow simulation approach makes it possible to estimate the location of a lot and to predict its future location. However, the approach is based on historical data and relations and needs to be occasionally verified to secure that it reflects the real material flow. Papers B and C explore, describe, and explain how a flow simulation model may be created.

The RFID marker method makes it possible to divide a continuous flow into lots, and each lot can then be traced and tracked to create traceability. This approach may be suitable for continuous processes similar to the distribution chain of pellets. The RFID method gives exact information about when transponders pass a reader and consequently a good track and trace ability (that is a good passive traceability). However, the RFID method needs to be complemented by, for example, a mathematical model for the flow of the lot to achieve the ability to predict the lot’s location in the future. Papers D and E explore, describe, and explain a possible design of an RFID application to achieve traceability.

Analyzing process data from a product change in a blast furnace with multivariate data and time series analysis methods makes it possible to construct a mathematical model of the transition time in the process. The transition model may then be useful for prediction of the lot location in the process at different times. The presented approach also provides the possibility to estimate and predict the location of a lot in a process. Like the flow simulation model, the constructed mathematical model should be occasionally verified to ensure that it truly reflects the actual transition time. Paper F explores and describes the analysis procedure that combines the two methods.

The research demonstrates possible traceability applications for all the studied flow systems. All the applied traceability methods are found among the methods presented in Paper A. Hence, the findings do not indicate any need for development of additional traceability methods to achieve traceability in the studied continuous processes. Moreover, for the studied systems, the identified traceability methods were able to handle several of the characteristics from Table 1.1 at once. Table 5.1 gives a rough suggestion of the identified characteristics that each traceability method may be able to handle. We see in Table 5.1 that all characteristics can be dealt with by at least one traceability method. However, at least one characteristic is problematic for every method. The fact that no method was indicated in Table 5.1 to have a problem with the continuous flow depends on that this characteristic was a prerequisite when identifying suitable traceability methods. Hence, Table 5.1 may be misleading as the continuous flow is probably one of the main problems when
trying to achieve traceability. Moreover, the mixture of continuous and non-continuous flows, reflux of material, and segregation seems to be the characteristics that cause problems for most of the identified traceability methods.

Table 5.1 Illustration of the characteristics which complicate traceability in the continuous processes that each traceability method may deal with. X indicates that the method may deal with processes that contain the specific characteristic and a blank field signifies that this characteristic may be problematic for the method.

<table>
<thead>
<tr>
<th>Traceability method</th>
<th>Continuous flow</th>
<th>Product may change state</th>
<th>Low added value to the product within the process</th>
<th>Mixture of continuous and non-continuous flows</th>
<th>Reflux of material</th>
<th>Extreme environment</th>
<th>Segregation</th>
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<td>Material signature</td>
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</table>

5.2 Research implications

The research implications of the results presented in this thesis are essentially connected to two areas, traceability in general and to problems with traceability in continuous processes.

The first implication is related to the lack of a common theoretical foundation for traceability in the scientific literature. This literature contains various traceability concepts, but no common definition of the concepts or description of the relation between them. The theoretical framework for traceability proposed in Chapter 3 can, therefore, be a first step towards the formation of a general theory about traceability. The presented framework focuses on the predictive ability within traceability in contrast to much of the existing traceability literature.

The second theoretical implication is related to the description and discussion of traceability methods from a continuous process perspective. To my knowledge
this has not been done before. The description of traceability in continuous processes presented in this thesis may therefore support the theoretical research on traceability in continuous processes as it provides guidelines about the advantages and disadvantages of various traceability methods.

5.3 Industrial implications

This section describes some practical implications of the research for industries with continuous processes in general and for the organizations that participated in the research project in particular.

Chapter 3 and Paper A present a list of traceability methods suitable for use in continuous processes and a mind-map of how to reach the traceability target level. The list describes the advantages and disadvantages of each method and it may therefore aid continuous process industries to select a suitable method when working with traceability. The mind-map can then guide them regarding the actions that need to be executed to reach the traceability target level.

Continuous process industries often have complex production processes, which may complicate traceability and prediction of the effect from process changes on product quality. A simulation model based on flow assumption, similar to the one presented in Papers B and C, may reduce these problems, since it can simulate the location of the lot at various times and the effects of process changes. There are many descriptions of simulation models in the literature. However, most of these simulation models only cover individual production steps. A reason for this can be that the models often use complex algorithms and, therefore, need to be limited to a process section to avoid impractical simulation times. However, the use of simplified material flow assumptions may allow simulations that cover several process sections. The two ideas may complement each other, as information from the complex simulation models may be used to fine-tune the models with more simplified flow assumptions. In some cases, it may be essential to simulate several process steps simultaneously to attain the desired information. For example, a simultaneous simulation of several process steps was necessary for the production of special product at LKAB described in Paper C. In this case, a flow simulation model based on ideal flow assumptions made such simulations possible.

The presented research shows that the RFID technique may be used in an environment previously seen as problematic for the technique, due to the high metal content and the high physical pressures. Hence, the RFID applications presented may open doors for additional applications in similar flow systems. The identified ways to improve the performance of an RFID system in Paper E may be used by other organizations and RFID suppliers to improve existing systems.
Furthermore, by using transponders with different physical characteristics segregation mechanisms in granular flows may be studied. Segregation studies should provide knowledge of, for example, how various storage levels affect the segregation and if it can be reduced. According to the equipment suppliers (Electrotech), they received valuable information from the installation and testing of the RFID application during the research project. Electrotech gained, for example, knowledge of how to increase the robustness of their equipment and how to improve the read rate for an application.

The combination of time series and multivariate data analysis methods offers organizations a tool to analyze time series data from multiple variables simultaneously. Apart from getting input for a traceability model, the method can be useful to determine transition times in processes. Knowledge about the transition time may aid an organization to, for example, decide on run length for an experiment and design control strategies for a process. Hence, the method has the potential to provide an organization with information that may contribute to improved experimentation and process control.

5.4 Reflections on the research process

The use of multiple data collection methods when exploring the traceability in continuous processes should have improved the research validity, since none of the methods on its own covered all the findings. However, apart from the literature search the used methods were limited to Swedish industries. This delimitation on Sweden probably resulted in initiatives in other parts of the world being missed. To broaden the scope of, for example, the interviews to encompass other parts of the world would have reduced this risk. However, additional interviews would have had to be performed at the cost of studying fewer traceability applications, because of time constraints. I decided to study more applications instead of performing interviews with companies in other countries, since such interviews were believed to be time consuming and to give only minor additional findings.

The research concerning traceability applications in continuous processes focused on processes in one organization (LKAB). This resulted in a deep understanding of the studied organization and its processes. Moreover, the selected approach illustrated that different traceability methods had to be used within an organization to achieve traceability throughout their processes. However, the focus on one organization resulted in findings that cannot be transferred to other organizations with continuous processes without reflection. Nevertheless, to study several organizations (at the same time) would, in my opinion, have been at the expense of a deeper level of understanding. Therefore, it needs to be noticed that
the performed research relies on analytical generalization. I do believe that most of
the findings regarding the application of the traceability methods should be relevant
for other organizations with continuous processes, as the processes, studied within
this thesis, together contained all the characteristics that complicate traceability in
continuous processes. However, to have studied additional organizations may have
resulted in the discovery of new characteristics complicating traceability. Furthermore,
when applying the methods in other processes new restrictions for the
methods might have been discovered. Nevertheless, the examined literature does
support the identified characteristics for continuous processes and the identified
restrictions for the studied traceability methods.

Papers C, E, and F used time series of process data gathered from LKAB’s
operation system for analysis. Neither I nor the other authors of the papers had the
possibility to check all the measurement equipment, due to limited knowledge and
time constraints. Therefore, the data sets may contain measurement errors and did
contain missing data. No correction of measurement errors was made in Papers C
and F. In Paper F, the measurement errors should not have affected the result as the
original variables were combined into principal components while measurement
errors are assumed to be part of the remaining unexplained noise. For Paper C, the
measurement errors may have affected the result in that they gave an increased
difference between the simulation model and the actual process outcome. Hence,
the performance of the model in Paper C may have been underestimated due to
measurement errors. In Paper E, the collected data was studied for potential outliers
that may have arisen due to measurement errors. The identified outliers were
examined and excluded from the data if an assignable cause was found or otherwise
analyzed with care. Hence, this procedure should result in a limited effect from
potential measurement errors on the results in Paper E. The examined times series in
Paper F contained a few missing data points and these points were estimated
through linear interpolation. However, the missing data should not have affected the
results, since only a few values were missing and had to be estimated. The time
series used in Papers C and E did not contain any missing data. Hence, the described
measures should imply that the effects of measurement errors and missing data can
be considered to have a limited effect on the presented results and conclusions.

5.5 Future research
A natural continuation of the research would be to study how to achieve traceability
in flow systems from other organizations with continuous processes. This would be
a way to strengthen the external validity of the performed research, as all the studied
systems in this research project come from an iron ore refinement process.
Another natural extension of the research would be to continue to study the presented traceability methods in various settings. Such a study could contribute to the identification of additional weaknesses with the methods and discoveries of remedies for the weaknesses. One example could be to study techniques to increase the read range for RFID applications. These studies may, for example, study the possibility to design a filter that reduces the needed signal to noise ratio for reading a transponder or the use of RFID based on surface acoustic waves (SAW). An increase in the read range would open new applications areas and may also improve the performance for existing RFID systems. Furthermore, the illustration of the possibility to use RFID to achieve traceability in the pellets distribution chain has resulted in ideas for future studies and applications. One idea is to combine RFID transponders with gauges for measuring physical stresses, which would make it possible to perform in situ measurements of stresses in a flow system. The RFID application for achieving traceability presented in this thesis has not yet been implemented. Therefore, a possible continuation of the research can be to study the implementation of this application. A study of an RFID implementation for traceability in continuous processes would be interesting, since no such study was found in the literature examined within this thesis. The implementation study could provide knowledge of critical success factors and pitfalls regarding implementation of traceability applications based on RFID for continuous processes.

The performed research has proposed a theory for traceability based on existing literature. However, the development was made from a continuous process perspective. Therefore, a possible continuation of the research could be to study traceability with a wider approach including discontinuous and service industries.

The extent of the presented traceability definition is the supply chain. However, a commonly used notation in the scientific literature is product life cycle assessment, which is the investigation and evaluation of the environmental impacts of a product or service throughout its lifetime. A possible research continuation can be to study the benefits of widening the traceability extent to encompass the whole product life cycle and not just the supply chain.
APPENDIX A: MULTIVARIATE DATA AND TIMES SERIES ANALYSIS METHODS

Appendix A presents the multivariate data and times series analysis methods used to estimate the transition time in Flow system 3 the blast furnace.

Multivariate data analysis

Multivariate data analysis methods consist of statistical methods designed to analyze data that arise from more than one variable. Paper F makes use of the principal component analysis (PCA) method. Johnson and Wichern (2002, p. 426) describe PCA as a method “concerned with explaining the variance–covariance structure of a set of variables through a few linear combinations of these variables” and the main objective of the method is to reduce dimensionality in the response space and interpretation. The method reduces dimensionality by extracting new, latent, uncorrelated variables called principal components (linear combination of the original variables) that together explain the main variability in the data. The extracted principal components are orthogonal to each other and ordered according to their variance. The underlying assumption is that the first few principal components, with larger associated variances, represent interesting signals in the data, while the higher order principal components are only related to the noise. The PCA method works as follows, let $\mathbf{Y}$ denote the $n \times m$ matrix with $n$ observations of each of the $m$ responses. Then if only $A$ first principal components are used to approximate the variability in $\mathbf{Y}$, it follows that:

$$\mathbf{Y} = \mathbf{T}\mathbf{P}' = \sum_{a=1}^{A} \mathbf{t}_a \mathbf{p}_a' + \mathbf{E}$$  \hspace{1cm} (1)

where $\mathbf{T}$ is an $n \times m$ matrix with the score vectors $\mathbf{t}_a$, $a=1,2,\ldots,A$, as rows, $\mathbf{P}'$ is an $m \times m$ matrix with the loading vectors $\mathbf{p}_a$ as columns, and the variability in the remaining $m-A$ principal components is summed up in the residual matrix $\mathbf{E}$. 


There are several methods to use to select $A$, that is the number of principal components used to model the response space. We may for example choose $A$ so that $A$ principal components at least reproduce a specific fraction of the variance in the original responses. For a further description of PCA and more methods to choose $A$, see, for example, Johnson and Wichern (2002, Chapter 8) and Jackson (2003).

**Time series analysis**

Time series analysis methods consist of tools to model and analyze time series. Box et al. (2008, p. 11) describe a time series as a sequence of observations taken sequentially in time. Paper F makes use of the times series methods transfer function-noise models and intervention analysis. These two methods make it possible to estimate the relationship between one or more time series inputs ($x_i$) and the time series output ($y_i$) of interest, where $i$ denotes the specific time series and $t$ denotes the observation number in the times series. Paper F only deals with single input time series and the thesis therefore only discusses the single input models. A large difference between transfer function-noise models and intervention analysis is the assumption of the input variable, $x_i$. The transfer function-noise models assume a quantitative input variable, while intervention analysis may deal with a qualitative input variable. Moreover, using intervention analysis, we need to postulate a model for the transfer function. However, for the transfer function-noise model, no assumption regarding the transition is needed.

A transfer function-noise model can be expressed as:

$$y_i = \frac{\phi(B)}{\delta(B)} x_{i-a} + \frac{\Theta(B)}{\Phi(B)(1-B)^d} \varepsilon_i$$  \hspace{1cm} (2)

where $B$ is the backshift operator on $t$, $\phi(B) = \phi_0 - \phi_1 B - \ldots - \phi_p B^p$ and $\delta(B) = \delta_0 - \delta_1 B - \ldots - \delta_q B^q$ determines the structure of the transfer function, $b$ is the 'pure delay' before $x_i$ starts to affect $y_i$, and $\Phi(B) = (1- \phi_1 B - \ldots - \phi_p B^p)$, $\Theta(B) = (1-B)^d$, $\varepsilon_i$ is the autoregressive moving average model, ARIMA($p,d,q$), for the unobservable zero mean noise. For a thorough description of transfer function-noise modeling see, for example, Jenkins (1979), Wei (2006, Chapter 14), Bisgaard and Kulahci (2006), Box et al. (2008, Chapter 11-12), and Montgomery et al. (2008, Chapter 6).

An intervention model can be expressed as:

$$y_i = \frac{\phi(B)}{\delta(B)} \xi_{s-a} + \frac{\Theta(B)}{\Phi(B)(1-B)^d} \varepsilon_i$$  \hspace{1cm} (3)

where $\xi_{s-a}$ is a binary deterministic indicator variable with value 0 for nonoccurrence and with value 1 for the occurrence of the event. For a closer
description of the intervention noise model see, for example, Jenkins (1979), Wei (2006, Chapter 10), and Box et al. (2008, Chapter 13).
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Methods for Traceability in Continuous Processes
- Experience from an Iron Ore Refinement Process

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Abstract: Every production process is exposed to disturbances leading to production of defective products. The disturbances are seldom immediately discovered, and need to be traced afterwards. Traceability, or the ability to follow a product through the process, is therefore vital since it aids the localisation of the source of the disturbance. Traceability has for a long time been a possibility in part production, but in the continuous process industry it is still problematic. Examples of problems are complex flows, closed systems and large buffers. Hence, the purpose of this paper is to describe methods that can be used to achieve traceability in continuous processes, and give an example of when they may be applied. To identify suitable traceability methods, a literature search was conducted as well as discussions with researchers from the process industry. How the methods work is presented together with their advantages and disadvantages. Furthermore, an example of which traceability methods could be used for achieving traceability in a continuous iron ore refinement process is given. Seeing the diversity of available methods, achieving traceability in continuous processes should be possible.

Keywords: Residence time distribution, iron ores, ore mineralogy, RFID

1. Introduction

An announcement of a product recall of about 90,000 locomotive toys was issued in September 2007 by Fisher-Price (U.S. Consumer Product Safety Commission). Product recall announcements like the mentioned one are issued daily by companies around the world and most consumer product stores handle product reclamations daily. This exemplifies that defective products and product deviations are not always identified directly, even if this is desirable. Instead the causes often need to be traced back through the process from customer complaints. The ability to trace a specific product during the process, usually called traceability, is consequently important for identification and elimination of causes of product deviations. Other benefits of traceability are that it minimises the extent of product recalls and ensures lot uniformity in products (Juran & Gryna, 1980). Furthermore, traceability can be used to identify causes of positive changes in product characteristics.

Traceability is common in part production and often easy to achieve, since various kinds of identification markers can be attached to a unit. Moreover, the literature about traceability is
dominated by applications in part production. However, creating traceability in continuous processes implies vast challenges: process flows can be parallel, serial and reflux; sub processes can be continuous as well as batch-wise; large buffers: no interruptions in product handling. These challenges imply that other types of traceability methods are needed for creating traceability. To understand more easily how these traceability methods can be applied, the authors consider that an example is appropriate. A suitable continuous process for exemplifying how various methods could be used was found in the iron ore mining industry, and the refinement of iron ore to iron ore pellets (the process is described in Section 5). The reason for choosing the iron ore refinement process is that all the special challenges connected to continuous process industries are present in this process. Therefore, the purpose of the article is to compose and describe different traceability methods that can be used for achieving traceability in continuous processes, and to illustrate how a method for traceability may be selected from the characteristics of a process section. The refinement process of iron ore starts in the mines. However, in this paper only the methods for achieving traceability from the concentrator plants to the final customer are discussed.

2. Research Methodology

This article is a result of extensive collaboration between the authors and the Swedish mining company LKAB. This collaboration focused on traceability and traceability methods in continuous processes. As a part of this collaboration, an iterative literature search was conducted aiming at identifying traceability methods. An initial literature search was performed in the databases Compendex, Emerald and ScienceDirect.

Most of the articles found were primarily related to other subject fields than traceability methods in continuous processes. However, from the related articles and discussions among the authors, colleagues and researchers at LKAB, new search strings, such as residence time distribution (RTD), trace elements, mineralogical signature and radio frequency identification (RFID), were identified. The second literature search together with the initial one led to the identification of the traceability methods described in this paper. The identified methods are described in Section 4, and each description includes a brief explanation of advantages, disadvantages, and examples of application. A conclusion from the literature search is that literature on traceability methods in continuous processes is rare and scattered in a diversity of research fields.

3. Theoretical Framework

3.1 Traceability

In this paper three terms for traceability with distinguishing aims will be consistently used: traceability, traceability system, and traceability methods.
Traceability is here defined as “the ability to preserve and access the identity and attributes of a physical supply chain’s objects” (Töyrylä, 1999, p. 38). Traceability is not binary but continuous and always present at some level. This means that it is possible to differentiate between what year, week, or day a product was manufactured.

Traceability system is defined as the system that enables traceability in a process by combining process information with models of material flow in the production process. According to Steele (1995), Töyrylä (1999) and Jansen-Vullers et al. (2003), there are four elements connected to the design of a lot-tracing system:

1. **Physical lot-integrity** - How large a batch of raw material is and how well the integrity of the batch is maintained will determine the resolution or precision of the traceability system. The resolution of a system is the minimum number of units that cannot be individually separated during the process, and for example emanate from the same delivery batch.
2. **Data collection** - Two types of data are needed: process data that records process information, and lot-tracing data that keeps a record of movement and merging of batches.
3. **Product identification** - The linking of product and process data.
4. **Reporting** - Retrieval of data from the system, the actual use of the system.

The most important element is physical lot-integrity, since it determines the maximal resolution of a traceability system. The physical lot-integrity for a process is affected by three elements: lot mismatching, lot-end-mixing and lot-sequence mixing (Steele, 1995). Lot mismatching occurs when a new batch is created and the size of the batch does not match the original one, for example when numbers of units simultaneously treated in two process steps differ. Lot-end-mixing arises if lots are processed in repetitive or continuous batches and the organisation fails to retain clear separation between batches, for example when products from parallel process steps with different cycle times are merged. Lot-sequence mixing takes place if the traceability system depends on the first-in—first-out principle and the process fails to pursue this principle, for example when all the rework is conducted at the end of a shift. The physical lot-integrity element is also the element that is primarily affected by the differences in continuous production and part production, since batches are usually not present in a continuous process. The traceability systems used for achieving traceability in part production should also be useful for achieving traceability in continuous production, since it is only the methods for creating the models of material flow that differ.

A traceability method, the third term, is defined as a method that can be used for creating models for material flow in process sections. The same traceability method is rarely suitable to use during the process, because of changes in material properties and various operations in process stages. Therefore, suitable traceability methods need to be identified for different process sections, and the material flow, consequently, needs to be modelled stepwise.
The traceability methods that are applied in part production processes can seldom be used in
continuous processes, due to the mentioned differences.

The relations between the three terms may be described according to the following
criteria: Models for material flow in process sections are constructed with traceability methods.
The different material flow models for the process sections are then combined by the
traceability system to achieve traceability through the process.

The precision of traceability in a process is therefore dependent on the traceability
system, which in turn relies on the models created by the traceability method. A mind-map of
how the terms are related and affected by one another is shown in Figure 1.

Figure 1. A mind-map of how a sufficient level of traceability can be reached in a production process.

3.2 Continuous process

In a continuous process, the products are gradually and with minimal interruptions refined
through a series of operations (Fransoo & Rutten, 1994; Dennis & Meridith, 2000). Therefore,
there are no natural product lots in a continuous process. The raw material in a continuous
process typically comes directly from the natural environment, for instance mines and forests
(Fransso & Rutten, 1994; Hild et al., 2000). In contrast to the raw material in part production,
it is usually not processed. Therefore, the raw material in a continuous process is usually
afflicted with a larger variation than the raw material in part production (Fransso & Rutten,
1994; Hild et al., 2000). To minimise the influence of the natural variation in the raw material
on the product and avoid interruptions in the production process, large mixing buffers are usually used during the process. Furthermore, reflux flows are common in continuous processes and often necessary for attaining an even and desired output from a process section. The physical characteristics of the material are often changed during the refinement process, which also makes it difficult to define a unit of measure (Fransso & Rutten, 1994). Finally, the added value in continuous processes is usually quite low (ibid).

4. Description of Traceability Methods

Traceability systems are usually based on daily observations or mathematical models. The mathematical models are created from measurements of how the material flow is affected by different process parameters. The traceability methods may be classified according to what type of model they create. Traceability methods creating mathematical models are here categorised as off-line methods. In contrast, traceability methods creating models based on daily observations are classified as online methods. Off-line methods are used during a shorter period of time, in contrast to online methods, which are used repetitively. All online methods can be used as off-line methods, but the other way around is seldom possible. Figure 2 shows a summary of the traceability methods presented in this paper.

All the methods presented are also useful in other types of industries than continuous process industries. However, it is not always necessary to use complicated methods for achieving traceability in continuous processes. An example of such a case is production in a single line with no reflux flows and no buffers.

4.1 Off-line methods (tracer methods)

Off-line methods aim at measuring the time a product/molecule/atom stays in a process section, the residence time, with experiments, and from the collected data creating models of the material flow. But, since some products/molecules/atoms exit faster and some stay longer in the process section, the residence time will vary. Therefore, to describe the behaviour of a flow in a process section, the residence time distribution (RTD) can be estimated. The RTD for a process section is usually estimated by making a change in the input to a process section and measuring the effect of the change in the effluent flow at different times. Usually the
change in input is made by adding a tracer substance. Commonly used addition techniques are impulse, step, square pulse, ramp, sinusoid and random variations (de Andrade Lima & Hodouin, 2005). An addition technique with small width and high altitude is preferable, since it offers the possibility to recover high-frequency response (Wen & Fan, 1975). The different flows and volumes in the process section also need to be measured when constructing a mathematical model of the RTD. How well the modelled RTD conforms to the real RTD depends on the number of experiments, the precision of each experiment and the selection of parameters used for the mathematical model.

Furthermore, not all particle types in a process necessarily have the same RTD. For example, in iron ore processing, the valuable iron minerals typically have higher densities than the gangue minerals (the undesirable minerals). The difference in densities leads to preferential grinding and enrichment steps. In addition, the minerals have varying particle size distribution, leading to both enhanced separation and selectivity problems. Moreover, materials with different physical forms may be present in a material flow, for example solid and fluid, which results in additional separation. Therefore, it is crucial to carefully select tracers with flow properties that resemble the particle type studied to attain a correct model.

With an RTD model the fraction of input exiting at different times is possible to calculate, and the model can hence be used for achieving traceability through a process section.

Which tracer substance is used for an experiment depends on the process examined and on the methods used for studying the material flow. Examples of different methods for studying and investigating the RTD of particles are chemical tracer, radioactive tracer, visual observations, photography, laser beam, playback videotaping and magnetic response (Ramaswamy et al., 1995). Chemical tracer and radioactive tracer are the most commonly used methods in the literature studied. These two methods are therefore described below in more detail.

4.1.1 Chemical tracer

One way to identify the RTD in a system is to add a chemical compound to the input and measure the concentration in the effluent flow as a function of time. Numerous chemical compounds are available for estimation of RTD. Furthermore, only an element of the compound may be of interest if the compound dissolves in the material flow. The applied tracer should be a compound that is accurately and easily detectable, has similar physical properties as the studied solid/fluid stream, acts like the studied solid/fluid stream in contact with other surfaces in the process, and, if a fluid is studied, also is completely soluble (Wen & Fan, 1975; Fogler, 2006). In addition, it is important that the tracer does not affect the process or product and it should preferably not be naturally occurring in the process. Before the addition of the tracer, it is necessary to have information about the background variation of the tracer compound or element in the process, the analytical detection limit and the amount of
material in the studied process section. This information makes it possible to calculate the minimum amount of compound that should be added.

There are several advantages to the chemical tracer method. It is flexible, since various trace compounds are available. This flexibility implies that the method may be used for processes with gas, fluids, solids and slurry, and in almost any environment. Moreover, special permits are often not required, in contrast to the radioactive tracer method. Hence, the chemical trace method is usually easier to apply.

Disadvantages include for example that the method quickly becomes costly for larger systems, if combined with expensive tracers and expensive analysis methods, since more samples need to be analysed and an increased amount of tracer needs to be added. The amount of tracer added needs to be increased since the tracer often mixes with the material flow. Hence, when using chemical tracers, the RTD is often estimated stepwise for the material flow in the process. Furthermore, it might be problematic to take representative samples in continuous flows. Such an example is sampling of crude ore in mines (Wills & Napier-Munn, 2006). Using non-representative samples severely affects the reliability of the final model. Finally, analysis of output is seldom possible to perform in real time. The result therefore depends on how well the sampling strategy suits the material flow. However, a few online gauges have become available, such as optic, electric conductive and fluorescence analyses (Hu & Kadri, 1999).

4.1.2 Radioactive tracer

Another way to estimate the RTD is to use a radioactive tracer. The radioactive tracer method implies that a part of the actual flow is radioactively charged or that radioactive particles are added to the input. RTD is then estimated by measuring the output, which typically is done continuously with a Geiger counter. The choice of radioactive element depends on the material being traced, the duration of the experiment and the detection method (Lelinski et al., 2002).

There are many advantages to the radioactive tracer method. Measurements may, for example, be performed in real time at various points (Yianatos & Bergh, 1992). Since no sampling needs to be carried out, it is also possible to measure at several locations in a process simultaneously and also interior flow patterns in, for example, reactors. The method is also adaptable to different types of material streams, and can thus be used for analysing flows in most environments.

The major concern with the tracer method is the health hazards linked to the usage and the disposal of radioactive material (Ramaswamy et al., 1995). Consequently, the method usually requires special permits and it is also necessary to ensure that safety regulations are followed. Therefore, the method often demands large resources in the form of time and money.
The radioactive tracer method is often used when other tracer methods are inadequate or when interior flow is of special interest, for example localisation of zones in mixers with poor mixing.

4.2 Online methods

Online methods often demand longer preparation and implementation times, compared to off-line methods, since they normally need to be individually suited for the specific process. Therefore, online methods are usually more expensive. However, the continuous measurement often results in more accurate estimations of RTD, since the estimation is usually based on more data. Consequently, online methods are preferable to use. The final model is also less sensitive to process modifications, since it is possible to continually verify and update the model. The online methods described here are the methods that were identified during the literature studies.

4.2.1 Material signature

In many production processes, it is almost impossible to obtain identical raw materials. Such an example is that in a pork chop, the exact amount and combination of chemical elements will depend on the origin, nourishment, soil, birth date and other variables. Hence, almost all pork chops are unique, since they will differ from one another in some of the mentioned factors. Another way to achieve traceability would be to identify unique signatures or structures in a product. The signature does not need to be unique to individual products; it may instead be unique to a group of products. How small the group must be depends on the demanded precision of the traceability system. Examples of signatures that could be used are fibre length in wood, natural variability in raw material, and variation in chemical composition deriving from differences in background. To find material signature or “fingerprint” it is necessary to carefully sample and analyse the process flow. The analysis methods used depend on the type of production and the signature sought for. This method is suitable to use when the material is constantly changing shape or when materials with different properties are mixed, which often is the case in the mineral industry.

For mineral materials, textural properties such as grain boundaries and shape depend on the ore body from which the mineral is extracted, and how they are located in the ore body. In the past, mineralogical studies were made manually by using techniques depending on the skill of the human (Henly, 1992). Today automated mineralogical techniques have been developed and become common in mineral industries (ibid).

Mineralogy of iron ore can be determined by using information from analyses such as X-ray diffraction methods (XRD), optical image analysis and scanning electron measurement techniques (Donskoi et al., 2006). To examine complex mineralogy, which is difficult to identify by optical analysis, it is advantageous to use a system that can give information about the mineralogy comprehensively and quickly. Particle Texture Analysis (PTA) is a system that
can be used to analyse this kind of sample. The PTA software gives plots and thumbnail images regarding mineral liberation, mineral association analysis and intergrowth analysis; for a comprehensive description of PTA, see Moen (2007).

One benefit of PTA is that it shows how the gangue minerals are distributed over the fractions and how the gangue minerals behave. Another advantage of the mineralogical signature method is that the signature is always the same in the processes, although the shape of the material is changing. One concern is the cost and the time required for each sample to be investigated. However, the method is still new and may be further improved in the future.

4.2.2 Process data

In many production processes, the differences in the raw material result in process data variation. Hence, instead of material signature, variability in process data could be monitored.

Lundqvist & Kubulnieks (1995) created traceability in a paper and pulp production plant using process data. Traceability was possible to create by comparing the appearance time and forms of deviations in kappa number (a measure indicating the bleach ability of wood pulp) and brightness (a measure of how much light is reflected) at different points in the process. From these comparisons, the RTD for process sections could be estimated, verified, and modelled.

The kappa number and brightness are two product parameters that are continuously measured during the process. Furthermore, the value of kappa number and brightness is often changed by the same absolute value in a process section or not changed at all. If a parameter with similar characteristics as the kappa number and brightness is present in a process, it can be used for achieving traceability.

One advantage of using process data is that the measurement tool usually already exists, and hence no further investments are needed. Furthermore, much data is directly available, since data from the measured points already has been gathered.

However, it may be difficult or even impossible to identify suitable variables to use for the estimation. In addition, the variable must display significant alterations over time; otherwise the RTD cannot be estimated by comparing the data for the variables.

4.2.3 Traceable unit

In part production, different batch structures are often used to achieve traceability. Batches do not usually exist in continuous processes, so using batch structures for achieving traceability is difficult. Creating virtual batches by dropping some type of marker in the material flow with regular intervals would, however, make it possible to use the batch technique for achieving traceability. The markers then act like imaginary start and end points of the different batches. Recording passage times of the markers along the process would then make it possible to trace a specific batch during the process. To achieve a genuine model, the marker must behave as the material in the material flow. Each marker should preferably be unique, so that the
potential mixture in the flow can be modelled. The precision with which a product can be traced is determined by the interval between the markers.

Radio frequency identification (RFID) is one technique that could be applied. The technique offers the possibility to create a traceable marker, by using tags with unique identification numbers. RFID is commonly used for tracing goods in the manufacturing industry. This method is applied today for achieving traceability by some retailers, manufacturers, and health care and pharmaceutical industries (Li et al., 2006). The method has also been used for coal tracking (Lauf); see Wyld (2006) for more on RFID.

One of the strengths of the RFID technique is that every tag is unique and can be measured automatically. Consequently, the residence time in the process can be precisely estimated for each tag. Furthermore, the observed object does not mix with the material flow, and consequently the number of units added to the process flow is not affected by the size of the studied process. Finally, it is feasible to estimate the residence time distribution simultaneously for several process sections, since no sampling is required.

Nevertheless, there are many shortcomings with the RFID technique. One shortcoming is that the RFID technique does not offer the same flexibility for use as other mentioned methods. Examples of attributes that hinder the flexibility are the physical size and fragility of the tags. The fragility results in the tags not being possible to use in process sections with for example grinding or extreme temperatures. Moreover, the RFID technique uses electromagnetic waves for communication between the reader and the tags. Therefore, the technique is improper to use at distances larger than a few metres or when the tags are in direct contact with metals or fluids (Porter et al., 2004). Finally, the technique is sensitive to electromagnetic fields in the surrounding environment.

5. An Example from a Continuous Process

LKAB (Luossavaara-Kirunavaara AB, Sweden) has since the beginning of the 1900s produced highly refined iron ore products from iron ore mines at Kiruna and Malmberget. The main product is iron ore pellets for blast furnaces and direct reduction furnaces.

In November 2006, LKAB inaugurated a new pelletising plant in Malmberget (hereafter PP2). After the start of the new pellets plant, the production volume increased and therefore the raw material taken from local ores in Malmberget was insufficient to uphold full production at the plant, due to, among other things, concession rights. Therefore, ore from Kiruna mines is also used in the production process. The different ores thus have to be mixed.

The iron oxides in Malmberget have a coarser grain size, different kinds of grain boundaries, different Fe-contents and levels of contaminants compared to those in Kiruna (Geijer, 1930). Hence, the iron oxides from Malmberget and Kiruna behave differently during the refinement process. This implies an increased risk of quality deviations in the final product and therefore more emphasis needs to be focused on traceability aspects, since it is important
for the customer that the mineralogical characteristics and chemistry of the final product do not differ considerably over time.

The product affected by the mixing of raw materials is the iron ore pellets (hereafter pellets) produced at Malmberget. As a result, a traceability system is most important for this product. The pellets are produced in a continuous process that is illustrated in Figure 3 and further described in the following part.

![Flow chart of the iron ore refinement process at Malmberget.](image)

**Figure 3.** Flow chart of the iron ore refinement process at Malmberget.

### 5.1 Production process

The Malmberget mine has more than ten different ore bodies that are currently in production. For each ore body, there are different characteristics such as mineralogical, chemical and textural properties.

From the mine, the material goes to the concentrator plant, which separates the minerals into two parts, tail and product. Before one of the concentrator plants, there is a cobbing step to separate the gangue mineral from the magnetite.

In the two concentrator plants (CP1 and CP2), ball mill grinding is used in three consecutive steps with wet low intensity magnetic separators in between; see Figure 4 for a flow sheet. It is important to grind to approximately 68% < 45μm to liberate gangue minerals, and to reach the desirable size distribution for the pellets feed. The grinding circuits are the last stage in the comminution; in this stage the particles are reduced by a combination of impact and abrasion (Wills & Napier-Munn, 2006).

![The grinding section in the concentrator plants (CP1 and CP2) with magnetic separators.](image)

**Figure 4.** The grinding section in the concentrator plants (CP1 and CP2) with magnetic separators.
Keeping traceability in the grinding sections is problematic, since the particle size decreases resulting in an increase of the number of individual particles. An example of how the particle size distribution is altered during grinding is illustrated in Figure 5. Moreover, the small size of the material complicates the possibility to achieve traceability in the grinding sections. Another major concern is that each section receives additional secondary material flows from other sections producing special products and general spillage within each section.

![Lin-log-plot](image)

Figure 5. The typical particle size distribution diagram for the input and output in a grinding section. In the grinding circuit, the $d_{80}$ for the particles is reduced from 4000 $\mu$m to 70 $\mu$m and the variation in particle size is reduced.

The next step is the pelletising plant. There are two pelletising plants in Malmberget, PP2 and the old PP1 from 1973. A flow chart over the pelletising plants in Malmberget is seen in Figure 6. Several factors make it difficult to achieve traceability during the pelletising process:

- The surroundings of the material constantly change, from slurry to being dry and finally heated.
- There are several buffers, the result of which is that the flow cannot be characterised by a linear flow (lot-sequence mixing).
- Material from different concentration plants are mixed (lot-sequence mixing).
- The material flow is split into smaller flows and then merged at several places in the production (lot-sequence mixing).
- The material flow differs between the two pelletising plants (lot-end mixing).
- Some of the process steps entail reflux flows (lot-end-mixing).
After the pelletising plants, the pellets are distributed to the final customers. A flow chart of the distribution chain is seen in Figure 7. All three elements that may impair the physical lot-integrity are represented in the distribution chain: the transport and storage rooms differ in size (lot-mismatching); there are two possible ways of transportation to customer (lot-sequence mixing); there is no clear separation between batches (lot-end-mixing).

Figure 6. Flow chart for the two pelletising plants at Malmberget

Figure 7. Flow chart of the distribution chain for iron ore pellets produced in Malmberget.
5.2 Application

Traceability can be created in the concentrator plants (Figure 4) by using the mineralogical signature method. The mineralogical signature method is suitable to use since it can achieve traceability even when the form of the material is changing, as it does during the comminution. Materials from different parts of the process should be sampled regularly and analysed, with regard to the content of mineral at different fractions, mineral liberation and mineral associations. By doing so it should be possible to trace a product in the concentrator plant, since part of the mineralogical signature stays constant during the process.

Samples have been taken from each grinding section and analysed with PTA (Oghazi et al., 2007). The abundance of analysis data makes it necessary to use multivariate tools to identify patterns. By using multivariate analysis it is possible to see correlation between different grinding sections, but no conclusion may yet be drawn (Oghazi et al., 2008). For more details of the multivariate analysis on the PTA data, see Oghazi et al. (2008).

To achieve traceability in PP1 and PP2, several methods have to be used, since no single method is preferable for all the different process stages in the pelletising plants. The process data method is preferable to use for most of the process sections in the pelletising plant, since the material flow can be estimated with existing measurements in the process. However, this method is not feasible for the slurry and mixing tank system (steps one and two in the pelletising plants presented in Figure 6) and the bin chamber (the fourth step in PP2 viewed in Figure 6). One reason is the large buffer in these process sections, which makes it difficult to estimate the material flow with the existing measurements. The mixing of two materials in the slurry and mixing tank system is another factor that makes the process data method insufficient to use for modelling the material flow.

The material flow in the slurry and mixing tank system can be estimated by using a chemical or radioactive tracer. The chemical tracer method is preferable here, since the material flow can easily be sampled and the size of the system is suitable for using a chemical tracer. Selection of a suitable chemical tracer is the next task. At this stage the material flow is a mixture of solid and fluids, and as previously discussed, the RTD can differ between solids and fluid. However, a previous investigation has shown no significant difference for RTD between solid and fluids in rod and ball mills at LKAB (Andreasson et al. 1985). And since the particles are smaller (same particle size distribution as the material of Mill#3(out) in Figure 5) in this process section, it is assumable that the particles behave as the fluid. Lithium chloride is suitable as a tracer, because it is soluble in water, does not affect the process or the end product, does not occur in high concentrations, and can easily be analysed.

Estimation of the RTD in the bin chamber can also be made with chemical or radioactive tracer methods. Here too the chemical method is preferable. However, lithium chloride is not suitable as a tracer element since the material is dry. Fluorescent colour can instead be used as a chemical tracer.
The residence time has been measured for the slurry and mixing tank system by chemical tracer substance experiments. In the experiments, lithium chloride was added momentarily to the flow, and the concentration of lithium in the effluent flow was sampled and analysed. Based on the data from the experiments a mathematical model with two tanks was fitted to the data. For more details, see Kvarnström and Bergquist (2008).

In the distribution chain (Figure 7), the RFID technique, the traceable unit method, may be appropriate to use for achieving traceability. This method is preferable as the residence time in the distribution chain is long and impossible to model by process data, as the material flow is a mixture of batch and continuous flows. Furthermore, the material (the pellets) is only exposed to insignificant external forces and the material is approximately the same size as a tag. The technique could be used to create virtual batches, since it is not realistic to equip each pellet with a tag. The tags would be used as the start and the end points of each batch. Process data can then be linked to a virtual production batch. Tags could be either attached directly to pellets or dropped into the material flow.

The RFID technique has been extensively tested in the distribution chain. The results show that the technique may be used to create traceability in the distribution chain. However, to achieve a sufficient read rate, more than 50 per cent, it is necessary to use RFID tags that are larger than the pellets. In the test, no significant difference in the behaviour between the larger RFID tags and pellets was observed. The tests and the results are further described in Kvarnström and Nordqvist (2008).

6. Conclusions and Discussion

Through a literature review and discussions with different researchers, suitable traceability methods for continuous processes were identified; the methods are summarised in Table I. As illustrated above, there are several methods for creating traceability in continuous processes, and as the example demonstrates, they are applicable at different types of process sections. None of these methods can be seen as a panacea for developing a traceability system, since every method has its own strengths and weaknesses. The methods described in this paper should be seen as examples of methods, and not as a complete list.

Furthermore, the example shows that by applying suitable traceability methods, it should be possible to improve traceability. However, no complete implementation of the methods has been made, and it is therefore still uncertain if traceability can be achieved in the iron ore refinement process. Though the results are promising, there is still work to do before some final conclusions could be made about the possibility to achieve traceability in the iron ore refinement process. For example, the analysis data from the concentrator needs to be further analysed. In the grinding sections many aspects need to be considered because the material is profoundly changed, for example the shape and the composition of the material is changed. The RTD of the bin chamber also needs to be investigated before traceability can be achieved.
Methods for Traceability in Continuous Processes
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Table I. A list of identified and described traceability methods with advantages and disadvantages.

<table>
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<tr>
<th>Traceability method</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td></td>
<td>Off-line</td>
<td></td>
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<tr>
<td>Chemical tracer</td>
<td>- Flexible</td>
<td>- Dilutes</td>
</tr>
<tr>
<td></td>
<td>- Easy to use</td>
<td>- Needs sampling</td>
</tr>
<tr>
<td></td>
<td>- Low-cost</td>
<td>- Based on historical data</td>
</tr>
<tr>
<td>Radioactive tracer</td>
<td>- Flexible</td>
<td>- Health hazards</td>
</tr>
<tr>
<td></td>
<td>- No sampling needed</td>
<td>- Permits required</td>
</tr>
<tr>
<td></td>
<td>- Interior flows can be measured</td>
<td>- Based on historical data</td>
</tr>
<tr>
<td>Process data</td>
<td>- Easy to use</td>
<td>- Hard to find</td>
</tr>
<tr>
<td></td>
<td>- Low-cost</td>
<td>- Low precision</td>
</tr>
<tr>
<td></td>
<td>- Based on real-time data</td>
<td>- Initial sampling needed</td>
</tr>
<tr>
<td>Traceable unit</td>
<td>- High precision</td>
<td>- Lower flexibility</td>
</tr>
<tr>
<td></td>
<td>- No sampling needed</td>
<td>- Can not be used for fluids</td>
</tr>
<tr>
<td></td>
<td>- Could be used in process sections</td>
<td>- Can only be used at shorter</td>
</tr>
<tr>
<td></td>
<td>with both batch and continuous flows</td>
<td>distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Costly implementation</td>
</tr>
<tr>
<td>Material signature</td>
<td>- Flexible</td>
<td>- Large amount of data handling</td>
</tr>
<tr>
<td></td>
<td>- Informative</td>
<td>- Time demanding</td>
</tr>
<tr>
<td></td>
<td>- High analyses precision</td>
<td>- Costly</td>
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The traceability mind-map presented in Figure 1 gives a structured model view of how a company can proceed to reach a sufficient level of traceability in a production process. Moreover, the traceability mind-map tries to distinguish the different terms for traceability used in the literature. No corresponding attempt to distinguish the traceability terms was found in the literature search. Instead, traceability has mostly been defined and used in conformity with different authors’ needs.

With the presented traceability methods, it should be possible to create traceability systems in continuous processes as well. The resolution of the traceability system in a continuous process will, however, often be inferior compared to traceability systems in part production processes. One major reason is that reflux flows are more common in continuous processes than in part production processes. These types of flows result in the physical lot integrity deteriorating during the production process.

Several of the presented methods display limitations such as low analysis speed and fragility. However, many of the methods are still in a development stage. To increase the analytical speed and to handle information faster in the mineralogical signature method, it might be interesting to use QemSCAN. QemSCAN is an instrument that offers rapid identification and analysis of minerals (several thousands per minute) in samples by creating a digital mineral image and performing mineralogical analysis on a size-by-size and particle-by-particle basis (Pirrie et al., 2004). The possibility to make rapid and different analyses in aspects such as bulk and particle mineralogical as well as specific mineral search makes the instrument useful in the search for different signatures.

The usually low product value added in continuous processes is a factor that complicates the design of traceability system and selection of traceability methods. However, the authors’
firm belief is that traceability can be achieved profitably even in continuous processes. Nevertheless, resources are always an important aspect that has to be kept in mind when choosing among different traceability methods and designing a traceability system.

The importance of traceability has been continuously increasing as a response to wishes to optimise the production process and new regulations. The importance of traceability in production processes can therefore not be stressed enough.

Acknowledgement

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- Experience from an Iron Ore Refinement Process


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<td>Journal of Manufacturing Technology Management, Vol. 21, No. 1, pp. 139-154</td>
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Using Process Knowledge for Simulations of Material Flow in a Continuous Process

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Abstract: In continuous process industries, large investments in automated process control systems are made to reduce variance, but the variance in key process parameters often remain unchanged. One reason is that the operators often lack tools to assess the impact of process changes on the final product properties. Dynamic simulation could be used to estimate effects of attempted changes, on models with current process information and dynamics. However, the use of dynamic simulation for such purposes is infrequent in process industry. Therefore, the purpose of this paper is to outline a simulation model for mineral processing using existing process knowledge. An iron ore pelletizing process was studied, and process knowledge was collected through interviews and research reports. The material flow mechanisms of a critical process section were also determined experimentally. A simulation model of the process was constructed in SIMULINK, and the effects of various variations were tested. The statistical properties of the output distribution of particle residence times were compared for various settings. Finally, various applications field in a mineral process for the simulation model is discussed, for example, predicting or explaining effect of corrective actions.

1. Introduction

The raw material for continuous process are often in an unprocessed form, fetched directly from forests, mines or farms [1, 2]. In contrast, the raw material for part production has usually been processed. Therefore, the raw materials in continuous processes usually are afflicted with a larger variation than the raw materials used for part production [1, 2]. In continuous processes, the products are gradually and with minimal interruptions refined through a series of operations [1, 3]. According to Rajaram & Robotis [4], there has been technological initiatives, including new process technology and automation to control continuous processes, and operational initiatives, including development of an effective interface between the operators and the process control system, to reduce output variation in the processes. However, in continuous processes the variance in key process parameters has often remained unchanged, though large investments in automated process control systems has been made to reduce variance [5]. According to Rajaram & Jaikumar [5], one reason is that there are no tools for operators to assess the impact of changes at individual stages on an overall production target.

Hence, developing tools for studying the impact of changes in the processes is vital for reducing the variation. Dynamic simulations could be used to test “what-if”s, such as response
to variation in feed, in continuous processes [6]. Therefore, dynamic simulations should be useful for studying the impact of changes.

According to Daniel T Brunner, pharmaceutical manufacturing, chemical manufacturing, and mining and mineral processing industry are areas where simulation has not yet been widely accepted [7]. Furthermore, Liu & Spencer [6] argues that there has been limited practical application of dynamic simulation in most of the mineral processing industries. Nevertheless, there are examples of simulations in the mineral processing industries, see for example [8], [9] and [10]. The examples are typically specific for a process section or a case, and based on data from numerous experiments.

Therefore, the purpose of this paper is to outline a simulation model for mineral processing using existing process knowledge. Moreover, the model can be used to analyze the propagation of variation through the process. Furthermore, the impacts of incorrect material flow assumptions in various process sections are tested. Finally, the accuracy in the process knowledge for a critical process section is investigated by an experiment.

2. Theoretical Framework

There are two types of ideal flow systems commonly used for modeling flow systems; plug-flow and perfectly mixed flow [11-13].

In a plug-flow system, the flow is assumed to be without radial variations, and no dispersions will occur; thus the particles exit and enter in the exact same order. When flows are without mixing, the time particles would reside in the system, or the residence time, would be equal to the system space time, \( r \), and it is defined as:

\[
    r = \frac{V}{v_0}
\]

where \( V \) is the volume of the system and \( v_0 \) is the volumetric flow rate entering the system. Plug-flow are often assumed to arise in tubular reactors [13]. In a perfectly mixed flow system, concentrations are assumed equal. Hence, the particles entering a perfectly mixed flow system are immediately completely dispersed. Perfectly mixed flow is for instance often assumed in continuous-stirred tank reactors [13]. However, real flow systems are non-ideal. Short circuiting (bypassing) and stagnant region (dead zones) are for instance often encountered [13] in real flow systems.

The particle residence time distribution function of the system, \( E(t) \), can be used to describe the flow behavior of any real system. The residence time distribution function can, for example, be determined by an addition of a tracer substance, such as an impulse addition into the incoming flow of a system. By measuring the concentration, \( C(t) \), in the effluent flow, \( E(t) \) can be calculated [13, 14]. With impulse additions when the volumetric flow rate is constant, \( E(t) \) is given by:
The first three distribution parameters, mean residence time, $t_m$, variance, $\sigma^2$, and skewness, $s^3$, are commonly used instead of $E(t)$ for characterization of a flow systems. These parameters can also be used for comparison of models, and are given by Eq. 3-5:

$$t_m = \int_{0}^{\infty} tE(t)dt$$

(3)

$$\sigma^2 = \int_{0}^{\infty} (t-t_m)^2 E(t)dt$$

(4)

$$s^3 = \frac{1}{\sigma^3} \int_{0}^{\infty} (t-t_m)^3 E(t)dt$$

(5)

$t_m$ is equal to the space time, $\tau$, in absences of dispersion and for constant volumetric flow.

3. Process Description

The iron ore pelletizing process at a Swedish mining company, LKAB, was chosen as the process to investigate and simulate. LKAB is specialized in extracting iron ore and developing highly refined iron ore products. A simplified flow sheet of two pelletizing plants, PP1 and PP2 is shown in Figure 1. The input to the pelletizing plants is a slurry, that is, a mixture of water and fine particles, in this case iron ore powder. Furthermore, the slurry comes from two sources with different composition. The ambition of the company is to produce one type of iron ore pellets, and, therefore, the slurries are mixed, see Figure 1.
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4. Method

The full research process with activities and the connection to the different element of the purpose are summarized in Figure 2, in chronological order. As a first step, all the existing process knowledge was collected using internal reports, unstructured individual interviews and a group interview with LKAB engineers. The process knowledge was then used to develop a map of process flows and residence times, and to outline an initial flow simulation model (hereafter initial model) of the process. The SIMULINK toolbox in MATLAB was used for creation and testing of the flow simulation model.

Figure 1: A simplified flowsheet of the two pelletizing plants (PP1 and PP2) at LKAB in Malmberget.

Figure 2: The research activities and the connection to the different element in the purpose.

To analyze the propagation of variations in the process, two settings were tested in the initial model, see Table 1, and a sampling interval of one minute was used. Setting 1 illustrates
a shorter disturbance in one of the incoming slurry flows, in this case slurry 1. Such a disturbance could, for example, be caused by a lesser contamination or a variation in the raw material. Setting 2 illustrates a shift in the process, such as those that could occur due to machinery breakdown or a process change. During the simulations, the levels in the slurry tanks and the bin chamber were set to an intermediate level.

Table 1: The two settings simulated.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pulse disturbance with amplitude 1 from input 1 during the period 0 to 0.1 h</td>
</tr>
<tr>
<td>2</td>
<td>Step change from 0 to 1 in both input at t = 0 h</td>
</tr>
</tbody>
</table>

Much of the process knowledge, obtained during the interviews, was based on approximations and supporting data were often lacking. The most important section with respect to residence time is the slurry tank, and a tracer experiment was therefore performed to validate and improve the knowledge about the flow and the residence time distribution of this tank. Due to the process design, the mixing tanks were also included in the experiment. A detailed flow sheet of the process section including the slurry and the mixing tanks is presented in Figure 3. The residence time may differ between water and the solid phase, but it is assumed that the slurry does not separate. Lithium chloride was chosen as the additive to test the flow mechanisms of the tanks, since lithium chloride is easily dissolved in water, only traces of lithium are normally found in the product, and the lithium content is easily measured also at trace levels. The lithium chloride was dissolved in water and added as an impulse to the slurry mixture entering the slurry tanks and the lithium content of the slurry was measured after the mixing tanks and used for calibration of the tank flow model.

Figure 3: Flowsheet for the slurry and mixing tanks.
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Two tracer experiments were performed, one for each slurry tank section, with six weeks in-between. The lithium concentration in the fluid part of the samples was analyzed with ICP-MS (inductively coupled plasma - mass spectrometry) after filtration. Roughly, a sampling time equaling the calculated space time plus one hour was used during the experiments. The tail of the concentration curve was estimated by fitting an exponential decreasing function to the experimental data using the least square method. During the experiments, the slurry levels of the slurry tanks were at an intermediate level.

Based on the experiment, the initial model was calibrated. In the calibrated model, the same two settings were simulated with the same process flow and levels in different sections. To evaluate the result of the incorrect assumption about the process flow, mean residence time, variance and skewness were compared for the simulations in the two models. Mean residence time, variance and skewness were calculated using numerical integration.

5. Results

Table 2 summarizes the process data, based on the findings in the interviews and the internal reports. The data are based on mean levels of slurry in the slurry tanks and on mean levels of iron powder in the bin chamber. The flow of the plant only differs little during regular production, and the process in Table 2 is assumed to be operating at normal flow rates. As the process knowledge for the bin chamber was insufficient, the bin chamber was simulated both as a plug-flow and as a perfectly mixed flow in the simulations.

Table 2: Description of the process sections in the two pelletizing plants. (MF= perfectly mixed flow, PF= plug-flow)

<table>
<thead>
<tr>
<th>Process section</th>
<th>Function</th>
<th>Space time (hour)</th>
<th>Flow mechanism, as estimated by process engineers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slurry tank</td>
<td>Buffer and mixer</td>
<td>7,05 6,85</td>
<td>MF</td>
</tr>
<tr>
<td>Mixing tank</td>
<td>Mixing the two slurries</td>
<td>0,02 0,02</td>
<td>MF</td>
</tr>
<tr>
<td>Filters</td>
<td>Dewatering the concentrate</td>
<td>0,06 0,03</td>
<td>MF</td>
</tr>
<tr>
<td>Bin chamber</td>
<td>Buffer and mixer</td>
<td>0 1,5</td>
<td>Insufficient process knowledge to suggest a model flow</td>
</tr>
<tr>
<td>Mixer</td>
<td>Blending concentrate with a binder</td>
<td>0,01 0,01</td>
<td>MF</td>
</tr>
<tr>
<td>Bin</td>
<td>Buffer</td>
<td>0,7 1,2</td>
<td>PF</td>
</tr>
<tr>
<td>Balling equipments</td>
<td>Balling formation</td>
<td>0,1 0,1</td>
<td>PF followed by a MF</td>
</tr>
<tr>
<td>Sintering furnace</td>
<td>Sintering</td>
<td>0,5 0,5</td>
<td>PF with reflux</td>
</tr>
</tbody>
</table>
The results from the tracer experiments in the slurry and mixing tanks indicate that an exponential model was appropriate for describing the decline of the effluent flow concentration of an impulse addition at the inflow, but the rapid rise and decline of the lithium concentration indicated that the full volume was not active. Non-active volume elements, so called dead zones are common, especially for low speed slurry flow, where solid state buildup may occur. An exponential decline is typical for perfectly mixed containers, and the active volume was thus assumed to be perfectly mixed. Furthermore, the design of the flow system suggests that the flow model should incorporate two perfectly mixed containers serially connected. The experimental calibration led to a mathematical model including a perfectly mixed slurry tank with a dead zone and a perfectly mixed mixing tank, see Figure 4. The model was fitted to the tracer data using the least squares regression, and the active volume share, $\alpha$, for the slurry was calculated.

$\begin{align*}
S & \text{Slurry tank} \\
\text{Position for} & \text{addition} \\
V_1 & = V_a + V_d \\
\alpha V_1 & = V_a \\
\end{align*}$

$\begin{align*}
M & \text{Mixing tank} \\
\text{Position for} & \text{sampling} \\
V_2 & = V_{l1} + V_{l2} \\
(1 - \beta) V_1 & = \beta V_1 \\
\end{align*}$

Symbol descriptions:
- $v$: inflow to the slurry tank.
- $V_a$: total volume of slurry in slurry tank.
- $V_d$: active volume in slurry tank.
- $V_{l1}$: dead volume in the slurry tank.
- $\alpha$: active volume share in slurry tank.
- $\beta$: share of outflow from slurry tank to sampled mixing tank.
- $v_{l2}$: inflow to sampling tank from other slurry tank.
- $V_{l2}$: volume of the mixing tank (assumed active since space time is small).
- $C_{d}(t)$: concentration of the studied substance in the background flow.
- $C_{o}(t)$: concentration of the studied substance in the outflow from the slurry tank.

Equations:

$\begin{align*}
\frac{dC_{o}(t)}{dt} & = \frac{\alpha}{V_a} C_a - \frac{\beta}{V_1} (C_{l1}(t) + \alpha \gamma (1 - \gamma)) \\
\frac{dC_{l1}(t)}{dt} & = \beta \gamma \left( C_{l1}(t) + v_{l2} C_{l2}(t) - \beta \gamma \left( v_{l2} + \beta \gamma \right) C_{o}(t) \right) \\
\end{align*}$

Equations:

- I. Change in quantity of the studied substance per second in the slurry tank at time $t$.
- II. Inflow of the studied substance to the slurry tank.
- III. Outflow of the studied substance from the slurry tank.
- IV. Change in quantity of the studied substance per second at time $t$ in the mixing tank.
- V. Inflow of the studied substance at time $t$ from the slurry tank with addition to the mixing tank.
- VI. Inflow of the studied substance from the slurry tank without addition to the mixing tank.
- VII. Outflow of the studied substance from the mixing tank.

Figure 4: The mathematical model and definition of the parameters used. In this case the studied substance was lithium.

The effluent flow concentration for the simulations of Setting 1 in the calibrated model is illustrated in Figure 5a and b. The disturbance in slurry mixture 1 results in an almost instantaneous concentration peak in the effluent flow of PP1, in both the calibrated model and
the initial model. The result was expected since the flow in PP1 mainly consists of perfectly mixed tanks. Furthermore, the concentration peak was higher for the calibrated model; this was an effect of the dead volume in the slurry tank. The dead volume, in the slurry tank, implies that the disturbance was mixed with a smaller volume of undisturbed product.

The effluent flow for PP2 with the bin chamber modeled as a plug-flow for the calibrated model, see Figure 5b, as well as the initial model had the same appearance, but the peak was shifted towards longer times. However, if the flow in the bin chamber was simulated as a perfectly mixed flow the peak was more rounded. Moreover, the effect of the disturbance in the output was almost two times higher in the calibrated model than in the initial model for both PP1 and PP2. Finally, the mean times were shorter in the calibrated model for Setting 1, also the variations has decreased. Furthermore, the disturbances in the effluent flow were more centered in the calibrated model.

![Figure 5](image1.png)

**Figure 5:** The response in the output to a disturbance in slurry mixture for the calibrated model. The flow in the bin chamber is simulated as plug-flow (PF) or as perfectly mixed flow (MF). Figure 5a shows Setting 1 results for PP1 Figure 5b: results according to setting 1, PP2.

The response in effluent flow from the simulations of Setting 2 is illustrated in Figure 6. The product change, from product 0 to product 1, results in an almost exponential response in the effluent flow of PP1, with a short delay caused by the bins before the balling equipments. Moreover, the calibrated model resulted in a steeper growth than the initial model. However, at approximately 25 hours, the response in the effluent flow for the two models in PP1 converges. The effluent flow for PP2, with the bin chamber modeled as a plug-flow, has the same appearance as the effluent flow in PP1, but is shifted forward in time. However, if the flow in the bin chamber was simulated as a perfect mixed flow, the exponential response is less steep. The perfectly mixed flow and plug-flow in the bin chamber could be seen as two extremes, and the actual flow should be somewhere in between the two extremes.

Finally, if a product contained more than 20% of a by-product, for example a 50/50 mixture of two product types, it would be classified as defective in the simulation. With such classification, the output from PP1 in the initial model would be downgraded during 8.5
hours. In the calibrated model, the production time downgraded was reduced to 5.2 hours. The same pattern in reduction was observed for the output of PP2.

Figure 6: The response in the output for the calibrated model to a product change, according to Setting 2, for PP1 (6a) and PP2 (6b).

6. Conclusions and Discussion

From the simulations of Setting 1, it can be concluded that the peak in concentration of a short-time disturbance is significantly lower in the effluent flow compared to the peak in concentration of the short time disturbance in the inflow. Hence, short-time disturbances could often be ignored in the pelleting process. The size and amplitude that can be ignored depends on the kind of disturbance, as the customers’ sensitivity differs for various disturbances, for example changes in iron content or contamination of a tracer substance. However, there are other factors affecting whether the disturbance can be ignored or if countermeasures need to be taken, for example the level in the slurry tanks. The simulation model could thus be used to select corrective actions in presence of disturbances. Therefore, the simulation model is useful as a decision tool to decide how to handle a disturbance in the process. Furthermore, the model helps to predict the amplitude of a disturbance in the system as well as when and for how long time the disturbance will affect the system at different locations.

From the simulations of Setting 2 it could be concluded that the full (99%) impact of a process change may be lagged up to a day, but also that most of the change will have taken place within ten hours, and that not much will change for the first three hours. As the effects of changes in the final product often are lagged and slow, the effects of operator’s actions are often not visible during their work shift, which makes it difficult for the operators to learn about the cause-and-effect relationship between control operations and process reactions. If a simulation model, such as the one presented here, was implemented at the operator level using on-line data logging, it would be possible to instantaneously simulate when the process reaction will take place. In this way the operators can study the result of control operations afterwards, and thereby learning the effects of different control actions.
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By comparing the responses to the simulation of PP2, where the flow in the bin chamber is simulated as a plug-flow or a perfectly mixed flow, effects of incorrect assumptions of a flow in a process section are seen. One effect of an incorrect assumption could be that a product is classed incorrectly, either as defective instead of correct or the other way around. Moreover, an incorrect assumption could result in that the effect of a disturbance is underestimated or overestimated. The passing time of a disturbance could also be misjudged if the assumption of the flow is incorrect. For the investigated flow the assumed type of ideal flow, the perfectly mixed flow, was correct, the dead zone was, however, not expected. As real flows seldom are ideal, it is important to investigate the flow for process sections with extensive residence time.

One way to increase competitiveness and unit price is to produce customer specific products. Another application of a simulation model, such as this one, could be to estimate how product changes should be performed, and when the new products will be produced, as well as when the products will be out of specifications. Such a model would also let the engineers estimate when the new product will enter different process sections, so sections settings could be changed in time. If special products are to be produced, the model could additionally predict if product changes would cause low grade or defective products to be produced, and what products that should be reworked or rejected. The model can therefore aid cost benefit analyses used to decide whether production of a special product is profitable, and how special products should be produced at minimal costs.

In the pelletizing process, various settings and levels in process sections are controlled and determined by the operator. For example, the filling and discharge of the bin chamber as well as the level in the bin chamber may be controlled by the operator. The possibility to control certain settings and levels in process sections implies that the operators to some extent may alter the process flow to, for example by changing stirring speed. The operation control may be used to improve the product characteristics and to minimize defective product by altering the process flow. This alteration needs to be based on data from product measurement in the process. However, normal product measurements often prevent the application of such operation control, since lab results are infrequent and to slow. Process simulations could aid in making this type of operation control practical, as simulations could be used to predict properties based on lab result of samples taken earlier in the process.

Simulation models can also be used for improving traceability of continuous processes. Examples of benefits with good traceability are: selective product recalls, product localization, and prevention and reduction of undesired events such as changes in material composition and particle size.

In the simulated mining process, it is the solid phase of the slurry that is of importance, and the model was calibrated using lithium content of the liquid phase. The assumption that the phases of the slurry has similar residence times is supported by earlier investigations of a milling operation [15]. The error associated with this assumption should be small, even though
the residence times are considerably longer in the tank sections than in the milling sections, since the particles of the ore is smaller in the slurry tanks and thus should be less prone to separate.

In summary, the result shows that simulations are useful tools for understanding the effect of disturbances and variations in processes such as the pelletizing process of iron ore. The presented simulation model resulted in new knowledge of how disturbances affect the pelletizing process. A regularly calibrated on-line installation would improve the usefulness of the simulation model further. Moreover, the next step to improve traceability of the iron ore products would be to include the whole production process in the simulation model. In this case, the concentrator plants, cobbing plants and the mines would be included in the simulation model.

7. Acknowledgements

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Improving Traceability in Continuous Processes Using Flow Simulations

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Abstract: Traceability is normally difficult to achieve in continuous processes, since there are no natural batch structures. In this article, we propose flow based simulation using process data to improve traceability in a continuous pelletizing process. In a field trial, the simulation forecasts successfully predicted process fluctuations during production of a special product. Using the simulation model, the engineers could test the impacts of process disturbances. Moreover, the simulation model could also be used to identify cause and effect relations and aid control in case of process disturbances.

Keywords: Continuous process; Traceability; Flow simulation; Pelletizing; Modelling; Residence time

1. Introduction

One way to improve processes and reduce variation is to identify special causes for variation, and then eliminate or reduce their effect (Shewhart, 1931), and a high level of traceability is important to identify these causes (Duffin, 1995). Traceability is here understood as “the ability to track, trace, and predict the location of a lot and its sub-components and raw materials through the supply chain”. Furthermore, traceability is important for process control (Oakland, 1995), and it is required in ISO 9001-2008 (ISO 9001, 2008 7.5.3)

Traceability is usually straightforward to achieve in discontinuous production (discrete or batch production), since identification markers such as bar codes or serial numbers can be attached to the product or packing. In contrast, descriptions of traceability systems for continuous processes, common in the process industry, are scarce in the literature. However, traceability systems for such processes may be important. The food and pharmaceutical industries are examples of continuous processes were a high level of traceability is required; see Flapper et al. (2002). Kvarnström and Oghazi (2008) argue that continuous processes contain several characteristics complicating traceability that are not usually discussed in the literature. One example characteristic that is problematic is the continuous flow of material, as traceability solutions normally relies on the definition of a batch (Skoglund and Dejmek, 2007). Furthermore, the products often undergo multiple changes of states when processed which also impedes traceability. The product may, for instance, be in slurry, gas, fluid, powder, granular form, or other non-discrete form.

Huda and Chung (2002) suggest the use of simulation models to better understand the production process and to see the effect of different production scenarios in, for example, food manufacturing processes. We argue that simulation models also may be used to achieve traceability in other continuous processes. However, simulation of continuous processes tend
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The traceability accuracy of any modelling approach of a continuous process will depend on how accurately the model can predict the product flow. Finely meshed computational fluid dynamic models or discrete element methods for granular material have been used to simulate small process sections with continuous flows, see Bhaskar et al., (2007) and Finnie et al. (2005). Such models may be required to attain modelling results close to actual flow behaviour of, for instance, how chemical fluctuations propagate in the process. In practice, the complexities of these models often result in computational times that quickly become impractical, and reduced accuracy in favour of swiftness may be a better, or the only viable solution. One approach using coarser estimates to create liquid food traceability using virtual batch calculations for a diary has been presented by Skoglund and Dejmek (2007).

The purpose of this paper is to develop a process simulation approach, and to describe and apply a simulation model based on process data and flow estimations for a continuous process. We also aim to identify limits of the modelling approach, some areas of use, and discuss the possibilities for generalization to other areas.

The article contains five sections besides the introduction. Section 2 describes different ideal flows and how the flow behaviour in a real system can be estimated. Section 3 presents the process and the production scenario for which the simulation model was developed and tested. In section 4 the simulation model development is described. The application of the simulation model and the results from the application is presented in section 5. Finally, the article is concluded and discussed in section 6.

2. Process flows

Any real flow of liquids, powders, slurries, or pulps has geometrically dependent flow velocities. The flow will range from the ideal states perfectly mixed flow to plug flow. The one extreme, the perfectly mixed flow, suggests that the matter (fluid, powder etc.) entering a process section is instantaneously mixed with all matter residing in the section. Hence, in this type of flow, each infinitesimal volume of the section’s content has the same properties (chemistry, temperature, microstructure, particle size et cetera) at any given time. The assumption of a perfectly mixed flow is often used for continuous-stirred containers.

The other extreme, the plug flow, implies that the matter entering a process section will remain unmixed through the section. Hence, there is a fixed residence time for each infinitesimal volume of the flowing matter. The flow in tubular reactors is often approximated by assuming plug flow.

For ideal flows, the mean residence time of infinitesimal volumes in the system would be equal to the system space time, \( \tau \), defined as:
where $V$ is the volume [m$^3$] of the system and $v_0$ [m$^3$/s] is the volumetric flow rate of flow through the system.

All real flows exhibit flow gradients, and the flowing material will therefore be mixed to some degree. This mixing is dynamic and the degree of mixing develops over time. Real flow systems also often include, for example, short-circuiting (bypassing) and stagnant regions (dead-zones) (Fogler, 2005, p. 979). Nonetheless, Fogler (2005, p. 979) suggests that most real flow systems could be approximated using ideal flow assumptions with addition of, for example, a short-circuiting variable and a stagnant region variable. The flow behaviour of real systems may be estimated by additions of tracers to the input flow and by repeated measures of the exhaust tracer concentration profile, see Fogler (2005, p 871).

3. The exemplified process

The exemplified process consists of two iron ore pelletizing plants owned by the Swedish mining company LKAB. Normally, these plants together produce 900 metric tons product per day: an iron ore pellet (hereafter pellet). The plants are fed by two water/iron ore powder slurries originating from different sources with differing iron ore properties (see Figure 1). The slurries are then mixed to ensure that both plants produce similar pellets. After the slurry mixing stage, the slurry is dewatered in the filter section, and the dewatered powder is then either temporarily stored or fed to a mixer where a binder is added. After the mixer, the powder flow is split into several streams and stored shortly before it is agglomerated and rolled into pellet granulates. During the rolling operation, the pellets are sieved, so that oversize pellets are crushed and returned to the mixing station. The granulate streams are then merged and sintered, which is the final treatment before distribution to the customer. The sintering furnace does also contain an internal backflow, where 20% of the sintered pellets are fed back to the furnace entry and used as a thermal protection for the equipment.
An important quality characteristic of the pellets is stable chemical and physical properties. However, the company sometimes need to induce variability into the production process for product development purposes. This article describes a case where a special pellet with different chemical composition were to be produced for tests in a pilot scale blast furnace. The needed volume of the special pellets was larger than what was practical to produce in laboratory and thus had to be produced in the regular production process. However, the special pellets needed to be separable from the regular product since it did not fulfil the specifications of the regular product. The change of chemical composition in the process is a slow process and the shift would, consequently, interfere with the regular production for a substantial time. Therefore, the production engineers wanted to minimize the product change window to minimize production losses. One of the difficulties to reduce the experimental product period was due to chemical analyses. These analyses were considered too slow for the control needs for producing the special product, since it usually took hours to receive laboratory results. Therefore, another method to control the process had to be developed.

**4. Development of the simulation model**

After discussing the control problem with the authors of this paper, the engineers decided to use a flow simulation approach aided by chemical analyses to plan for and monitor the product change. To be useful, the simulation model had to be fast and accurate enough to improve the engineers' own guesses of how fast the changes would reach and leave different process sections. However, no such model existed for the process and had to be created.
Estimates of the process flow mechanisms and process data were needed to create the model. This information was obtained through interviews of process engineers and through studies of internal documents. Engineers from different process sections and departments were asked to describe the process steps and their ideas of the flow mechanisms in the various process sections during the interviews. Each process section’s residence time was then estimated through space time calculations using Equation 1. The estimations were based on the mean production flow, container volumes taken from blueprints, and from discussions with the engineers. Table 1 summarizes the results of these primary studies.

**Table 1:** Description of the process sections in the two pelletizing plants. (PMF= perfectly mixed flow, PF= plug-flow).

<table>
<thead>
<tr>
<th>Process section</th>
<th>Function</th>
<th>Plant 1</th>
<th>Plant 2</th>
<th>Flow mechanism, as estimated by process engineers</th>
<th>Physical state for the product flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive container</td>
<td>Store of additive</td>
<td>3,3</td>
<td>3,3</td>
<td>PMF with a 25% dead-zone</td>
<td>Slurry</td>
</tr>
<tr>
<td>Additive mixing container</td>
<td>Mix of additive with concentrate</td>
<td>0,02</td>
<td>0,02</td>
<td>PMF</td>
<td>Slurry</td>
</tr>
<tr>
<td>Slurry container</td>
<td>Buffer and mixer</td>
<td>7,05</td>
<td>6,85</td>
<td>Insufficient process knowledge</td>
<td>Slurry</td>
</tr>
<tr>
<td>Mixing container</td>
<td>Mixing of the two slurries</td>
<td>0,02</td>
<td>0,02</td>
<td>PMF</td>
<td>Slurry</td>
</tr>
<tr>
<td>Filters</td>
<td>Dewatering</td>
<td>0,06</td>
<td>0,03</td>
<td>PMF</td>
<td>Slurry</td>
</tr>
<tr>
<td>Iron powder storage</td>
<td>Buffer and mixer</td>
<td>0</td>
<td>1,5</td>
<td>Insufficient process knowledge</td>
<td>Powder</td>
</tr>
<tr>
<td>Mixer</td>
<td>Mix concentrate with binder</td>
<td>0,01</td>
<td>0,01</td>
<td>PMF</td>
<td>Powder</td>
</tr>
<tr>
<td>Bin</td>
<td>Buffer</td>
<td>0,7</td>
<td>1,2</td>
<td>PF</td>
<td>Powder</td>
</tr>
<tr>
<td>Balling equipments</td>
<td>Balling formation</td>
<td>0,1</td>
<td>0,1</td>
<td>PF followed by PMF</td>
<td>Powder</td>
</tr>
<tr>
<td>Sintering furnace</td>
<td>Sintering</td>
<td>0,5</td>
<td>0,5</td>
<td>PF with reflux</td>
<td>Powder</td>
</tr>
</tbody>
</table>

The flow mechanisms in Table 1 were based on engineers’ guesses, mostly without supporting data. Nevertheless, the collected information identified the slurry containers as the section affecting traceability the most, since these containers generate the longest residence times. However, the engineers had only vague ideas of the flow behaviour in the slurry containers. Therefore, a tracer experiment was performed to identify a suitable flow characteristic for the slurry containers, see Kvarnström (2008). The experiment suggested that the slurry container flow could be approximated as perfectly mixed, but with a stagnant dead volume. A stagnant dead volume does not take part in the mixing and thus reduces the volume being mixed. The active volume share for the slurry containers were estimated to 0.61 for plant 1 and to 0.75 for plant 2 based on the experimental data.
Improving Traceability in Continuous Processes Using Flow Simulations

A flow simulation model of the process was built after mapping the process flows and residence times in MATLAB® with the SIMULINK® toolbox. Table 2 presents the process variables used in the flow simulation model for the various process sections. A stepwise overview of how the model was created is given in Figure 2. Appendix A describes how the two flow types were simulated.

Table 2: The process variables used to model each process stage (from additive container to filters), what each variable was based on, and if the variable was varied or kept constant during the simulation.

<table>
<thead>
<tr>
<th>Process stage</th>
<th>Process variable</th>
<th>Data collection</th>
<th>Input Initial model</th>
<th>Final model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive container</td>
<td>Pulp density</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Weight percent solid</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Additive quota</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Active share</td>
<td>Estimated</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Maximum volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Additive mixing container</td>
<td>Pulp density</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Weight percent solid</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Volumetric flow (in and out)</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Slurry container</td>
<td>Pulp density</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Weight percent solid</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Buffer level</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Active share</td>
<td>Estimated</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Maximum volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Slurry divider</td>
<td>Proportion slurry to plant 1 from</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>slurry container plant 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proportion slurry to plant 1 from</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>slurry container plant 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixing container</td>
<td>Pulp density</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Weight percent solid</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Volumetric flow (in and out)</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Filters</td>
<td>Pulp density</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Weight percent solid</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Volumetric flow (in and out)</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Numbers of filters in use</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
</tbody>
</table>

1 Process data is data collected by the ordinary process system. The process data may vary over time and is controlled by the engineers. Product data is data decided during the manufacturing of the equipment and constant.
over time. Estimated data is data that is/cannot be measured or controlled during normal operations. The estimated data is therefore based on previous experiences or on estimations from process engineers.

Table 2 b): The process variables used to model each process stage (from iron powder storage to sintering furnace), what each variable was based on, and if the variable was varied or kept constant during the simulation.

<table>
<thead>
<tr>
<th>Process stage</th>
<th>Process variable</th>
<th>Data collection</th>
<th>Initial model</th>
<th>Final model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron powder storage</td>
<td>Buffer level</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Volume flow (in)</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Volume flow (out)</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Active share</td>
<td>Estimated data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Maximum volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Mixer</td>
<td>Volumetric flow (in and out)</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Bins and Balling equipment</td>
<td>Buffer level</td>
<td>Process data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Volumetric flow (in and out)</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Number of bins in use</td>
<td>Process data</td>
<td>Constant</td>
<td>Varied</td>
</tr>
<tr>
<td>Sintering furnace</td>
<td>Time in furnace</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Return flow</td>
<td>Equipment data</td>
<td>Constant</td>
<td>Constant</td>
</tr>
</tbody>
</table>

3 The balling equipment was modelled as a plug flow followed by a perfectly mixed flow.
A complication for the simulation was that the product undergoes a change of state, from slurry to powder, in the simulated section. This was handled by simulating the flow of the powder constituent only. This was possible since the water part was not of interest and the water share at different stages was known and constant. Another complication was the insufficient knowledge of the flow in the iron powder storage bin. This complication was handled by parallel simulations, differing only in which of the two ideal flow types that was used for powder flow through this bin. The simulation results only differed marginally and a perfectly mixed flow was therefore assumed for the bin.

5. Production of the special product

Before the special product was produced, the engineers wanted to know how to select production rates and buffer volumes to reduce the product change window. The authors made initial simulations varying these parameters to see their effect on the production window, and to find means to minimize the time needed for the change. The simulation results of the progression of chemical compositions in the product for various process conditions, for example shifting buffer levels and production speeds were then discussed with the engineers. Based on the outcome of these simulations, the engineers discussed various control strategies, calculated the preliminary time for product removal, and arranged the time schedules for various resources. The simulation model was also used when operator guidelines were generated. To minimize the production of secondary product and change periods, an
important guideline was to keep buffer levels low, just large enough not to risk material shortage. This way, the chemistry would change more quickly due to a minimum amount of product mixing.

The authors made a new simulation at the start of the product change, using actual levels and flows in the process for the simulation. This simulation was performed to assist detailed planning of the product change, to foresee future events during the change, and to plan for preventive actions for unwanted events. Furthermore, the outcomes of various actions were simulated beforehand to aid decision-making.

At the beginning of the product change, it was discovered that a buffer was running low. If the buffer would run out of material, the production rate would have to be reduced. One possible solution to avoid the problem was to pump slurry from another container, and with the model, the engineers could see the effect of the control action and decide whether it was suitable.

Laboratory results of the samples taken from the process were continuously used to calibrate and fine-tune the simulation results during the field trial to improve predictions of the change in chemical composition. The new data also made it possible to better estimate the dead volume in the various buffers and to adjust the model for type of flow in different sections. However, these adjustments were small and the improvement of the simulation results was considered marginal.

The simulation model was originally designed to simulate a process where the process variables where constant during the simulation period. However, the process variables varied during the field trial run, and assuming constant variables resulted in an unnecessary large simulation error. Therefore, the simulation model was modified to include logged process data in addition to the estimated data. The model change improved the fit between the simulation output and the analysis data; see Figure 3. The changes between the initial simulation model and the final simulation model are highlighted in Table 2.
6. Conclusions and Discussion

In the article, we presented a stepwise approach to create a simulation model for a continuous process based on ideal flow assumptions, see Figure 2. Using the simulation model, engineers could visualize the impacts of process disturbances. We believe that the method of using coarse estimations for flow behaviour, small scale experiments to obtain finer models for vital process sections, and using online measurements for model calibration could be used to improve process predictions in many continuous processes. This kind of modelling may also be used to link existing process data from different locations and thereby create a process based data framework, see, for example, Skoglund and Dejmek (2007).

According to the LKAB engineers, the product change run was successful and the simulation model had performed better than expected and provided important input. Nevertheless, the first simulation results that were not based on logged data predicted a faster change of the chemical content than experienced. The major reasons for this difference were that the initial model was based on larger process flows and smaller buffer volumes than what was seen during the experiment. This sensitivity versus incorrect flow and buffer volume assumption were known before the experiment, and several simulations with differing flow and buffer volumes were therefore made and the results were discussed with the engineers. The deviation between the predicted and the actual chemical change stresses the importance of correct assumptions. Including the possibility to vary the flow in the simulation model over time improved the simulation results. Additional improvements would probably demand better flow estimations and new tracer experiments.
The case study shows how process data coupled with simulation may increase the traceability of the product within a continuous process where normal laboratory analysis of samples is too slow for prediction abilities. After the experiment, the engineers stated that the initial model had produced valuable results before and during the experiment. However, the process contained sections where they often had to adjust flows or buffer volumes during production or during experiments. Therefore, the ability to use different flow volumes in the simulation model may be seen as an important improvement.

Process simulation could be used in other cases where normal sampling is too infrequent or laboratory analysis of samples is too slow for control purposes. Other means to obtain traceability for pellets distribution have also been proposed. For example, Kvarnström and Vanhatalo (2010) have suggested the use of the radio frequency identification (RFID) technique to achieve traceability in a pellets distribution chain.

Mixing is one characteristic that differentiates continuous processes from discrete processes. Two effects of mixing were seen in the simulations: disturbances were smoothened and the impact of changes delayed. Mixing reduces the amplitudes of disturbances downstream, but the effect is also prolonged. In addition, the degree of mixing depends on the process and how it is operated during the disturbance (volume of containers, speed of mixers are examples of process settings that will influence system response). The maximum tolerable duration and amplitude of a disturbance will vary depending on the sensitivity of downstream operations.

Cox et al. (2006) argue that the simulation speed is a key to efficient use of simulations and state that the simulation speed should at least be about 50 times faster than real time. In comparison, the presented simulation model speed was 500 times faster than real time on a regular PC.

The impact of a process change upstream in the studied process was lagged, and an upstream disturbance would not affect product properties for several hours. We believe that such dynamic characteristics are common in many continuous processes and, therefore, the effects of operator’s actions in continuous processes are often invisible during their working shift. Such delays may hinder operator learning. The simulation model we used provided a satisfactorily accurate prediction of the process response to a given disturbance. Therefore, the model could be and was used for predicting effects of corrective actions. Hence, the model can facilitate operator learning as the model can accurately simulate the result of a process change. Besides understanding about the process lag, the simulations provided predictions of the amplitude, longevity, and whereabouts of process shifts.

If the process is to produce different products, such as was the case here, there is a need to estimate the location of the shift, possibly at several positions and times. We argue that a simulation model could aid the estimation of when a product will enter various process sections.
Improving Traceability in Continuous Processes Using Flow Simulations

The control actions made in a process is usually based on various measurements. However, some properties may only be measured through laboratory analysis, and the laboratory analysis is usually too slow for most control purposes. From our demonstration, we conclude that process simulations could be a decision support in such cases as the simulation can predict the development of the property of interest.

Such as with any model, incorrect assumptions will affect the correctness in the output. For the studied process, the simulation model was based on existing process knowledge and calibrated using a small experiment, and the simulation results did, according to the engineers, correspond well with the measurements taken during the change. A simple model based on existing process knowledge may therefore be sufficient for continuous processes like the one studied here.

Acknowledgements
We sincerely thank LKAB for allowing us to study the process, and the financial support that made the research possible. We also gratefully acknowledge the financial support from the Swedish mining company LKAB, Electrotech, VINNOVA (The Swedish Governmental Agency for Innovation Systems), and the Regional Development Fund of the European Union, grant 43206, which made this research possible. Finally, we thank the editors and reviewers for insightful comments that improved this paper.

Appendix
The simulation model contains 14 different steps, see Figure A1. All the process steps where designed individually in SIMULINK® and then connected in process order. In the simulation model the two plants where kept apart, except for the slurry divider which where shared by the two plants in the simulation model. Each process section was either constructed as a perfectly mixed flow or a plug-flow in accordance with the identified flow in Table 1.

![Figure A1. The different sections included in the simulation model in flow order and the assumed flow for the different sections.](image-url)
The model structure of a section classified as a perfectly mixed flow is demonstrated in Figure A2 and the structure of a section classified as a plug-flow is demonstrated in Figure A3. In the modelled section, the inflow volume, the concentration in the inflow for the substance of interest, the outflow volume, and the active volume of the section are known. With the model, our aim is to predict the concentration of a chemical in the current and future exhaust flows of the section.

We start by calculating the incoming amount of the substance that is entering the system, which is done by multiplying the inflow volume with the concentration of the substance in the inflow. The incoming amount is then added to what is already present in the system (remaining amount in Figure A2). The substance leaving the section is calculated through multiplying the entire amount of the substance in the section with the volumetric ratio leaving the section. Finally, the remaining amount in the section is calculated by subtracting the exiting amount from the entire amount in the section. The exiting amount is then used in the next simulation step.

![Figure A2](image)

**Figure A2.** A graphical display of how a perfectly mixed section is designed in the simulation model. The grey boxes are mathematical operations while the white boxes describe the variable resulting from an operation.

The first step to predict the chemical concentration a plug-flow system (e.g., a container) is to calculate the amount of the substance that is entering it. The amount entering a system is given by the inflow volume multiplied by the concentration of the inflowing substance. For plug-flow systems, the concentration of the substance flowing out of the system is identical to the concentration of the substance entering it, but with a delay given by dividing the system volume with the outflow. The exit concentration and flow is then used for the simulation of the following process step.
Improving Traceability in Continuous Processes Using Flow Simulations

**Figure A3.** A graphical display of how a plug-flow section is designed in the simulation model. The grey boxes are mathematical operations while the white boxes describe the variable resulting from an operation.

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Using RFID to Improve Traceability in Process Industry - Experiments in a Distribution Chain for Iron Ore Pellets

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Abstract
Purpose: The purpose of the article is to explore the application of Radio Frequency Identification (RFID) to improve traceability in a flow of granular products and to illustrate examples of special issues that need to be considered when using the RFID technique in a process industry setting.

Design/methodology/approach: The article outlines a case study at a Swedish mining company including experiments to test the suitability of RFID to trace iron ore pellets (a granular product) in parts of the distribution chain.

Findings: The results show that the RFID technique can be used to improve traceability in granular product flows. A number of special issues concerning the use of RFID in process industries are also highlighted, for example, the problems to control the orientation of the transponder in the read area and the risk of product contamination in the supply chain.

Research limitations/implications: Even though only a single case has been studied, the results are of a general interest for industries that have granular product flows. However, future research in other industries should be performed to validate the results.

Practical implications: The application of RFID described in this article makes it possible to increase productivity and product quality by improving traceability in product flows where traceability normally is problematic.

Originality/value: Prior research has mainly focused on RFID applications in discontinuous processes. By contrast, this article presents a novel application of the RFID technique in a continuous process together with specific issues connected to the use of RFID.

Keywords: Radio Frequency Identification (RFID); granular product; process industry; mining industry; traceability; continuous flow.

1. Introduction
Most companies strive to deliver high-quality products with a minimum number of defects. However, product recall announcement in newspapers and at internet sites are not uncommon, which proves that defective or deviating products are not always identified before
they reach the customer. Traceability is important to minimize the extent of product recalls (Juran and Gryna, 1980), but also to be able to relate deviating products to potential causes. Traceability makes it possible to trace products through the supply chain back to the production process or even further upstream. Similarly, a high level of traceability makes it possible to identify products that are suspected to be affected by a known deviation in, for example, the production process.

To achieve traceability in discontinuous (discrete or batch) production can be rather straightforward since identification markers, such as bar codes or serial numbers, can be attached to the product/batch or its package and be scanned at predetermined locations in the distribution chain. The problems with traceability in discontinuous production are instead related to the design of a traceability system, see, for example, Petroff and Hill (1991), Cheng and Simmons (1994), and Ramesh et al. (1997).

Descriptions of traceability in continuous processes, common in the process industry, are scarce in the literature. Yet, traceability is important in process industry and especially in the food and pharmaceutical industries, see Flapper et al. (2002). Traceability has been in focus in the food and dairy industries since the 1990s due to the outbreak of food crises, such as, BSE (mad-cow disease), foot-and-mouth disease, and recently the scandal of infant milk tainted with Melamine in China.

Continuous processes are processes where the products are refined gradually and with minimal interruptions through a series of operations (Dennis and Meredith, 2000, Fransoo and Rutten, 1993). Kvarnström and Oghazi (2008) argue that continuous processes have special traceability concerns that need further attention. An important problem is that traceability systems normally rely on the definition of a batch. Hence, traceability becomes more complicated in continuous process, since continuous production has no natural batches that can be defined and traced.

In this article, we propose that Radio Frequency Identification (RFID) can be used to create 'virtual batches' in process industries with continuous flows. The idea is to use RFID transponders as start and end points of the virtual batches, which could then be traced in the distribution chain by reading the transponders. In this way traceability could be achieved in parts of the distribution chain for continuously operating process industries, where traceability previously has been difficult or even impossible.

To achieve traceability, the transponders need to behave similarly to the product they are intended to trace. Products from process industries are often in powder, fluid, slurry, granular form and other non-discrete states (Dennis and Meredith, 2000, Fransoo and Rutten, 1993). We argue that the RFID technique is currently best suited to trace products in granular form, since it may be difficult to achieve appropriate transponder flow properties for other non-discrete product flows.
Research show that differences in mechanical properties, such as size, shape, density, and surface roughness can lead to flow-induced segregation among individual products in granular form, see Aranson and Tsimring (2006). Hence, the transponders need to have similar mechanical properties as the granular product to prevent flow-induced segregation among products and transponders.

Possible benefits of improved traceability in process industries are many. For example, it provides an opportunity to study how the products are affected by the handling in the distribution chain, since product analyzes from different stages in the distribution chain can be compared. Furthermore, detailed flow models over previously poorly understood stages in the distribution chain can be created, for example, if and where flow-induced segregation of the products occurs. RFID can also make it possible to track low-quality products, for later disposal or downgrading. Perhaps most important, the RFID technique would make it easier to trace customer complaints back to the production process for identification of the sources of the complaints.

Today, RFID is frequently used in discontinuous process to improve traceability in the supply chain. For example, US Department of Defense, Wal-Mart, and Target Corporation have mandated their suppliers to be RFID enabled, see Speckman and Sweeney (2006). However, the use of the RFID technique to trace products in process industries with continuous production is scarce, but the idea was promoted already by Hind (1995) who suggested that RFID could be used to improve productivity in the mining industry.

Indeed, the use of RFID in process industries such as the minerals and mining industries is increasing, but the technique has, up to this day, mainly been used for applications such as employee safety, vehicle localization, and authorized access control. Despite an extensive literature search, only a few descriptions of applications where RFID have been used to improve productivity in process industries were found. Optimization of mine truck loading using RFID to aid the positioning of the trucks is a Swedish example where the RFID technique has been used to improve productivity and product quality in a process industry. An application more similar to the one described in this article was presented by Lauf (2008), where RFID transponders were attached to coal batches to improve power plant efficiency by an improved traceability of coal quality. In addition, RFID has been used to study the flow pattern of granular material in a small scale silo containing iron ore pellets, see Chen (2005).

We argue that our idea to add RFID transponders directly into the product flow to trace the movement of products is unexplored for process industries that handle granular materials. The different limitations of the RFID technique will likely affect the possibility to use it to improve traceability for granular products. Also, the specific process environment in which the technique is used will probably highlight certain obstacles that need to be overcome to use the technique. Application tests and piloting is needed to study the possibility to use the RFID technique in new ways, which is also highlighted by Penttilä et al. (2006).
The purpose of this article is to explore the application of RFID to improve traceability in a flow of granular products and to illustrate special issues that need to be considered when using the RFID technique in such settings. The article outlines a case study at a Swedish mining company focusing on experiments to investigate the suitability of the RFID technique to trace a continuous flow of granular products.

2. Traceability in the Process Industry

Process industries are according to the APICS dictionary (Blackstone, 2008, page 104) “the group of manufacturers that produce products by mixing, separating, forming and/or performing chemical reactions.” The raw material in process industries is typically unprocessed and comes directly from, for example, mines, forests, and farms, and is therefore normally afflicted with more variation than pre-processed raw material, see Fransoo and Rutten (1993). To reduce the consequences of variation in the raw material, large buffers and reflux flows are often used. Due to the reflux flows and varying buffer levels, the residence time in a process industry differs among individual products and it becomes hard to predict when a product will pass through a specific process section. Consequently, it is difficult to identify cause and effect relations between, for example, variability in the raw material and deviations in the final product. In addition, the added value to each product is often low in process industries which limits the resources that can be spent on traceability activities for each individual product. Moreover, the products in process industries often shift states during the production process which further complicates traceability initiatives. Several solutions (traceability methods) for different process sections throughout the production and delivery process may therefore be needed to achieve a good overall traceability. For a more thorough discussion of the problems to achieve a high level of traceability in process industries, see Kvarnström (2008).

This article discusses the use of the RFID technique to trace granular products. Kvarnström and Oghazi (2008) give an overview of other methods suitable to use at different process sections in process industries depending on product and process characteristics, for example, chemical tracers, radioactive tracers, and material signatures.

3. Radio Frequency Identification (RFID)

RFID is a wireless and automatic data capturing technique that resembles the bar code technique commonly used in consumer stores. According to Wyld (2006), the RFID technique has five primary abilities that make it different compared to bar codes: it does not require line of sight to be read, each transponder can have a unique code, it is more durable, it can hold more data, and it allows for almost simultaneous readings of multiple transponders. To use RFID requires a transponder, a reader, and software forwarding the information from the reader. The transponder can be attached to a product or added directly into the product flow. The reader communicates with the transponder through radio waves.
Transponders can be passive, without an energy source, or active, usually powered by a battery. Active transponders are larger and have an enhanced read range but a shorter life length and they are more expensive compared to passive transponders. Passive transponders are supplied with energy by the reader and therefore require more powerful readers. The transponder consists of four components: an antenna, a chip connected to the antenna, an energy source (if active), and a protecting shell. Today, passive transponders as small as 10 mm are available, but smaller transponders are continuously introduced on the market. The application described in this article uses only passive transponders.

The read rate (the percentage of read transponders) and the read range (the working distance between the transponder and the reader) are vital factors in an RFID application. According to Wyld (2006), the read rate is determined by transponder selection and placement, antenna selection and placement, and reader settings. Other factors that affect the read rate is the orientation of the transponder, motion speed of the transponder, and the number of transponders in the read area, see Porter et al. (2004). The read range for an RFID application varies from a few millimeters to above 15 meters, see Finkenzeller (2003). Wyld (2006) describes four variables that affect the read range:

- the frequency used for communication between the reader and the transponder (higher frequency gives a longer read range but makes the reader more sensitive to extraneous factors),
- the energy available in the system (more energy results in longer read range),
- the size of the transponder and the reader antenna, and
- environmental conditions and structures.

According to Want (2006), three primary problems hold back the widespread use of RFID: cost, design, and acceptance. There are also extraneous factors in processes that complicate the use of RFID. The presence of water and metal in the reading field can, for example, cause significantly decreased read rate, see Wyld (2006). Furthermore, there is a risk of radio signal interferences arising from, for example, walkie-talkies, which can interfere with the functionality of the reader, see Penttilä et al. (2006) and Wyld (2006).

4. Method

To explore the suitability to use RFID transponders to trace granular products in a continuous flow in process industry, a case study was performed with focus on experiments in the distribution chain of iron ore pellets at a Swedish mining company. In essence, the idea was to add passive RFID transponders into the product flow directly after the granular product had been manufactured. The movement of products through the distribution chain could then be traced by reading the transponders at predefined locations. To determine the suitability for the intended application it was important to test if the RFID transponders were possible to read,
behaved similarly to the original product throughout the distribution chain, and endured the stresses in the distribution chain. Hence, three experiments were conducted to determine the readability of the RFID transponders (experiment 1), test transponder behavior (experiment 2), and evaluate the transponders’ stress sensitivity (experiment 2 and 3), see Table 1. The following two sections describe the studied case and the experimental equipment.

### Table 1. Overview of the experiments described in this article. The type of transponder, transponder container, and the position for adding and reading of transponders are given for future reference.

<table>
<thead>
<tr>
<th>Experimental purpose and experiment code</th>
<th>Experiment type</th>
<th>Position for adding the transponder</th>
<th>Position for reading the transponder</th>
<th>Type of transponder/containers used in the experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Readability:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Experiment 1A</td>
<td>Laboratory</td>
<td>Laboratory</td>
<td>Laboratory</td>
<td>12 mm glass transponder</td>
</tr>
<tr>
<td>• Experiment 1B</td>
<td>Small scale</td>
<td>T3</td>
<td>T3</td>
<td>12 mm glass transponder</td>
</tr>
<tr>
<td><strong>Transponder behavior:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Experiment 2A</td>
<td>Full-scale</td>
<td>T1</td>
<td>T3</td>
<td>A, B, C, D, E, H</td>
</tr>
<tr>
<td>• Experiment 2B</td>
<td>Full-scale</td>
<td>T1</td>
<td>T3</td>
<td>A, B, C, D, E, F, G, H</td>
</tr>
<tr>
<td><strong>Stress testing and verification:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Experiment 3</td>
<td>Verification</td>
<td>T3</td>
<td>T3</td>
<td>F, G</td>
</tr>
</tbody>
</table>

### 4.1 The case: A distribution chain of iron ore pellets

There are many types of process industries with granular products in which the suitability of the RFID technique could be explored. In this work, the distribution chain of iron ore pellets (hereafter pellets) from Malmberget to Luleå at the Swedish mining company Luossavaara-Kiirunavaara AB (LKAB) was chosen to be studied. The distribution chain of pellets provided a possibility to test the RFID technique to improve traceability for a granular product. Also, LKAB showed a great interest to participate and support the study.

LKAB extracts and refines iron ore from deposits in northern Sweden and the primary product is various types of highly developed iron ore products. At the site in Malmberget (in focus in this article), there are two pelletizing plants, here called PP1 and PP2. The two plants each produce approximately 350-500 tonnes of pellets per hour. A simplified flow chart of the distribution chain in Malmberget is presented in Figure 1.
There are seven product silos (intermediate storages) in the distribution chain, see Figure 1. Since the level of the pellets in the silos varies over time, the residence time in the distribution chain varies accordingly. Moreover, loading and unloading of the product silos do not follow predetermined patterns and depends on the level in the silos at the time of departure or arrival of the train or the boat. Furthermore, some of the pellets are delivered directly to a customer in Luleå, without passing the harbor facility. Hence, the residence time will be shorter for some products. Finally, there is no constant time interval between shipments in the distribution chain and the capacity also varies between shipments. Altogether, these issues add to the complexity of traceability initiatives in the distribution chain.

Today, in case of customer complaints, LKAB cannot, without a substantial amount of work and vague assumptions, identify when a product was manufactured. It is therefore difficult to identify cause and effect relations between processing conditions and deviating product quality. Furthermore, it is often useful to be able to trace the location of a specific amount of products in the distribution chain, which is currently complicated. Improving traceability in the distribution chain would reduce the described problems. An improved traceability would also make it easier to produce and separate customer-specific products or products used for product development experiments. Moreover, improved traceability makes it possible to issue selective product warnings or, fairly exactly, recall a specific amount of products in the case of a known production problem or disturbance. Hence, in the long run, improved traceability increases competitiveness and profitability.

4.2 The experimental equipment

After discussions with the RFID supplier, the authors found that suitable positions to add and try to read the RFID transponders were on conveyors used at three positions in the distribution chain before the pellets reach the final customer. The first conveyor transports the pellets from the two pelletizing plants to the product silos in Malmberget (T1 in Figure 1), the second is located between the discharge of the train and the product silos in Luleå ore harbor (T2 in Figure 1), and the third moves the pellets from the product silos in Luleå to the boat.
The conveyors are 1.2 meters wide and move at a speed of 1 meter per second. The thickness of the pellet bed on the conveyors varies between 0.15 and 0.2 m.

An RFID reader was installed at the conveyor after the product silos in Luleå ore harbor (position T3 in Figure 1). A 1.35 meters wide and 0.5 meters high reader antenna was used and the antenna was mounted around the conveyor. When a transponder is read, the reader sends information to a transponder database containing:

- **Transponder ID**—the transponder's unique identification number,
- **Time**—the time when the transponder was read,
- **Number of readings**—the number of correct readings of each transponder during the passage of the reader, and
- **Maximum signal strength**—the maximum signal strength of the transponder during passage of the reader.

If the RFID-technique is found suitable, additional RFID readers can be installed at the other conveyors (position T1 and T2 in Figure 1) in the process and perhaps also at the customers to further improve traceability.

**5. Experiment 1 – Readability of RFID transponders**

In the first experiment, twelve mm long glass RFID transponders were used. The experiment was first performed in a laboratory environment (1A) and then in the actual distribution chain (1B). In 1A, the transponders' readability in the center of the reader antenna, the orientation in the x-y plane, and speeds up to two meters per second were tested with a temporary reader. For experiment 1B, the reader installed at position T3 (see Figure 1) was used.

Experiment 1B tested the sensitivity in orientation for stationary transponders, transponders under slow motion, transponders transported on the conveyor, and the minimum distance required between two transponders to read both. To test the minimum distance and orientation sensitivity a wooden lath with pre-drilled holes in different angles was used. Finally, tests were made to estimate the read rates that could be expected during actual running of the conveyor. During these tests, twelve transponders were placed on the conveyor during loading.

The results from the first experiment are summarized in Table 2 and Figure 2 explains how the different angles and planes should be interpreted in relation to the reader antenna in the orientation test, and describes the installation of the reader antenna around the conveyor.
Table 2. The results from experiment 1. Here α indicates the angle of the transponder in the specific plane. See Figure 2 for illustration of different values of α.

<table>
<thead>
<tr>
<th>Experiment code</th>
<th>Angles in which transponders cannot be detected</th>
<th>Minimum distance between transponders to be read in the y-axis direction</th>
<th>Read rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x-y plane (when z=0°)</td>
<td>x-z plane (when y=0°)</td>
<td>y-z plane (when x=0°)</td>
</tr>
<tr>
<td>1A: Laboratory  (speed 2 m/s)</td>
<td>80° &lt; α &lt; 100° right and left</td>
<td>Not tested</td>
<td>Not tested</td>
</tr>
<tr>
<td>1B: Static conveyor</td>
<td>70° &lt; α &lt; 110° right and left</td>
<td>70° &lt; α &lt; 110° up and down</td>
<td>All</td>
</tr>
<tr>
<td>1B: Test of moving unloaded conveyor (speed 1 m/s)</td>
<td>60° &lt; α &lt; 120° right and left</td>
<td>70° &lt; α &lt; 110° up and down</td>
<td>All</td>
</tr>
<tr>
<td>1B: Moving loaded conveyor during normal operation (speed 1 m/s)</td>
<td>Not tested</td>
<td>Not tested</td>
<td>Not tested</td>
</tr>
</tbody>
</table>

In a real case scenario, the angle of a transponder passing through the reader antenna is random and cannot be controlled. Mathematically, the possible angles for the RFID transponders passing through the antenna can be seen as equivalent to the surface area of a sphere with a radius corresponding to the length of the transponder. Thus, the fraction of transponders that can be read are identified by calculating the surface area that can be detected.
by the reader and dividing it by the surface area of an equivalent sphere. Since all the intervals of angles in which a transponder can be read are equilateral in a specific plane, the calculation can be simplified by calculating the readable angle interval for one section and then multiplying it by a constant equal to the number of sections. Using this approach, the read rate was calculated to 62.6 percent in the test of moving unloaded conveyor based on the detection limits given in Table 2, see also Formula 1. The boundaries for the integrals in Formula 1 equal the angles in Table 2 after conversion to radians.

\[
\frac{A_{\text{readable}}}{A_{\text{tot}}} = \frac{8 \cdot \int_0^{\pi/3} r^3 \sin \theta \, d\theta \, dr}{4 \pi r^2} = \ldots = \frac{2}{3} \cos(\pi/9) \approx 0.626
\]

From the results in Table 2, we conclude that an increased speed of the conveyor seems to have a small but negative effect on the read rate. This is in agreement with the results presented by Porter et al. (2004). Furthermore, the results from our experiments show that the orientation of the RFID transponder affects the read rate, which Porter et al. (2004) also concluded. The difference in orientation sensitivity between the $x$-$y$ plane and the $x$-$z$ plane can be explained by the rectangular form of the reader antenna used for the experiments. Furthermore, the read rate with load was 50 percent, which indicates a small reduction compared to the read rate without load, which was theoretically calculated to about 63 percent. The differences in read rates are however small and may be due to random variation, since only a few measurements were performed and some minor equipment problems occurred during the experiments. The problems were connected to data transfer between the reader and the software. These problems were resolved before the second experiment.

Based on the results from experiments 1A and 1B, it seems reasonable to assume that a read rate of approximately 50 percent can be expected on the conveyor using a 12 mm RFID transponder. According to the authors, this read rate was high enough to justify further application testing.

6. Experiment 2 – Transponder behavior

Although the results from Experiment 1 indicated that about 50 percent of the added RFID transponders could be read, questions that remained were [1] if the transponders could be designed to behave as pellets through the distribution chain without breaking, and [2] if larger RFID transponders than 12 mm could improve the read rate and still behave similarly to the pellets.

Hence, the second experiment was designed as a full-scale experiment in which different types of protective casings as well as sizes of RFID transponders were tested. The experiment was divided into two parts, experiments 2A and 2B, performed separately to minimize the effects of possible equipment malfunction during the experiment. In experiments 2A and 2B,
eight passive transponder-container combinations (from now on abbreviated TCCs), with various coating mixtures, shapes and sizes of transponders, were tested. An explanation of the different types of TCCs and the number of added TCCs in each experiment are presented in Table 3 and Figure 3.

In both experiment 2A and 2B the TCCs were added in random order with a 30 second interval onto the conveyor after the pelletizing plants (position T1 in Figure 1) and the transponder identification number, type of container, and adding time were recorded. The TCCs were to be read by the reader in Luleå harbor (position T3 in Figure 1).

The read rates for the different TCCs are presented in Table 4. Type H and G had the highest read rate. Of the tested characteristics, transponder size seemed to affect the read rates the most, see Table 5 and Table 6. No significant impact on the read rate was observed due to shape, and coating. Compared to Experiment 1, the read rate is somewhat lower for four out of five TCCs using the same 12 mm RFID transponder. Possible reasons for the decrease in read rate in the distribution chain are further discussed in connection with the results from Experiment 3.
Using RFID to Improve Traceability in Process Industry
- Experiments in a Distribution Chain for Iron Ore Pellets

Table 2. A description of the different TCCs tested in the full-scale experiments (2 and 3).

<table>
<thead>
<tr>
<th>Transponder-container combination (TCC)</th>
<th>Transponder size</th>
<th>Coating mixture for casing</th>
<th>Shape and size</th>
<th>Number of containers used in each experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2A</td>
</tr>
<tr>
<td>A</td>
<td>12 mm glass tube</td>
<td>60 % hematite and 40 % epoxy</td>
<td>Rectangular parallelepiped 16<em>6</em>6 mm</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>12 mm glass tube</td>
<td>30 % hematite and 70 % epoxy</td>
<td>Rectangular parallelepiped 16<em>6</em>6 mm</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>12 mm glass tube</td>
<td>60 % hematite and 40 % epoxy</td>
<td>Sphere 13 mm</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>12 mm glass tube</td>
<td>30 % hematite and 70 % epoxy</td>
<td>Sphere 13 mm</td>
<td>5</td>
</tr>
<tr>
<td>E (pellet)</td>
<td>12 mm glass tube</td>
<td>Inserted in predrilled pellet</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>F</td>
<td>22 mm glass tube</td>
<td>75 % dolomite and 25 % polyester composite</td>
<td>Cylinder 30*13 mm</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>22 mm glass tube</td>
<td>75 % dolomite and 25 % polyester composite</td>
<td>Sphere 30 mm</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>50 mm plastic disc</td>
<td>Polyvinylchloride</td>
<td>Hexagon 55<em>60</em>25 mm</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3. The TCCs tested in experiments 2 and 3 together with one iron ore pellet for comparison. The TCCs are coded according to Table 2.
Table 4. The read rates for the different TCCs in experiments 2A and 2B.

<table>
<thead>
<tr>
<th>Transponder-container combination (TCC)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read/total added</td>
<td>4/10</td>
<td>2/8</td>
<td>2/10</td>
<td>1/10</td>
<td>1/10</td>
<td>4/10</td>
<td>7/10</td>
<td>9/10</td>
</tr>
<tr>
<td>(read rate)</td>
<td>(40%)</td>
<td>(25%)</td>
<td>(20%)</td>
<td>(10%)</td>
<td>(10%)</td>
<td>(40%)</td>
<td>(70%)</td>
<td>(90%)</td>
</tr>
</tbody>
</table>

Table 5. The read rate for different transponder sizes and shapes in experiments 2A and 2B. Differences in coating mixture are not considered in this comparison. Each cell gives information about read rate, number of added transponders (in brackets), and type of TCC.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Transponder size</th>
<th>Oblong</th>
<th>Spherical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 mm</td>
<td>33 % (18) A, B</td>
<td>15 % (20) C, D</td>
</tr>
<tr>
<td></td>
<td>22 mm</td>
<td>40 % (10) F</td>
<td>70 % (10) G</td>
</tr>
</tbody>
</table>

Table 6. The read rate for different coating mixtures and shapes in experiments 2A and 2B. In this comparison, the transponder size is kept constant at 12 mm. Each cell gives information about read rate, number of added transponders (in brackets), and type of TCC.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Coating mixture</th>
<th>Oblong</th>
<th>Spherical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 % hematite and 70% epoxy</td>
<td>25 % (8) B</td>
<td>10 % (10) D</td>
</tr>
<tr>
<td></td>
<td>60 % hematite and 40% epoxy</td>
<td>40 % (10) A</td>
<td>20 % (10) C</td>
</tr>
</tbody>
</table>

To test for statistically significant differences among the TCCs, the number of readings and maximum signal strength were compared for the read transponders using multiple sample comparisons. We use the Tukey-Kramer procedure at 5% significance level. The Tukey-Kramer procedure, see Montgomery (Montgomery, 2005, pp. 94-95), assumes that the observations are independent and normally distributed with constant variance. A Shapiro-Wilks test was used to investigate if the residuals, generated by the Tukey-Kramer procedure, could be assumed to be normally distributed. Moreover, Levene’s test was applied to test the assumption of equal variances among the samples. Furthermore, we assume that the observations are independent since the containers were added in a random order. All prerequisites for using the Tukey-Kramer procedure were fulfilled for the number of readings, and by log-transforming the maximum signal strength. The results of the multiple sample comparison with 5% significance level are shown in Figure 4a and Figure 4b. Note that TCC D and E were excluded from the comparison since only one TCC of type D and E was detected.
The multiple sample comparison for number of readings in Figure 4a only shows a significant difference between TCCs A and H for number of readings. Furthermore, the multiple sample comparison for the log-transformed maximum signal strength in Figure 4b shows significant differences between the TCCs with the 22 mm transponders (types F and G) and two of the TCCs with the 12 mm transponders (types A and B), between the TCC with the 50 mm transponder (type H) and two of the TCCs with the 12 mm transponders (types A and B), and between TCCs G and C.

However, the limited number of observations (on average five observations per TCC) makes it difficult to find significant differences in means. Even though it was not possible to see any statistically significant effect on read rate for transponder size, the results indicate that TCCs using the 22 mm and 50 mm transponders are easier to detect than those using the 12 mm transponder. No significant difference for either maximum signal strength or number of readings was, however, found between the TCCs with the 22 mm transponders and the TCC with the 50 mm transponder or between TCCs with the same transponder size.

The behavior in the product flow of the different TCCs was evaluated less formally by comparing the sequence in which the TCCs were added and read and the difference in time interval between the addition and reading of TCCs. No obvious differences were found among different TCCs regarding the sequence.

However, at one time during the experiments, three TCCs of type H passed through the reader almost simultaneously, which may indicate a deviating behavior of type H compared to the pellets. Therefore, TCC H should not be used without further testing.

The overall results from experiment 2 indicated that TCC G followed by TCC F, both using 22 mm glass tube transponders were the most promising types. They both gave a good read rate and a behavior similar to the pellets in the product flow (even though they are both somewhat larger than an iron ore pellet).
7. Experiment 3 – Stress testing and verification

After having identified interesting candidates of TCCs, Experiment 3 was performed to further compare how the stresses in the distribution chain affected the read rate. Five units of TCC F and five units of TCC G were randomly added with a 30 second interval directly after the product silo at Luleå ore harbor during loading of a boat. The TCCs in Experiment 3 were thus exposed to less handling-induced stress than those tested in Experiment 2. The read rates in Experiments 2 and 3 can therefore be compared to give information about the possible stress effect (lost or broken TCCs) on the read rate.

By comparing the read rates from experiment 2 with experiment 3, we concluded that the read rate for TCC G was approximately the same, 70 % (7/10) for experiment 2 compared to 80 % (4/5) for experiment 3. The read rate for TCC F was, however, substantially lower in experiment 2B, 40 % (4/10) compared to 100 % (5/5) in experiment 3. Four tentative explanations for the decrease in read rate, besides chance, were recognized by the authors, see Table 7.

<table>
<thead>
<tr>
<th>Reason</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position in bed</td>
<td>Since there was a multi-layer bed of pellets on the conveyor, the transponder position in the pellets bed could affect the read rate. If the position in the pellet bed affects the read rate, the same decrease should have been noted for TCC G. Since this decrease was not seen, the position in the pellets bed was not a likely explanation for the decrease in the read rate.</td>
</tr>
<tr>
<td>Heat exposure</td>
<td>The TCCs may be damaged since the temperature of the pellets, when the containers are added, exceeds the temperature limit of the transponders. If the heat destroys the transponders, the same decrease in read rate would be expected for TCC G, since the difference in critical mass was low between TCCs F and G, while the time spent in the heat was extensive. Heat destruction was, therefore, not seen as a likely explanation in these cases.</td>
</tr>
<tr>
<td>Abrasion</td>
<td>Due to its form, TCC F may be more exposed to abrasion and more sensitive to abrasion in the distribution chain than TCC G. Consequently, the tendency to break could be higher for TCC F, which may explain the decrease in read rate for TCC F.</td>
</tr>
<tr>
<td>Lost transponders</td>
<td>The probability for a TCC to disappear or get stuck in the distribution chain is probably affected by its shape. For example, flat TCCs with sharp corners may have a higher probability to get stuck in, for example, chutes and product silos than square TCCs with rounded corners. However, no significant effect of the shape was found for the read rate in experiment 2, see Table 4, Table 5 and Table 6. Hence, the shape of the TCC was not the most likely explanation of the decrease in read rate in this case.</td>
</tr>
</tbody>
</table>

Abrasion is the most likely factor to have caused the decrease in read rate for the type F TCC. The decrease may depend on other factors than those described in Table 7, but the authors argue that the reasons described in Table 7 should be considered as typical examples of problems that need to be considered when designing the RFID application.

After the three experiments, the most promising TCC seems to be type G, which produced a high read rate in both experiments 2 and 3 and a behavior similar to the pellets in the product flow.
8. Conclusions and discussion

The results presented in this article show that the RFID technique can be used to improve the traceability in the distribution chain for iron ore pellets; a product flow that previously has been difficult to trace. We propose an application where RFID transponders are encapsulated in a protective casing and added directly into the product flow to create a ‘virtual batch.’ By following the movement of the transponders in the distribution chain the traceability is improved. The results indicate that read rates of up to 70 percent can be possible to achieve in the application, which we consider to be good.

For future full-scale applications, the number of added transponders and the interval between additions must be settled simultaneously considering the desired resolution of the traceability system and the natural mixing throughout the product flow, the cost of the transponders and their casing, and the read rate of the application. Concentrated investments to create detailed models of the product flow can motivate many transponders to be added within a short interval. During normal production, a less cost-intensive initiative can be enough to provide the desired traceability.

We argue that our proposed application of the RFID technique provides a method to substantially improve the traceability of granular products in, for example, distribution chains in industry. Examples of benefits that can be gained due to an improved traceability are: an increased knowledge about previously poorly understood flow phenomena in the distribution chain, the possibility to track low-quality products for later disposal or downgrading, and the tracing of customer complaints and product deviations (both positive and negative) to the processing conditions that may have caused the deviation. We note that other traceability methods may be required for other parts of the production process that can be combined with the RFID technique to achieve a desired overall traceability, see Kvarnström and Oghazi (2008). The use of the RFID technique to trace products in process industry is probably limited to other industries with similar products in granular form, since the size and the behavior of the RFID transponders and their protective casings may not match the needs in processes with, for example, products in powder or fluid form.

Our study shows that it was advantageous to use TCCs somewhat larger than the pellets, since the read rates observed for the TCCs with the smaller 12 mm transponders were considered insufficient. No obvious difference in behavior among the different TCCs in the distribution chain was seen during the experiments, except for the largest one - TCC H. Of the tested TCCs, a 22 mm glass tube transponder encapsulated in a protective spherical container made from a 75% dolomite and 25% polyester composite mixture (type G) performed best considering both read rate and behavior. Furthermore, an increased transponder size had a significant and positive effect on the numbers of readings and maximum signal strength. No significant effects were seen on the read rate due to different shapes of the transponder containers or coating mixtures.
We have also found some special issues that need to be considered when using the RFID technique in a process industry setting. One limiting factor for increased use of RFID for tracing granular products is the size of the transponder. Today the available sizes of transponders makes the technique is suitable to use for granular materials with particle size down to about 10 mm, but new application areas will appear due to the ongoing miniaturization of transponders. Another issue that we found was the heat sensitivity of the RFID transponders. The heat problem has, to our knowledge, not previously been discussed as a limiting factor in RFID literature. High temperature processes are common in process industries, and the temperature sensitivity is hence an important limiting factor for an increased use of the RFID technique. The heat sensitivity of the transponders can perhaps be decreased by giving the transponders an isolating casing. Moreover, products are often subjected to larger stresses in continuous processes than in parts production, due to, for example, large silos and transportation of products in chutes and on conveyors. The transponders’ stress sensitivity is therefore another factor that needs to be considered when using the technique in process industries.

A high read rate is vital to create a high level of traceability and to keep the RFID application cost-efficient. At the same time, the orientation of the transponders in a granular flow during passage of the reader is impossible to control and affects the read rate. We propose that one way of increasing the read rate of the application would be to use multiple readers, serially mounted at different angles in relation to the passage of the product flow. This should result in significantly higher read rates due to reduced sensitivity to transponder orientation. The increase of the read rate will depend on the possibility to rotate the angles of the readers and the number of additional readers. Another important issue when using the RFID technique in process industries will be to find suitable positions for the readers, since the read range is limited. In our study, suitable positions were found during transportation of the product on conveyors. However, for larger flows than the ones in this study, the size of the needed antenna can become a problem. A possible solution may be to divide a large flow into several smaller flows.

Another possible limitation for the application proposed in this article is that the RFID transponders and their casing can become a ‘contaminating factor’ in processes further downstream. This is not a problem for iron ore pellets where the transponders are melted by the heat in, for example, the blast furnace. It can, however, be problematic for other types of products and the transponders may have to be sorted out by the customer. There are various sorting methods available, for examples of ore sorting methods see Willis and Napier-Munn (2006). If there is a necessity to sort out transponders in the supply chain, it needs to be considered already during the design of the TCCs to avoid sorting problems.

In the future, we plan to perform additional experiments to investigate more thoroughly the effects of different characteristics, such as size, shape, and coating mixture. Furthermore,
future experiments using the RFID technique during normal operation would also make it possible to study residence time distributions, flow-induced segregation and mixing in the distribution chain.

About the authors

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Acknowledgements

The authors thank LKAB for the access to the studied case and the financial support that enabled this research. Furthermore, they thank Henrik Lindström and Juha Rajala at Electrotech for support with the mounting of the RFID reader and technical issues, Kent Tano and Sofia Nordqvist at LKAB for their valuable help with practical issues, and Bjarne Bergquist and Kerstin Vännman at Luleå University of Technology for valuable input to this article. The authors thank the editor and reviewers for insightful comments that improved this article.

References


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</tr>
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RFID to Improve Traceability in Continuous Granular Flows
- An Experimental Case Study

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Abstract: Traceability is important for identifying the root-causes of production related quality problems. Traceability can often be reached by adding identification markers on products, but this is not a solution when the value of the individual product is much lower than the incurred cost of a marking system. This is the case for continuous production of granular media. The use of Radio Frequency Identification (RFID) technique to achieve traceability in continuous granular flows has been proposed in the literature. We study through experiments different methods to improve the performance of such an RFID system. For example, larger transponders and multiple readers are shown to improve the RFID system performance.

1. Introduction

Defective products appear in most production processes due to, for example, human errors, failing production equipment or flaws in the raw materials. It may take a while before the operators detect that the process is off target, and the staff may hence need to identify the root-cause of the defects afterwards using off-line analysis. A production system therefore needs some element of traceability, that is, the ability to trace, track, and predict the location of a lot and its subcomponents through the supply chain. Furthermore, traceability is important for process control (Oakland, 1995), and reduces the extent of product recalls (Fisk and Chandran, 1975; Jacobs and Mundel, 1975). Traceability is also often requested through quality management systems, see for example ISO 9001 (2008, 7.5.3).

Kvarnström and Oghazi (2008) argue that continuous processes have special characteristics that complicate traceability. Continuous processes are processes where products are refined gradually and with minimal interruptions through a series of operations (Fransoo and Rutten, 1993; Dennis and Meredith, 2000).

Some products produced in continuous processes are in granular form, that is, conglomerates of discrete macroscopic particles, such as piles of wheat grains or gravel. Granular materials are often excavated directly from natural sources, and the physical characteristics of the granular materials, such as density, shape, and size, may therefore exhibit large variation. Moreover, granular materials tend to segregate due to differences in physical
characteristics, especially size, but also density (Ottino and Khakar, 2000; Hjortsberg and Bergquist, 2002), which further complicates traceability.

Kvarnström and Oghazi (2008) propose that the RFID (radio frequency identification) technique might be suitable for tracing granular material flows, as it is durable, offers automatic identification not requiring line of sight, and provides a unique identification. An RFID application in granular flows has also been demonstrated by Kvarnström and Vanhatalo (2010). However, we argue that the performance of an RFID system needs to be studied further. In this article we, therefore, investigate factors that may affect the performance of RFID systems in granular flows.

The article has the following structure. In Section 2 we introduce the RFID technique, as a means to create traceability in a granular continuous process, and outline the studied case process in Section 3. In Sections 4, 5, and 6, we identify and discuss methods to improve the performance of RFID systems in the intended application and present our four research questions. Sections 7 and 8 describe the two performed experiments and the results and conclusions are presented in Section 10.

2. Radio Frequency Identification (RFID)

An RFID system is an automatic identification systems that consists of readers, transponders, and a database, and it works as follows. The reader antenna constantly emits a radio signal. If a transponder is within the transmission field of the reader, the transponder is triggered and it returns a signal. The transponder signal is collected by the reader and stored in a database.

The design of the RFID system depends on many factors related to the considered application. The read range (the greatest distance at which a transponder can be read), cost sensitivity, and reader environment need to be considered (Lehpamer, 2008). Two types of RFID systems exist, of which the more common one is based on transponders with integrated circuits (IC), the other being based on transponders using surface acoustic waves (SAW). Since the SAW technique is less common and was not known by the authors at the time of the experiment, the IC type systems are used and discussed in this paper and referred to as RFID. For an extensive description of RFID, see Finkenzeller (2003), Shepard (2005), or Lehpamer (2008).

The RFID transponders are usually attached to individual units or batches. However, for all cases we can think of, it would be too expensive to equip all granules in continuous granular flows with RFID transponders, since the value of each granule is low compared to a transponder. Furthermore, it is not possible to mark batches in these flows since the continuous flow implies that there are no batches. A solution is to create virtual batches, with transponders acting as markers of the batch borders, so that the movement of these batches may be monitored.
3. The Case

Luossavaara-Kiirunavaara AB (LKAB) is a Swedish mining company that produces iron ore pellets (hereafter pellets). The company has two major production sites, and this article studied the distribution chain of pellets from the Kiruna production site to the customers through the harbor of Narvik. The distribution chain from Kiruna to the customers contains continuous granular flows and it is therefore a suitable process for the study.

The studied distribution chain includes three intermediate storage steps, two longer transports (one by train and one by boat), and several shorter transports on conveyors between storages and the longer transports, see Figure 1. The production process and distribution chain together contain a mixture of continuous and batch flows, and can therefore be categorized as a semi-continuous process. The inflow to the buffer silos at the product plant is continuous, while the remaining flows are batch flows. The batch volumes of pellets going into or out of the process sections are not constant. Instead, the buffer levels and arrival or departures of trains and boat determine the batch volumes. Traceability in the distribution process is further complicated by the design of some process steps, where the flow includes mixing or reflux. The combination of intermittent and continuous flow induces variation in the residence time (the time it takes for a unit to move between two locations) of the granules.

![Figure 1. The studied pellets production and distribution chain at LKAB.](image)

4. Performance of an RFID System

The performance of an RFID system is primarily determined by the read rate (the rate of transponders read) and the read range. The read range also defines the systems’ reading field, that is, the three-dimensional volume in which a reader can read a transponder.

The read rate and read range are affected by several factors, see for instance Wyld (2006), Porter et al. (2004), and Rao et al. (2005). In this article we focus on:

- the transponder type,
- the transponder response threshold,
- the transponder position and orientation,
The reader antenna position and orientation, and
the angle between the transponder and the reader antenna.

The reason for choosing to study these factors is that we assume them easiest to change in a system while other characteristics, such as transponder orientation in a continuous product stream, are hard to control. The first three characteristics are discussed in Section 5 and the remaining two in Section 6.

5. Transponder Selection

When choosing an IC type RFID transponder, the first choice is if the transponder should be passive or active. Active transponders offer longer read ranges than the passive transponder and can log sensory data. On the other hand, the passive transponders are smaller and cheaper. The next choice is the system’s radio frequency band. High frequency (HF) transponders have longer read ranges, but a low frequency (LF) radio signal has superior penetration ability. The size of the transponder antenna also has a direct effect on the read range. Larger transponder antennas produce longer read ranges but demand larger transponders. See also Liu et al. (2009).

5.1 Granular segregation

In this article, transponders are inserted into the granular product flow. Granular flows where the properties of individual granules differ tend to segregate. The transponders therefore need to have similar behavior as the granular media when the purpose is to trace it. It is reasonable to expect that a transponder with similar size, shape, and density as a granule will behave similarly and thus follow the granular product. Granules are often small, which places a restriction on the size of any transponder that shall be used to replicate the granular motion. RFID transponders are manufactured as small as 50*50 μm, so called RFID dust, and the transponders may thus be available for the smallest type of granules. However, since small transponders usually have lower read rates (Rao et al., 2005) and have shorter read ranges, small granule-like encapsulated transponders may be hard to detect. Therefore, some RFID applications may need to use transponders with casings larger than the granules to get an acceptable read rate.

The risk of segregation occurs where the granular media exhibit flow gradients, for example, during discharge of silos or other buffer systems. However, it may be possible to compensate differences in one physical property by changing another. Several researchers have investigated how to avoid segregation due to vertical vibrations, the so-called Brazil-Nut effect. To minimize the effect of vertical vibrations Hong et al. (2001) conclude that spheres with different diameters could be given the density according to the following equation

\[
\frac{d_p}{d_i} \approx \frac{\rho_s}{\rho_l}
\]
where $d_s$ is the diameter of the smaller sphere, $d_l$ is the diameter of the larger sphere, $ho_s$ is the density of the smaller sphere, and $\rho_l$ is the density of the larger sphere.

5.2 Transponder selection

For the LKAB distribution chain, we decide to use passive LF transponders due to their smaller size and their superior penetration ability. Kvarnström and Vanhatalo (2010) have shown that transponders with similar size as the granule have low read rate (approximately 20%). The use of larger transponders may increase the read rate (Kvarnström and Vanhatalo, 2010), but we suspect that larger transponders may segregate. Therefore, this study aims to investigate the following research questions:

1) May transponder density be used to compensate for segregation due to size differences?
2) May the transponder size and casing affect the performance of the RFID system? If so, in what way?

Research question 1 and 2 are here explored using transponders with different sizes and different types of protective casings. Each combination of transponder size and protective casing is denoted as a treatment to underline that both transponder sizes and casing combinations may vary.

6. Reader Antenna Position and Orientation

The RFID system performance is closely related to the reader and reader antenna design and power. The optimal antenna design and power is determined by the position and orientation of the antenna, the background noise, and the transponder type. However, in bins or storages, the range between the transponders and the reader may be too far even with optimal antenna power, but transportation locations, for example, conveyors may offer suitable read ranges.

The orientation between the reader antenna and the transponder antenna in a system also affects the read range. Systems where the required read range is larger than the read range for the worst combination of reader and transponder orientation are called orientation sensitive. The read rate for orientation sensitive systems will thus vary if the orientation of the transponder cannot be controlled.

6.1 Design of reader antenna and dropping mechanism

The reader and transponder antenna design for this study is orientation sensitive and described further in Kvarnström and Vanhatalo (2010). One remedy for such systems is to use three-dimensional transponder antennas. However, these transponders are larger than suitable for this application and are therefore disregarded. Another option is to use reader antennas placed at different orientations to be able to detect different transponders, which is used here. We hypothesize that multiple readers with different antenna orientations and positions will improve the read rate. The reader performance as a function of the antenna orientation or position is also of interest. We therefore examine the following research questions:
3) May multiple reader antennas improve the performance of an RFID system? If so, in what way?

4) May the reader orientation or position affect the performance of an RFID system? If so, in what way?

According to Lehpamer (2008), the presence of multiple transponders in the reading field of a reader antenna increases the read time. This may be problematic since the transponders in our case stay less than two tenths of a second within the reading field. Therefore, the transponders are inserted into the product stream at specific intervals with a dropping mechanism. The dropping mechanism used is located between the pelletizing plant and the buffer silos at the plant and it records the time for insertion and the transponder identity.

7. Research Method

Two experiments were performed to seek answers to the four research questions. The first experiment was analyzed before the second one was performed so that the first results could influence the design of the second.

Two RFID readers (reader 1 and 2) with different antenna orientations and positions were installed at a conveyor between the buffer silos and the product silos at the plant, see Figure 2 and Table 1. The readers were installed 20 meters apart to avoid reader-to-reader disturbances.

Table 1. Descriptions of the readers.

<table>
<thead>
<tr>
<th>Reader</th>
<th>Antenna position</th>
<th>Antenna orientation</th>
<th>Length (meters)</th>
<th>Width (meters)</th>
<th>Speed of conveyor (meters/second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reader 1</td>
<td>Below conveyor</td>
<td>Lying below the conveyor</td>
<td>2,0</td>
<td>0,5</td>
<td>3</td>
</tr>
<tr>
<td>Reader 2</td>
<td>Around conveyor</td>
<td>Standing around the conveyor</td>
<td>2,0</td>
<td>0,5</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 2. Left: Reader 1 and 2 mounted between the buffer silos and the product silos at the production plant. Right: The two reader-antenna shapes. The antenna of reader 1 is mounted under the conveyor and the antenna of reader 2 is mounted around it.

We used two response variables for the analysis of the experiments. The first response variable measures if the reader have read the transponder or not. The second response variable
measures the transponder residence time, that is, the time between the insertion of the transponder into the product stream and the reading of the transponder by reader 1 or 2.

The process setting, like silo levels and the production speed varied over time in the studied process. We were interested in performing experiments at different process settings to obtain results that were valid for many process settings. The variation in process settings cause heterogeneity in the pellets’ residence time. Therefore, a block structure was chosen for the experiment so that the residence time performance at different production settings could be compared. Each block was performed with different process settings.

However, note that since we use passive, battery free transponders, we do not expect that the residence time variation would affect the system’s read rate. Hence, the block partitioning is only of interest when evaluating the transponder residence time and not for read rate comparisons. The dropping mechanism was charged with the transponders in random order within each block. Note that residence time was only available for the read transponders.

8. Experiment 1

In the first experiment, we tested three treatments described below in addition to the two reader antennas earlier described. Treatment A is a transponder with a similar size, shape, density, and surface structure as a regular pellet, and it was used to emulate the pellet’s flow behavior. Treatment A may thus be called a control treatment to which other types of treatments could be compared. The pellets are normally spherical, with a diameter ranging from nine to fifteen millimeters and the density of a pellet is approximately 4.3 g/cm³. Treatment A contain a 12 mm long low radio frequency passive transponder encapsulated in a spherical protective casing with a diameter of 14 mm and a density of 4.3 g/cm³, see Figure 3 and Table 2.

![Figure 3. From left a pellet, the 12 mm transponder, and the three treatments used in experiment 1.](image)

The other two treatments, B and C, both contained a 22 mm long transponder and their casings were therefore larger than a pellet, but their casing design differed. Treatment B had a casing with a cylinder shape, a length of 24 mm, and a diameter of 12 mm. A spherical casing was used for treatment C with a diameter of 24 mm. B’s casing was more similar to the pellets in volume and in size in two dimensions, whereas C maintained the spherical shape of a pellet, albeit being larger. For more details about the treatments, see Figure 3 and Table 2. The
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densities of treatment B and C were set according to equation (1). We expected a higher read rate for treatment B and C than treatment A. However, we feared that B and C would have different flow behavior compared to treatment A, and anticipated that any diversity in flow behavior would be manifested in differing residence times.

The first experiment was performed in three blocks, and all three treatments were used in each block. We wanted to have similar expected numbers of transponders read for each treatment to get an experiment as balanced as possible when comparing the residence time. Hence, the higher read rate for the 22 mm transponders observed by Kvarnström and Vanhatalo (2010) was reflected in the design. Each block therefore contained 40 treatment A transponders but only 16 transponders each of treatments B and C, see Table 3. The numbers of read transponders are also given in Table 3.

**Table 2.** The treatments used in experiment 1.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Transponder size [mm]</th>
<th>Material mixture for casing</th>
<th>Density [grams/centimeter³]</th>
<th>Casing shape and size</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12</td>
<td>35 % lead oxide, 25 % dolomite and 40 % epoxy</td>
<td>4.3</td>
<td>Sphere with diameter 14</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>20 % lead oxide, 40 % dolomite and 40 % epoxy</td>
<td>3.2</td>
<td>Cylinder length 24 and diameter 14</td>
</tr>
<tr>
<td>C</td>
<td>22</td>
<td>10 % lead oxide, 50 % dolomite and 40 % epoxy</td>
<td>2.5</td>
<td>Sphere with diameter 24</td>
</tr>
</tbody>
</table>

**Table 3.** Summary of the number of inserted and read transponders in experiment 1.

<table>
<thead>
<tr>
<th>Block</th>
<th>Treatment</th>
<th>Number of transponders inserted</th>
<th>Number read by reader 1</th>
<th>Numbers read by reader 2</th>
<th>Overall number read (reader 1 or reader 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>40</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>16</td>
<td>12</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>16</td>
<td>10</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>40</td>
<td>0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>16</td>
<td>9</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>16</td>
<td>8</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>40</td>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>16</td>
<td>7</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>16</td>
<td>9</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>In total</td>
<td></td>
<td>216</td>
<td>55</td>
<td>78</td>
<td>98</td>
</tr>
</tbody>
</table>
8.1 Comparison of the residence time

The residence time in each block in experiment 1 differed largely because of the discontinuous out-flow from the silo. However, no data regarding discharge times were stored in the process and the level measurement within the silos was too inexact to use. We, therefore, had to make a coarse estimation of the discharge times. Figure 4 and Table 4 show the residence time for each block after it was compensated for the estimated discharge times.

Figure 4. Dot-plots for the estimates of the residence time within each block, coded according to treatment. Block 1 at the top, block 2 in the center, and block 3 at the bottom. Note 1) that the mean level of the residence time differs between the blocks. Note 2) the large difference in residence time between block 2 and the other two blocks.
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Table 4. Number of read transponders for each treatment within each block, mean and standard deviation of residence time for the treatments within blocks. Note the different number of observations in Table 3 compared to Table 4. The difference is caused by the dropping mechanism that failed to detect a few of the transponders before insertion into the pellets flow. Consequently, the residence time could not be calculated for all transponders, whereas the read rates could be determined.

<table>
<thead>
<tr>
<th>Block</th>
<th>Treatment</th>
<th>Number of observations</th>
<th>Mean residence time [s]</th>
<th>Standard deviation, residence time[s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>4</td>
<td>4152</td>
<td>1374</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>9</td>
<td>5827</td>
<td>810</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>9</td>
<td>5168</td>
<td>1216</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>4</td>
<td>60558</td>
<td>2591</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>10</td>
<td>61494</td>
<td>1571</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>8</td>
<td>61631</td>
<td>1294</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>3</td>
<td>6392</td>
<td>777</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>7</td>
<td>7559</td>
<td>1077</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>8</td>
<td>7414</td>
<td>1320</td>
</tr>
</tbody>
</table>

Both Figure 4 and Table 4 indicate a shorter residence time, and thus a different flow behavior, for treatment A compared to the other treatments. Furthermore, in two of the three blocks (block 2 and 3) there is only a small difference in mean residence time between treatment B and treatment C.

8.2 Comparison of the read rate for treatments and readers

We are also interested in how the treatments and the readers affect the read rate. It is reasonable that the number of read transponders can be modeled using a binomial distribution. Hence, we fit a logistic regression model to analyze the read rate data. The general logistic regression model is

$$
\pi = \frac{\exp(\mathbf{x}'\mathbf{\beta})}{1 + \exp(\mathbf{x}'\mathbf{\beta})} = \frac{1}{1 + \exp(-\mathbf{x}'\mathbf{\beta})}
$$

where $\pi$ is the probability to read a transponder, $\mathbf{x}' = [1, x_1, x_2, \ldots, x_5]$ is the vector of regressor variables, and $\mathbf{\beta} = [\beta_0, \beta_1, \beta_2, \ldots, \beta_5]$ is the corresponding vector of coefficients. This model is a special case in the family of generalized linear models (GLM). For a GLM with a binomial distributed response, the logit link function used in model (2) is the standard choice, see Myers et al. (2010). For more details about GLM, see Dobson and Barnett (2008) or Myers et al. (2010). The logistic regression model estimated here, including interaction terms, is

$$
\pi = \frac{1}{1 + \exp\left(-\left(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5\right)\right)}
$$

where $\beta_i$, $i = 1, 2, \ldots, 5$ are the coefficients, $x_1$ is 1 for treatment B and else –1, $x_2$ is 1 for treatment C and else –1, and $x_3$ is 1 for reader 2 and –1 for reader 1. We use the GLM option
in JMP® 8.0.2 for the analysis of model (3). Moreover, we apply the Firth bias adjusted estimates technique implemented in JMP® 8.0.2 for the analysis, since the technique improves the estimation of the coefficients, see Firth (1993).

In the fitted model, the main effects of treatment as well as the treatment-reader interactions effects are significant at 5% significance level, see Table 5, and the main effect of the reader is close to the significance threshold of 5% (Prob.>Chi-Sq. = 0.0596). The likelihood ratio test shows that the full model is significantly better than the minimal model. The Pearson chi-square and the deviance goodness-of-fit test methods compare the performance of the fitted model to the saturated model. Since the probabilities Prob.>Chi-Sq. are well above 0.05 for both tests we conclude that the fitted model provides a satisfactory fit to the data. Furthermore, the residual analysis does not give reasons to reject the fitted model. For a thorough discussion of the model tests see, for example, Collett (1991), Hosmer and Lemeshow (2000), and Dobson and Barnett (2008).

Table 5. The result of the logistic regression analysis based on model (3). \( \hat{\beta}_i, i = 0, 1, \ldots, 5 \) are the estimated coefficients in (3).

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>S.E. Coef.</th>
<th>Chi-Sq.</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>( \hat{\beta}_0 )</td>
<td>0.3749</td>
<td>0.1602</td>
<td>8.9674</td>
</tr>
<tr>
<td>Treatment B</td>
<td>( \hat{\beta}_1 )</td>
<td>2.0354</td>
<td>0.4087</td>
<td>106.2938</td>
</tr>
<tr>
<td>Treatment C</td>
<td>( \hat{\beta}_2 )</td>
<td>1.9067</td>
<td>0.4078</td>
<td>89.9268</td>
</tr>
<tr>
<td>Reader</td>
<td>( \hat{\beta}_3 )</td>
<td>0.0871</td>
<td>0.1602</td>
<td>3.5488</td>
</tr>
<tr>
<td>Treatment B*Reader</td>
<td>( \hat{\beta}_4 )</td>
<td>-0.8717</td>
<td>0.4087</td>
<td>13.3324</td>
</tr>
<tr>
<td>Treatment C*Reader</td>
<td>( \hat{\beta}_5 )</td>
<td>-0.9588</td>
<td>0.4078</td>
<td>16.6405</td>
</tr>
</tbody>
</table>

Goodness-of Fit Tests

<table>
<thead>
<tr>
<th>Method</th>
<th>Chi-Sq.</th>
<th>DF</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson</td>
<td>14,1569</td>
<td>12</td>
<td>0.2908</td>
</tr>
<tr>
<td>Deviance</td>
<td>15,2859</td>
<td>12</td>
<td>0.2262</td>
</tr>
</tbody>
</table>

Likelihood Ratio Test

<table>
<thead>
<tr>
<th>Difference between reduced and full model</th>
<th>-Log Likelihood</th>
<th>DF</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67.0778</td>
<td>5</td>
<td>&lt;0.0001*</td>
</tr>
</tbody>
</table>

Model (3) has similar coefficient estimates for B and C and the two estimated coefficients for the treatment-reader interactions are also similar. We therefore suspect the transponder size, and not the casing differences, to be the primary reason for the difference in the read rates.
Note that treatments B and C have the same transponder size and only differ in casing, see Table 2. Hence, the following simplified logistic regression model is considered

\[ \pi = \frac{1}{1 + \exp\left(-\left(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 x_4 \right)\right)} \]  (4)

where \( x_1 \) is 1 for reader 2 and −1 for reader 1, and \( x_2 \) is 1 for the 22 mm transponder and −1 for the 12 mm transponder. Table 6 gives the result of the analysis of model (4).

Table 6 shows that the coefficients for the main effects of the transponder size and the reader, as well as the reader-transponder size interaction effects are all significant, with Prob.>Chi-Sq. < 0.001. Furthermore, neither the likelihood ratio test, the goodness-of-fit tests, nor the residual analysis gives reason to reject the fitted model. After comparison of models (3) and (4), we conclude that (4) performs slightly better, since all parameters in (4) are significant with low values of Prob.>Chi-Sq. Furthermore, the values of Prob.>Chi-Sq. for the Pearson chi-square and the deviance goodness-of-fit tests are larger for model (4) than (3). Model (4) is also more parsimonious. Based on the conclusion that model (4) is slightly better; we conclude that differences in transponder size are the major cause for differences in read rate. The effect on the read rate due to the casing design is hence not discernible.

### Table 6. The result of the logistic regression analysis based on model (4). \( \hat{\beta}_i, i = 6, 7, 8, 9 \) are the estimated coefficients in model (4).

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>S.E. Coef.</th>
<th>Chi-Sq.</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.5955</td>
<td>0.3685</td>
<td>87.1104</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Reader</td>
<td>1.0015</td>
<td>0.3685</td>
<td>25.4714</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Transponder size 22</td>
<td>1.9717</td>
<td>0.3685</td>
<td>161.4487</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Reader *Transponder size 22</td>
<td>-0.9161</td>
<td>0.3685</td>
<td>20.7004</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

### Goodness-of-Fit Tests

<table>
<thead>
<tr>
<th>Method</th>
<th>Chi-Sq.</th>
<th>DF</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson</td>
<td>15.3908</td>
<td>14</td>
<td>0.3520</td>
</tr>
<tr>
<td>Deviance</td>
<td>16.4276</td>
<td>14</td>
<td>0.2880</td>
</tr>
</tbody>
</table>

### Likelihood Ratio Test

<table>
<thead>
<tr>
<th>Difference between reduce and full model</th>
<th>-Log Likelihood</th>
<th>DF</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>84.2662</td>
<td>3</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

Figure 5 shows the 95% confidence intervals for the expected read rate according to the fitted model (4) for both transponder sizes and readers. For details about calculations of the confidence intervals, see Myers et al. (2010, pp. 141-143). Note that the confidence intervals...
for the two readers overlap for the larger transponders. Hence, the mean read rate is not significantly different for the two readers when large transponders are used. The confidence intervals in Figure 5 for the small transponders do not overlap. Hence, for the small transponders there is a significant difference in the mean read rate. Moreover, there is a significant difference between the read rate for large and small transponders for both readers and we conclude that the 22 mm transponder gives a significantly higher read rate compared to the 12 mm transponder.

Figure 5. 95% confidence intervals for the expected read rate according to model (4) for the reader and transponder size combinations.

8.3 The effect on the read rate using multiple readers

The effect on the observed read rate from using multiple readers is seen in Figure 6. The comparison does not include treatment A, since treatment A is not read by reader 1. Figure 6 shows that the combination of reader 1 and 2 increases the read rate for treatment B in all three blocks and for treatment C in 2 out of 3 blocks. From Table 3 we see that, if ignoring treatment A, 55 transponders were read by reader 1 and 59 were read by reader 2. Using the two readers jointly, 79 of all 96 transponders were read. Hence, using two readers instead of one increases the average observed read rates for all blocks for treatment B and C from approximately 60% to approximately 80%. Comparing the overall read rate using two readers to the read rate from reader 1, we find the difference in read rate to be at least 14%, using an approximate 95% one-sided confidence interval. The overall read rate is at least 10% higher than the read rate of reader 2. Hence, two readers with different antenna orientations and positions will improve the performance for the RFID system, if the system uses the 22 mm
transponders. Note that since not only the orientation versus the conveyor differs, but also the position of the antenna, we cannot isolate which of these or if both affect the read rate.

Figure 6. A column chart over the read rates for each of the readers (reader 1 and reader 2) and the read rates if information from both readers is used (overall).

8.4 Conclusions and discussion of experiment 1

The purpose of experiment 1 is to see if transponder casing properties and transponder size, as well as the use of multiple readers with different reader antenna orientations and positions affect the performance of the RFID system. In this section, we discuss research questions 1 to 4, in light of the results of experiment 1.

Research question 1: The result in experiment 1 indicates that treatments B and C have longer residence times than treatment A. Hence, the density and size compensation method based on equation (1) does not appear to work for the granular distribution system in this study.

Research question 2: Figure 5 shows that the two transponder sizes have different read rates. The difference between the read rates for treatments that contain the same transponder sizes is small with overlapping confidence intervals, and we therefore assume that it is the transponder size, rather than casing design that determines read rate.

Research question 3: There is a significant increase in read rate for the 22 mm transponders when information from two readers was used instead of information from one reader only. The smaller transponders are only read by one of the readers. Two readers with different antenna positions and orientations may therefore increase the read rate.
Research question 4: Experiment 1 shows that for the 12 mm transponder the two readers perform differently, but the difference in read rate for the 22 mm transponders was insignificant for the two readers. Hence, the reader arrangement affects the read rate for small transponders.

In experiment 1, the storage volume varied between the blocks, but it is hard to say if these differences affected the results due to the large variation. However, the conclusions related to our research questions are more or less consistent for all blocks. We therefore assume that the result should be valid within the range of tested storage volumes. It also seems likely that the conclusions hold true for storage volumes outside the experimental region.

9. Experiment 2

Since the low-density treatments B and C had longer residence times than treatment A in the first experiment, the second experiment was set up to study two new treatments (M and H) with a higher density than A see Table 7. Moreover, both treatments were shaped as C, that is, as spheres. We also decided to perform the experiment in five blocks instead of three to cover a larger range of storage volumes in the experiments. Instead, fewer transponders were used in each block to produce a similar total number of transponders read as in the first experiment. Another difference between the experiments was that a new volume measurement technique had been installed at the buffer silos that improved the precision in the residence time compensations. A summary of the second experiment is given in Table 8.

Table 7. The treatments used in experiment 2. Note 1) that treatment M and A have the same density as the pellets. Note 2) that treatment H has a higher density than the pellets and the other treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Transponder size [mm]</th>
<th>Material mixture for casing</th>
<th>Density (grams/centimeter³)</th>
<th>Shape and size</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12</td>
<td>35 % lead oxide, 25 % dolomite and 40 % epoxy</td>
<td>4,3 Sphere with diameter 14</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>22</td>
<td>35 % lead oxide, 25 % dolomite and 40 % epoxy</td>
<td>4,3 Sphere with diameter 24</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>22</td>
<td>60 % lead oxide, 0 % dolomite and 40 % epoxy</td>
<td>6,1 Sphere with diameter 24</td>
<td></td>
</tr>
</tbody>
</table>
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Table 8. Summary of the number of inserted and read transponders in experiment 2.

<table>
<thead>
<tr>
<th>Block</th>
<th>Treatment</th>
<th>Number of transponders inserted</th>
<th>Numbers read by reader 1</th>
<th>Numbers read by reader 2</th>
<th>Overall number read (reader 1 or reader 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>30</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>30</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>30</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>30</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>30</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

In total 210 48 52 68

9.1 Comparison of the residence time

The compensated residence time for each transponder is shown in Figure 7, where two possible outliers are seen in block 3. We exclude the two outliers from further analysis, since the discontinuous discharge can explain the difference in residence time for these two transponders. Figure 7 also shows that the average residence times differ between blocks. We continue the analysis and perform a two-way ANOVA with treatment and block as factors to compare the residence time for the treatments. Table 8 shows that the number of read transponders differs for the treatment and block combinations. Hence, the two-way ANOVA will be unbalanced. This implies that a general linear model is needed to analyze the experiment, see, for example, Milliken and Johnson (2009).

The following model is assumed:
\begin{equation}
    y_{ijk} = \mu + \tau_i + \beta_j + (\tau \beta)_{ij} + \epsilon_{ijk}
    \end{equation}

where \( \mu \) is an overall mean, \( \tau_i \) is the \( i \)-th treatment effect, \( \beta_j \) is the \( j \)-th block effect, \( (\tau \beta)_{ij} \) is the interaction effect between the \( i \)-th treatment and the \( j \)-th block, and \( \epsilon_{ijk} \) is the normally and independently distributed \( N(0, \sigma^2) \) random error term for the \( k \)-th observation of the \( i \)-th treatment in the \( j \)-th block.

**Figure 7.** Scatter plot showing the compensated residence time for each transponder within each block. Note 1) that two transponders with treatment M within block 3 show a deviating residence time. Note 2) that the average residence times differ between the blocks.

The residual analysis of the ANOVA for model (5) shows violation of the constant variance assumption and that the variance differs between the blocks. We therefore perform a weighted ANOVA by analyzing a simple transformation of the residence time according to the following model:

\begin{equation}
    y'_{ijk} = y_{ijk} / w_j = \mu + \tau_i + \beta_j + (\tau \beta)_{ij} + \epsilon_{ijk}
    \end{equation}

where \( w_j \) is the standard deviation of residence time for the \( j \)-th block. In model (6), the standard deviation \( w_j \) is unknown and in the analysis, the estimated standard deviation is used. We use JMP® 8.0.2, with \( y'_{ijk} \) as response for the calculations. The residual analysis of the estimated model in (6) does not show that the model assumptions are unreasonable.

**Table 9** presents the result of the ANOVA. The only significant effect at 5% significance level is the block effect, see also Figure 7. Hence, there is no reason to reject the assumption that treatments H and M have a similar residence time as treatment A within the studied buffer silos.
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Table 9. The ANOVA for the weighted general linear model in (6) for the residence time

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adjusted Sum of Squares</th>
<th>Adjusted Mean Square</th>
<th>F-ratio</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td>4</td>
<td>2360,18</td>
<td>590,04</td>
<td>631,15</td>
<td>0,000</td>
</tr>
<tr>
<td>Treatment</td>
<td>2</td>
<td>0,06</td>
<td>0,03</td>
<td>0,03</td>
<td>0,967</td>
</tr>
<tr>
<td>Block*Treatment</td>
<td>8</td>
<td>12,83</td>
<td>1,60</td>
<td>1,72</td>
<td>0,117</td>
</tr>
<tr>
<td>Error</td>
<td>52</td>
<td>48,61</td>
<td>0,93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9.2 Comparison of the read rate for treatments and readers for experiment 2

To compare the read rate for treatments and readers in experiment 2 we use logistic regression analysis. The logistic regression model used to fit the results of experiment 2, including the interaction terms, is:

$$\pi = \frac{1}{1 + \exp(- (\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4))}$$

(7)

where $\beta_i$, $i = 1,2,...,5$ are the coefficients, $x_1$ is 1 for treatment M and else −1, $x_2$ is 1 for treatment H and else −1, and $x_3$ is 1 for reader 2 and −1 for reader 1. The result of the analysis of model (7) is similar to the result of the analysis in experiment 1. We therefore suspect that the transponder size can be the primary reason for the difference, as in experiment 1. Hence, the following simplified logistic model is considered:

$$\pi = \frac{1}{1 + \exp(- (\beta_0 + \beta_3 x_3 + \beta_4 x_4))}$$

(8)

where $\beta_i$, $i = 6,7,8,9$ are the coefficients, $x_3$ is 1 for reader 2 and −1 for reader 1, and $x_4$ is 1 for the 22 mm transponders and −1 for the 12 mm transponders. Table 10 gives the result of the analysis based on model (8).

Table 10 shows that the coefficients for the reader, the transponder size, and the reader-transponder size interaction are all significant, with Prob.>Chi-sq<0.001. The likelihood ratio test, the goodness-of fit tests, and the residual analysis show no reason for rejection of model (8). After comparisons of models (7) and (8), we conclude that the models perform similar but model (8) is more parsimonious and therefore preferable.
Table 10. Logistic regression results based on model (8): $\hat{\beta}_i$, $i = 6, 7, 8, 9$ are the estimated coefficients in model (8).

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>S.E. Coef</th>
<th>Chi-Sq.</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>$\hat{\beta}_0$</td>
<td>-1.5144</td>
<td>0.3184</td>
<td>74.1640</td>
</tr>
<tr>
<td>Reader</td>
<td>$\hat{\beta}_1$</td>
<td>0.6616</td>
<td>0.3184</td>
<td>13.0226</td>
</tr>
<tr>
<td>Transponder size 22</td>
<td>$\hat{\beta}_2$</td>
<td>2.3239</td>
<td>0.3184</td>
<td>267.3075</td>
</tr>
<tr>
<td>Reader * Transponder size 22</td>
<td>$\hat{\beta}_3$</td>
<td>-1.2076</td>
<td>0.3184</td>
<td>46.8416</td>
</tr>
</tbody>
</table>

**Goodness-of Fit Tests**

<table>
<thead>
<tr>
<th>Method</th>
<th>Chi-Sq.</th>
<th>DF</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson</td>
<td>18.7903</td>
<td>26</td>
<td>0.8476</td>
</tr>
<tr>
<td>Deviance</td>
<td>23.2271</td>
<td>26</td>
<td>0.6201</td>
</tr>
</tbody>
</table>

**Likelihood Ratio Test**

<table>
<thead>
<tr>
<th>Difference between reduce and full model</th>
<th>-Log Likelihood</th>
<th>DF</th>
<th>Prob.&gt;Chi-Sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>158.4281</td>
<td>3</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

Figure 8 shows the 95% confidence intervals for the expected read rate according to model (8) for the different transponder sizes and readers. The figure shows that there is no significant difference in the read rate for the two readers when the 22 mm transponders are used, since the confidence intervals overlap. However, we see a significant difference in read rate between the two readers for 12 mm transponders. Figure 8 also shows that the use of 22 mm transponders instead of 12 mm transponders significantly improves the read rate for both reader 1 and reader 2.

The two logistic regression models for the experiments, model (4) and (8), do have similar parameters estimates. Hence, we may compare the analysis results of the two experiments for validation purpose.
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Figure 8. The 95% confidence intervals for the reader and transponder size combinations based on (8).

9.3 The effect on the read rate using multiple readers

One purpose of the experiment was to test if use of multiple readers improves the read rate, and the effect of multiple readers on the read rate is seen in Figure 9. The read rate comparison does not include treatment A, since treatment A was not read by reader 1. In all but one block, reader 1 reads the most transponders, and the overall read rate is improved by the use of the additional reader 2 in two cases, see Figure 9. From Table 8 we see that, if ignoring treatment A, 48 transponders were read by reader 1 and 34 were read by reader 2. Using the two readers jointly 50 transponders were read among the 60 transponders dropped. Hence, the use of two readers in experiment 2 gives an average read rate exceeding 80% for the 22 millimeter transponders. A similar read rate was observed in the first experiment using two readers.

Comparing the overall read rate using two readers to the read rate from reader 2 we find the difference in read rate to be at least 13%, using an approximate 95% one-sided confidence interval. Hence, the use of two readers gives a significantly higher read rate than the use of only reader 2. Although we found transponders that we would not have found using only reader 1 and thus logically find a positive effect of having two readers, this difference is not statistically significant. The increase in the read rate for the 22 mm transponders when information from both readers are used is therefore not as pronounced in experiment 2 as in experiment 1.
9.4 Conclusions and discussion of results from experiment 2

We now discuss research questions 1 to 4, in light of the results of experiment 2. Research question 1: The result of experiment 2 does not indicate that the residence time differs between treatment A and the two other treatments. Hence, the experiments indicate that density can be used to avoid segregation due to size differences. In the experiment, a density equal or higher than the smaller spherical transponder treatment gave the two larger treatments similar residence times as the pellets shaped transponder.

Research question 2: Experiment 2 shows that the transponder size affects the read rate. However, the experiment does not show difference in read rate for the two treatment densities with the same transponder size. The two experiments consequently give similar results.

Research question 3: In experiment 2, we could logically see that the use of two readers increased the read rate slightly compared to using only reader 1 since reader 2 detected two transponders that had passed reader 1 undetected, but the increase was not statistically significant. The increase was however significant compared to using only reader 2. The increase in read rate from using two readers was larger in experiment 1.

Research question 4: Based on experiment 2, we conclude that for the 12 mm transponder, reader 2 has a significant higher read rate. The read rate for the 22 mm transponder is higher with reader 1 than reader 2, but the difference is small and not statistically significant. The two experiments, hence, gave similar results concerning research question 4.
10. Conclusions and discussion

The article aimed to study how the performance of an RFID system in continuous granular flows can be improved. Table 11 summarizes the research questions and the experimental findings.

Table 11. A summary of the experimental results connected to the four research questions.

<table>
<thead>
<tr>
<th>Research question</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>May transponder density be used to compensate for segregation tendencies that occur due to size differences? We did not detect segregation tendencies if the larger transponder treatment had equal or higher density than the smaller transponder with similar physical characteristics as the granular product.</td>
</tr>
<tr>
<td>2</td>
<td>May the transponder type and casing affect the performance of the RFID system? If so, in what way? Transponder sizes had a significant effect on the performance of the RFID system. The analysis of the experiment showed no effect in the performance depending on the transponder casing.</td>
</tr>
<tr>
<td>3</td>
<td>May multiple reader antennas improve the performance of an RFID system? If so, in what way? A significant increase in read rate was seen for the 22 mm transponders using two antennas instead of one in most of the experimental runs. The read rate for the 12 mm transponder was not increased by using multiple antennas, which is because only one of the two readers could detect it.</td>
</tr>
<tr>
<td>4</td>
<td>May the reader orientation or position affect the performance of an RFID system? If so, in what way? For the 12 mm transponder, the two readers with different orientation and position performed differently, where the reader under the conveyor belt did not detect any transponders. We cannot conclude if the orientation or the position was the reason behind the difference. No significant difference was found between the two readers for the 22 mm transponder.</td>
</tr>
</tbody>
</table>

We identified two methods to increase the performance of an RFID system in a continuous granular flow. The largest performance increase was obtained by the use of larger 22 mm transponders, instead of 12 mm transponders. However, the casing design is important to avoid the segregation tendencies occurring with the larger transponders. Nevertheless, larger transponder casings could be designed to have similar residence time as smaller transponders with pellet like properties. The read rate could also be improved using multiple RFID reader antennas with different orientations and positions, but the improvement obtained by adding a reader below the conveyor was prominent only for the 22 mm transponders, whereas the smaller transponders only were detected by the antenna mounted around the conveyor.

That the 22 mm transponders could be read by an antenna below the conveyor belt is interesting since conveyor belts tend to oscillate sideways and may thereby damage antennas.
mounted around the them. Placing antennas below the conveyors also makes assembly and disassembly of the reader antenna easier.

Finally, conducting experiments in the continuous distribution chain of pellets led to many difficulties. We agree with Vanhatalo and Bergquist (2007) that experimentation in continuous processes implies special considerations that need to be tackled already during the planning phase. The complexity of experimentation in continuous processes may lead to that some experimental runs fail, and consequently, to missing data, and it is therefore important that the experimental designs are robust versus missing data. Experimental evaluation of antenna positions and orientations is time consuming and difficult. Another option is to use simulations, at least as a preliminary tool before installation, see Lindgren et al. (2010).

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A Method to Determine Transition Time for Experiments in Dynamic Processes
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A Method to Determine Transition Time for Experiments in Dynamic Processes

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Abstract: Process dynamics is an important consideration during the planning phase of designed experiments in dynamic processes. After changes of experimental factors dynamic processes undergo a transition time before reaching a new steady state. To minimize experimental time and reduce costs and for experimental design and analysis, knowledge about this transition time is important. In this article, we propose a method to analyze process dynamics and estimate the transition time by combining principal component analysis and transfer function-noise modeling or intervention analysis. We illustrate the method by estimating transition times for a planned experiment in an experimental blast furnace.

Keywords: Time series analysis, Transition time, Principal component analysis, Transfer function-noise model, Intervention analysis, Design of Experiments, Blast furnace.

1. Introduction

Dynamic processes are frequently found in continuous process industries, where production steps such as: mixing, melting, chemical reactions, silos, and reflux flows contribute to their dynamic characteristics. Planning, conducting, and analyzing experiments in dynamic processes highlights special issues that the experimenter needs to consider. Examples of such issues are: process dynamics (inertia), a multitude of responses, large-scale and costly experimentation, and many involved people, see Hild et al. (2000) and Vanhatalo and Bergquist (2007). In this article we focus on the dynamic characteristic of continuous processes and argue that process dynamics must be considered during the experimental planning phase.

In a dynamic process, a delay, here called the transition time, will occur between the change of an experimental factor until the response is affected, whereas in a responsive system, this change is almost immediate, see, for example, Saunders and Eccleston (1992) and Black-Nembhard and Valverde-Ventura (2003). Consequently, time series of the responses need to be studied after each experimental treatment is applied to allow for the possible effect of the experimental treatment to manifest itself. By contrast, responses can often be measured on individual experimental units directly after the experimental treatment has been applied in many parts production processes.

When planning an experiment in a dynamic process it is important to have some knowledge of the transition time caused by process dynamics. The transition time affects the required length of each experimental run and long transition times may call for restrictions in
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the randomization order of the experimental runs, see, for example, Vanhatalo and Vännman (2008). Knowledge about the transition time will help the experimenter to avoid experimental runs that are either too short for a new steady state to be reached, and thus wrongly estimate the treatment effects, or unnecessarily long, which increases costs. Including response observations from the transition time in the analysis of the experiment will likely lead to underestimation of location effects and overestimation of dispersion effects. By knowing the required transition time, the experimenter can choose a better design that produces the needed information at a lower cost, without jeopardizing experimental validity.

Determining the transition time in a dynamic continuous process can be difficult due to a number of reasons. Continuous processes are often heavily instrumented to measure different aspects of the process and the product, and multiple responses are often needed to capture the effect of experimental treatments. The transition time may also vary for different responses and treatment changes may affect some responses but not all. Process variables are typically correlated and often react to the same underlying event, see Kourti and MacGregor (1995). In such cases latent variable techniques such as principal component analysis (PCA) can be used to achieve data reduction and aid interpretation, see, for example, Wold et al. (1987) and Jackson (2003).

The sample rates of the measurements in continuous processes are often frequent enough to estimate process dynamics, usually with a higher sampling frequency than the frequency of the process oscillations. Slow drifts and oscillations combined with high sampling frequencies lead to positively autocorrelated responses. The autocorrelation indicates that time series analysis could be a useful analysis tool. Time series analysis contains techniques where stochastic and dynamic models are developed to model the dependence between observations sampled at different times. The time series analysis techniques transfer function-noise modeling and intervention analysis have been proposed to model the dynamic relation between an input time series $X_t$ and an output series $Y_t$ and between a known intervention at time $t$ and an output series $Y_t$ respectively, see, for example, Box et al. (2008), Wei (2006), and Montgomery et al. (2008).

In this article, we propose a formal method to determine the transition time in the planning phase for experiments in a dynamic process. The proposed method combines multivariate statistical methods and time series analysis techniques to analyze process dynamics and estimate the transition times in dynamic processes. Section 2 introduces the method where PCA summarizes the systematic variation in a multivariate response space. Transfer function-noise modeling or intervention analysis is then used to model the dynamics and determine the transition time between an input time series event and output time series response using principal component scores. The approach is illustrated in Section 3 using data from an experimental blast furnace.
2. Proposed method

Continuous processes running in, for example, process industries usually have servers filled with old data, and often important processes that have run for some time have undergone trials or experiments to improve them. This means that engineers often can locate past interventions that coincide with those planned for an upcoming experiment. If similar past interventions do not exist, a trial run (if possible) designed to induce the transition may be justified to estimate the transition times. Typical engineering knowledge should be enough to set up a trial run where the experimental factor(s) are changed and allowing for the process settle after each change. When there are no past data available and trial runs are not possible, the engineer must consult his or her prior knowledge to settle the transition time with the associated uncertainty. The formal method proposed in this paper assumes that data from the process are available.

Normally, analysis of continuous processes is a multivariate task, and determining the transition time can be rather difficult. For this problem we use PCA to create a few, independent, linear combinations of the original response variables that together summarize the main variability in the response space. We then use time series analysis on the principal component scores to investigate the transition time. The following sections introduce PCA and the time series analysis techniques transfer function-noise models and intervention analysis.

2.1 Principal component analysis (PCA)

PCA can reduce the dimensionality of the response space by extracting a few new, latent, uncorrelated variables called principal components (linear combinations of the original variables) that together explain the main variability in the data, see, for example, Johnson and Wichern (2002) and Jackson (2003). The use of the PCA technique to summarize the response space is outlined below.

Let \( \mathbf{y} = [y_1, y_2, \ldots, y_m] \) represent a random response vector describing an \( m \)-dimensional response variable with covariance matrix \( \Sigma \). Let \( \Sigma \) have the eigenvalue-eigenvector pairs \((\lambda_1, \mathbf{p}_1), (\lambda_2, \mathbf{p}_2), \ldots, (\lambda_m, \mathbf{p}_m)\). The \( m \) principal components (PCs) are formed as linear combinations of the original responses:

\[
\begin{align*}
    PC_1 &= \mathbf{p}_1^\prime \mathbf{y} = p_{11}y_1 + p_{12}y_2 + \cdots + p_{1m}y_m \\
    PC_2 &= \mathbf{p}_2^\prime \mathbf{y} = p_{21}y_1 + p_{22}y_2 + \cdots + p_{2m}y_m \\
    &\vdots \\
    PC_m &= \mathbf{p}_m^\prime \mathbf{y} = p_{m1}y_1 + p_{m2}y_2 + \cdots + p_{mm}y_m
\end{align*}
\]

The PCs are orthogonal to one another, ordered according to their variances. The first PC has the largest variance, the second PC the second-largest variance and so on, where the eigenvalues, \( \lambda_a, \ a = 1, 2, \ldots, m \), are the variances of the PCs. The eigenvectors, \( \mathbf{p}_a, \ a = 1, 2, \ldots, m \), have unit length, \( \mathbf{p}_a^\prime \mathbf{p}_a = 1 \), and are called the PC loading vectors. PCA is scale-dependent and the responses are usually scaled to unit variance, using standardized variables, before the PCA. The PCs of the standardized variables are obtained by calculating the
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eigenvalues and eigenvectors of the correlation matrix of \( y \) instead of the covariance matrix, see, for example, Johnson and Wichern (2002). In the applications studied here we scale to unit variance before the PCA and, hence, use the correlation matrix of \( y \) to derive the eigenvectors and eigenvalues.

The correlation matrix is unknown in practice and estimated by the sample correlation matrix calculated from an observed \( n \times m \) \( Y \) matrix with \( n \) observations of each of the \( m \) responses. The values of the PCs for each observation are here called PC scores, and the score vectors, \( t_a, a = 1, 2, \ldots, m \), represent the \( n \) observed values of the PCs based on the observed \( Y \) matrix.

The goal of the PCA is reduction of dimensionality, and if the variables are highly correlated, much of the systematic variation described by a correlation or covariance matrix can be described using \( A < m \) dimensions, and the remaining \( m - A \) dimensions are considered to contain mostly random noise. The underlying assumption is that the first few PCs with larger associated variances represent interesting signals in the data, while higher-order PCs only are related to the noise. The method outlined in this article then tests if the signals in the first few PCs are correlated to, for example, the change of experimental factors.

The loading vectors, \( p_a, a = 1, 2, \ldots, A \), define the reduced dimensional space \( A \) with respect to the original responses and the score vectors, \( t_a, a = 1, 2, \ldots, A \), are the projections of the original observations onto the \( A \)-dimensional reduced space.

The number of retained principal components \( A \) can be derived by several methods, see Jackson (2003). One way is to extract the number of components that are needed to reproduce a specific fraction of the variance of the original response data. When working with standardized variables, it is also common to only keep PCs with eigenvalues larger than one, so each PC explains at least as much of the total variation as one of the original variables. Cross-validation, see Wold (1978), is also frequently used to select the appropriate number of components.

If only the \( A \) first PCs are used to approximate the variability in \( Y \), we can write:

\[
Y = TP' = \sum_{a=1}^{A} t_a p'_a + E
\]

where \( T \) is an \( n \times m \) matrix with the score vectors as rows, \( P' \) is an \( m \times m \) matrix with the loading vectors as columns, and \( E \) is the \( n \times m \) residual matrix.

2.2 Transfer function-noise models

This section gives a brief introduction to transfer function-noise models. For further descriptions, see, for example, Jenkins (1979), Box et al. (2008, Chapter 11), Wei (2006, chapter 14), Bisgaard and Kulahci (2006), and Montgomery et al. (2008, chapter 6).

Consider the single-input time series \( x_t \) and the single-output time series \( y_t \). Assume that the input time series can be represented by a quantitative continuous variable. Further
assume that the input time series has been manipulated and we want to study its effect on the output. Note that the output series could be an original response or, as proposed in this article, a linear combination of many responses represented by principal components. Assume that both $x_t$ and $y_t$ are zero-mean stationary time series and that they are related through the linear filter:

$$y_t = \nu(B)x_t + N_t$$  \hspace{1cm} (3)

where $B$ is the backshift operator on $t$, $\nu(B) = \sum_{i=0}^{\infty} \nu_i B^i$ is the transfer function, and $N_t$ represents the unobservable zero-mean noise. The number of coefficients in $\nu(B)$ are usually assumed to be limited to a fairly small number and to follow the structure:

$$\nu(B) = \frac{\omega(B)}{\delta(B)} = \frac{\omega_0 - \omega_1 B - \ldots - \omega_r B^r}{1 - \delta_1 B - \ldots - \delta_t B^t}$$ \hspace{1cm} (4)

The coefficients $\omega_0, \ldots, \omega_r$ and $\delta_1, \ldots, \delta_t$ determine the structure of the transfer function, $\nu(B)$, and $s$ and $r$ are the orders of the numerator and denominator respectively. The coefficients $\nu_t$, also called the impulse response function, can be obtained recursively from the coefficients $\omega_0, \ldots, \omega_r$ and $\delta_1, \ldots, \delta_t$, see Montgomery et al. (2008, chapter 6). Sometimes there is a delay before $x_t$ starts to affect $y_t$. If we assume that this 'pure delay' is $b$ time units, the transfer function-noise model can be represented by:

$$y_t = \frac{\omega(B)}{\delta(B)} x_{t-b} + N_t$$ \hspace{1cm} (5)

Furthermore, it is assumed that $N_t$ is uncorrelated with $x_t$ and that $N_t$ can be represented by an autoregressive integrated moving average model, ARIMA$(p, d, q)$:

$$\Phi(B)(1-B)^d N_t = \Theta(B) \varepsilon_t$$ \hspace{1cm} (6)

where $\Phi(B) = (1 - \phi_1 B - \ldots - \phi_p B^p)$, $\Theta(B) = (1 - \theta_1 B - \ldots - \theta_q B^q)$, and $\{ \varepsilon_t \}$ represents white noise. See, for example, Montgomery et al. (2008) for more on how to fit ARIMA models.

By combining (5) and (6), the transfer function-noise model can be expressed as:

$$y_t = \frac{\omega(B)}{\delta(B)} x_{t-b} + \frac{\Theta(B)}{\Phi(B)(1-B)^d} \varepsilon_t$$ \hspace{1cm} (7)

### 2.3 Identifying transfer function-noise models

The following seven steps are taken to obtain the transfer function, $\nu(B)$, and the noise model, see also Montgomery et al. (2008). In the following descriptions we assume that the input and output series have been scaled so the mean is zero for each series.
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Step 1: Prewhiten the input series \( x_i \)
If the input series \( x_i \) is autocorrelated, the method of prewhitening is needed to obtain the transfer function. Prewhitening is a procedure that transforms the input series \( x_i \) into white noise. Normally, an appropriate ARIMA model is used to filter \( x_i \):

\[
\alpha_i = \frac{\Phi \{ (B) (1 - B)^d \} x_i}{\Theta \{ B \}}
\]

(8)

where the filtered input series, \( \alpha_i \), should be white noise with zero mean and variance \( \sigma^2_a \).

Step 2: Apply the prewhitening filter to the output series \( y_i \)
The same prewhitening filter is then applied to the output series \( y_i \) to obtain

\[
\beta_i = \frac{\Phi \{ (B) (1 - B)^d \} y_i}{\Theta \{ B \}}
\]

(9)

where the filtered output series has variance \( \sigma^2_y \) and is not necessarily white noise. The cross correlation function between the prewhitened input series \( \alpha_i \) and filtered output series \( \beta_i \) is directly proportional to the weights, \( \nu_i \), in the transfer function. We have the following relation, see Montgomery et al. (2008),

\[
\nu_i = \frac{\sigma_y}{\sigma_x} \rho_{xy} (i)
\]

(10)

where \( \rho_{xy} (i) \) is the cross correlation function between \( \alpha_i \) and \( \beta_i \) at lag \( i, i = 0, \pm 1, \pm 2, \ldots \).

Step 3: Obtain initial estimates of the impulse response function \( \nu_i \)
Using the sample estimates \( \hat{\rho}_{xy} (i) \), \( \hat{\sigma}_a \), and \( \hat{\sigma}_y \) of \( \rho_{xy} (i) \), \( \sigma_a \), and \( \sigma_y \), respectively and applying Eq. (10) we obtain the initial estimates of the impulse response function \( \nu_i \) as:

\[
\hat{\nu}_i = \frac{\hat{\sigma}_y}{\hat{\sigma}_a} \hat{\rho}_{xy} (i)
\]

(11)

Montgomery et al. (2008) recommend using \( \pm 2 \sqrt{n} \), where \( n \) is number of observations in the time series, as the approximate 95 % confidence interval to judge the significance of the cross correlations and thus the estimated weights \( \hat{\nu}_i \).

Step 4: Specify \( b \), \( r \), and \( s \) and obtain a preliminary estimate of the transfer function
The possible delay, \( b \), is identified by studying \( \hat{\rho}_{xy} (i) \). A tentative specification of the orders \( r \) and \( s \) in the transfer function is made by matching the pattern of \( \hat{\nu}_i \), obtained from (11), with known theoretical patterns. Examples of theoretical patterns of the impulse response function for comparison can be found in, for example, Box et al. (2008, p. 453), Wei (2006, pp. 325-
When \( b, r, \) and \( s \) have been chosen, preliminary estimates \( \hat{\theta}_j \) and \( \hat{\delta}_j \) can be obtained through their relationships with \( \tilde{b}_j \). Thus, a tentative transfer function can be formed as:

\[
\hat{\chi}(B) = \frac{\hat{\omega}(B)}{\hat{\delta}(B)}
\]

**Step 5: Model the noise \( N_t \)**

Once the preliminary transfer function has been established, the estimated noise series, \( \hat{N}_t \), can be calculated as:

\[
\hat{N}_t = y_t - \frac{\hat{\omega}(B)}{\hat{\delta}(B)} x_{t-s}
\]

By studying the time series plot, the autocorrelation function and the partial autocorrelation function of the estimated noise series in (13), an appropriate ARIMA model is chosen to model any remaining structure in the noise series.

**Step 6: Fit the overall model**

The first five steps have produced a tentative model specification:

\[
y_t = \frac{\omega(B)}{\delta(B)} x_{t-s} + \frac{\Theta(B)}{\Phi(B)(1-B)} \varepsilon_t
\]

The final estimates of the parameters \( \delta = (\delta_1 \ldots \delta_p)' \), \( \omega = (\omega_1 \ldots \omega_p)' \), \( \varphi = (\phi_1 \ldots \phi_p)' \), and \( \theta = (\theta_1 \ldots \theta_q)' \) are obtained by an iterative maximum likelihood fit of the specified model to the time series.

**Step 7: Model adequacy checks**

The validity of the estimated model is studied by checking two important assumptions of the fitted model. First, the residuals from the model, \( \varepsilon_t \), should be white noise. Second, the independence between \( x_t \) and \( \varepsilon_t \) should also be checked, see also Wei (2006) and Montgomery et al. (2008).

### 2.4 Intervention analysis

This section provides a brief introduction to intervention analysis and its application to study the effect of a known intervention on an output time series. For further descriptions, see Jenkins (1979), Box et al. (2008, Chapter 13), and Wei (2006, chapter 10).

Assume that the single-output time series \( y_t \) is affected by a known event such as a change of a qualitative treatment. For example, different input materials to a continuous process may have to be represented by a qualitative indicator variable summarizing all possible differences in the materials. Let
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\[ y_t = \frac{\phi(B)}{\theta(B)} x_{t-h} + \frac{\Theta(B)}{\Phi(B)(1-B)^\delta_t} \delta_t \]  

(15)

where \( \xi_{t-h} \) is a binary deterministic indicator variable with value 0 for nonoccurrence, and with value 1 for occurrence of the specific event and \( b \) determines the possible pure delay of the intervention effect. Two common types of indicator variables are the step variable:

\[ S_t^{(s)} = \begin{cases} 0, & t < T \\ 1, & t \geq T \end{cases} \]  

(16)

and the pulse variable:

\[ p_t^{(p)} = \begin{cases} 1, & t = T \\ 0, & t \neq T \end{cases} \]  

(17)

where \( T \) is the time of the intervention.

Due to the deterministic nature of the indicator time series, the method of prewhitening is no longer meaningful. The form of the intervention model must therefore be specified by considering the mechanisms that might cause the change and by studying the time series to suggest an appropriate model, see Jenkins (1979).

A step function is well suited for the intervention exemplified in this article, a shift of raw materials. Assuming that the intervention can be represented by the simple step variable in Eq. 16, Figure 1 shows the intervention response for different values of \( \delta_t \) given a transfer function on the form \( \phi(B)/(1-\delta_t B) \). Often a gradual response is reasonable to assume, which corresponds to the case \( 0 < \delta_t < 1 \).

Figure 1. Response to an intervention in form of a step function based on a step variable and a simple transfer function depending on different values of \( \delta_t \). The figure is adapted from Box et al. (2008, p. 531).
3. Transition time in an Experimental Blast Furnace

To illustrate the proposed approach to determine the transition time in a dynamic process we use data from an Experimental Blast Furnace (EBF). The EBF is owned and operated by Luossavaara–Kiirunavaara AB (LKAB), a Swedish producer of iron ore products (iron ore pellets in particular). The EBF is a pilot scale blast furnace, specifically designed for experimental purposes and the production capacity of the EBF is approximately thirty-five tons of hot metal per day (compared to up to 10,000 tons per day for the largest full scale furnaces). For more details about the experiments run in the EBF, see Vanhatalo and Bergquist (2007) and Vanhatalo and Vännman (2008).

Two of the most frequently used experimental factors in the EBF are the types of iron bearers (mostly iron ore pellets) and the blast parameter settings. The transition time after changes of these experimental factors is not fully known but highly important when planning the experiments in the EBF. Figure 2 presents an outline of the EBF and examples of measurement possibilities.

3.1 Transition time when changing oxygen content in the blast air

During experiments in the EBF, it is often of interest to change the production rate to test the raw materials under different conditions. The production rate can be changed either by altering the oxygen content of the blast or by changing the blast volume. The needed transition time when changing the oxygen content is therefore important to estimate. Responses calculated from, for example, pressure sensors and thermocouples in the EBF can be used to study how the process reacts to the changes. Table 1 presents the responses used to analyze the transition time for the EBF.

![Figure 2. Outline of the EBF. Examples of possible responses are underlined. The two types of changes studied in this article (pellets and oxygen content in the blast air) are indicated by bold uppercase font.](image-url)
A Method to Determine Transition Time for Experiments in Dynamic Processes

Table 1. Important process responses from the EBF. The numbering is for future reference.

<table>
<thead>
<tr>
<th>Response</th>
<th>Unit</th>
<th>Response</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential pressure over furnace</td>
<td>bar</td>
<td>12. Gas speed top</td>
<td>m·s⁻¹</td>
</tr>
<tr>
<td>Differential shaft pressure, dp5–45°</td>
<td>bar</td>
<td>13. Flame temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Differential shaft pressure, dp5–225°</td>
<td>bar</td>
<td>14. Production rate</td>
<td>ton·h⁻¹</td>
</tr>
<tr>
<td>Top temperature</td>
<td>°C</td>
<td>15. Specific blast volume</td>
<td>m³·ton⁻¹</td>
</tr>
<tr>
<td>Temperature BR 1</td>
<td>°C</td>
<td>16. Direct reduction rate, DRR</td>
<td>%</td>
</tr>
<tr>
<td>Temperature BR 2</td>
<td>°C</td>
<td>17. Solution loss</td>
<td>kg[C]·ton⁻¹</td>
</tr>
<tr>
<td>Burden descent rate</td>
<td>cm·min⁻¹</td>
<td>18. Wall flow index</td>
<td>°C</td>
</tr>
<tr>
<td>ΨCO (CO gas utilization)</td>
<td>%</td>
<td>19. Center flow index</td>
<td>°C</td>
</tr>
<tr>
<td>Cooling effect tuyeres</td>
<td>kW</td>
<td>20. Top gas flow</td>
<td>m³·ton⁻¹</td>
</tr>
<tr>
<td>Blast speed</td>
<td>m·s⁻¹</td>
<td>21. Burden resistance index, BRI</td>
<td>No unit</td>
</tr>
<tr>
<td>Gas speed furnace</td>
<td>m·s⁻¹</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: m³·N refers to the corresponding gas volume under standard conditions of 1 atmosphere pressure and 0°C.

When planning for an experiment in the EBF it was of interest to estimate the transition time when changing the oxygen content of the blast air between two target values: 45 and 90 m³·N/h. Consequently, data from a past experiment in the EBF were located, where the same target values had been used. The data consisted of 371 observations (hourly averages) for each of the responses in Table 1 and during these 371 hours the oxygen content had been changed from high to low level and back to the high level again.

PCA was conducted on the response variables listed in Table 1. We found that the first PC, which explains the largest part of the variability in the responses, separates the two oxygen contents. See Figure 3a-b, where the scores t₁ of the first PC are plotted against the scores t₂ of the second PC. We conclude that the change of oxygen content seems to explain the main variability visible in the responses in Table 1. None of the other PCs showed similar clear dependence on the oxygen content. Hence, only the scores t₁ will be studied in the following analysis. Figure 4 shows a time series plot of the 371 observations on t₁ together with the input oxygen content.

Table 2. Results from the PCA on the 371 observations of the responses in Table 1.

<table>
<thead>
<tr>
<th>PC</th>
<th>Explained variance [%]</th>
<th>Cum. explained variance [%]</th>
<th>Eigenvalue</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.5</td>
<td>32.5</td>
<td>6.83</td>
</tr>
<tr>
<td>2</td>
<td>24.0</td>
<td>56.5</td>
<td>5.04</td>
</tr>
<tr>
<td>3</td>
<td>14.9</td>
<td>71.5</td>
<td>3.14</td>
</tr>
<tr>
<td>4</td>
<td>9.0</td>
<td>80.5</td>
<td>1.89</td>
</tr>
</tbody>
</table>

From Figure 4 we see that the oxygen content clearly affects the first principal component. When the oxygen content is increased, the first PC decreases. Visual inspection of the time series can be used to make a crude estimation of the transition time. However, the time series plot of the first PC exhibits strong autocorrelation and noise, which makes exact
determination of the transition time difficult. We therefore use transfer function-noise modeling to produce a more precise estimate.

Figure 3a. PC score scatter plot, $t_1$ vs. $t_2$ coded according the oxygen target levels.

Figure 3b. PC loading plot $p_1$ vs. $p_2$. See Table 1 for the variable codes.

Figure 4. Time series plots of a) the oxygen content of the blast air and b) $t_1$.

Transfer function-noise modeling

The time series of $t_1$ may be modeled as an ordinary time series, not acknowledging the change in oxygen content, and this was done for comparative reasons. An ARIMA(0,1,1) model was fitted, where first differencing was needed to account for the nonstationary
behavior (the shifts in $t_i$). The nonstationary behavior means that the expected value of $t_i$ changes over time.

Since the level of $t_i$ seems to depend on the level of the oxygen content of the blast air we try to explain the nonstationary behavior in $t_i$ by fitting a transfer function-noise model. In the transfer function-noise model we use the oxygen content of the blast air to try to account for the shifts in $t_i$. If the noise in the transfer function-noise model can be modeled by an ARMA model (no differencing) we assume that the shifts in $t_i$ are mainly explained by the changes of the oxygen content. To test the explanatory performance of a transfer function-noise model for the time series in Figure 4b, models were developed in a stepwise manner following the description in section 2.2. The models found were then compared. The software JMP® 8.0 was used for the calculations.

The oxygen content was used as the single input series $x_i$ and the scores $t_i$ as the single output time series. First the input and output series were prewhitened using an ARIMA(0,1,1) model to form $t_D$ and $t_E$, according to Steps 1-2 in Section 2.2. In Step 3 the cross correlation function (CCF) between $t_D$ and $t_E$ was estimated, see Figure 5.

![Figure 5. Cross correlation function between $\alpha_i$ and $\beta_i$. The sampling interval was one hour.](image)

By interpreting Figure 5 tentative values of the delay $b$ and the orders of $r$ and $s$ in (4) can be found as discussed in Step 4 in Section 2.2. A pure delay of one hour ($b = 1$) seems reasonable, since the lag 1 cross correlation coefficient is the first significant coefficient. We see one (possibly two) significant spikes in the CCF at lag 1 and 2.

We are only interested in the cross correlations at lag 0 and positive lags to see how changes of the input are correlated with $t_i$. Large spikes at negative lags are likely due to spurious correlations.

Since the cross correlation coefficients are proportional to the impulse response function according to (10), the pattern in the CCF was compared to theoretical patterns of the impulse response function in Montgomery et al. (2008, pp. 305-306). From this comparison two
tentative transfer functions were identified and fitted. The transfer functions were assumed to have denominator of degree 0, that is \( r = 0 \). Two possible values for the numerator in the transfer function were considered, \( s = 0 \) (one spike) and \( s = 1 \) (two spikes). The remaining correlation structure in the noise from both models was eliminated, as described in Step 5, by an ARIMA(1,0,0) model. Note that this is a AR(1) model and hence the shifts in \( t_i \) can be explained by the oxygen content. Finally, the overall models were fitted as described in Step 6 in Section 2.2. Table 3 gives a summary of the two transfer functions-noise models found together with the ARIMA(0,1,1) model that does not consider changes of the input variable.

We present model criteria for comparison in Table 3. For details about these criteria, see, for example Montgomery et al. (2008, pp. 57-60). Generally, models with small standard deviation of the residuals, small mean absolute error, high adjusted coefficient of determination, and small values on the Akaike Information Criterion (AIC) and Schwarz Information Criterion (SIC) are preferable. The AIC and SIC criteria penalize the sum of squared residuals when including additional parameters in the model. Montgomery et al. (2008) recommend using SIC over AIC.

Table 3. Comparisons of the transfer function-noise models and a univariate ARIMA(0,1,1) model for the time series of the first principal component, \( t_i \). The models were fitted using JMP® 8.0 statistics software. The standard errors for the fitted parameters are given above or below the parameter values. The arrows next to the model criteria indicate if the corresponding criterion should be large (↑) or small (↓).

<table>
<thead>
<tr>
<th>Fitted models (hourly averages)</th>
<th>d.f. ↑</th>
<th>s.d ↓</th>
<th>MAE ↓</th>
<th>( R^2 ) ↑</th>
<th>AIC ↓</th>
<th>SIC ↓</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) ARIMA (0,1,1) ( \Delta t_i (t) = \left( 1 - 0.21 B \right) \lambda_i )</td>
<td>369</td>
<td>0.72</td>
<td>0.54</td>
<td>0.92</td>
<td>811</td>
<td>815</td>
</tr>
<tr>
<td>b) b, r, s (1,0,0) ( t_i (t) = 7.47 - 0.11 n_{i-1} + \frac{\lambda_i}{\left( 1 - 0.67 B \right) 0.038} )</td>
<td>367</td>
<td>0.64</td>
<td>0.49</td>
<td>0.94</td>
<td>727</td>
<td>740</td>
</tr>
<tr>
<td>c) b, r, s (1,0,1) ( t_i (t) = 7.53 + \left( -0.09 - 0.02 B \right) n_{i-1} + \frac{\lambda_i}{\left( 1 - 0.67 B \right) 0.038} )</td>
<td>365</td>
<td>0.64</td>
<td>0.49</td>
<td>0.94</td>
<td>725</td>
<td>741</td>
</tr>
</tbody>
</table>

Notes: \( \Delta t \) indicates that the first difference of the time series is modeled.

d.f. = degrees of freedom; s.d = standard deviation of the residuals; MAE = Mean Absolute prediction Error

AIC = Akaike Information Criterion; SIC = Schwarz Information Criterion.

Model b) and c) perform equally well. According to model b), the gain due to the change of oxygen content is completely realized one hour after the change and according to model c) two hours after the change. However, the standard error of second parameter in the transfer function in model c) is large compared to the estimated coefficient. We therefore choose to exclude model c) from further consideration and conclude that the shift in \( t_i \) seems to occur within the first hour after the oxygen content in the blast air has been changed.

Model b) and c) perform equally well. According to model b), the gain due to the change of oxygen content is completely realized one hour after the change and according to model c) two hours after the change. However, the standard error of second parameter in the transfer function in model c) is large compared to the estimated coefficient. We therefore choose to exclude model c) from further consideration and conclude that the shift in \( t_i \) seems to occur within the first hour after the oxygen content in the blast air has been changed.
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Increased resolution of the transition time

Because the change was considered to be completed within the first hour after the change, we increased the resolution by analyzing the time series using ten-minute averages instead of hourly averages. We kept the PC loadings based on the PCA of the hourly averages and calculated ten-minute averages (based on minute values) for the original responses in Table 1. PC scores were then computed using the ten-minute averages while the PC loadings were based on hourly averages. Because sampling frequency was much greater than the frequency of observable changes in the response variables, observations within 10-minute intervals would not add important information to the PCA only many redundant observations.

Using the same analysis procedure as described above, transfer function-noise models were fitted to the data and the best model is given in Table 4. The parameters \( \phi_0 \) and \( \phi_1 \) in the transfer function were significant, which indicated that the change in \( t \) occurred within the first 20 minutes after the change in oxygen content of the blast air. The noise was now described by an ARIMA(2,0,1) model. Note to preserve model hierarchy we keep \( \phi_1 \) when estimating the model in the software although \( \phi_0 \) is not significant.

Table 4. Transfer function-noise model for the first principal component, \( t \), based on ten-minute averages. The standard errors for the fitted parameters are given above or below the parameter values.

<table>
<thead>
<tr>
<th>Fitted model (ten-minute averages)</th>
<th>d.f. ( t )</th>
<th>s.d. ( \epsilon )</th>
<th>MAE</th>
<th>( R^2 )</th>
<th>AIC</th>
<th>SIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t ) ( (t) = 7.33 + \left( 0.066 + 0.0082B + 0.033B^2 \right) \epsilon ) ( \epsilon )</td>
<td>0.36 0.0099 0.010 0.0099 2 ( 0.029 )</td>
<td>0.040 0.034</td>
<td>7.33 0.066 0.0082 0.033 0.033</td>
<td>10.83</td>
<td>1.37 0.40</td>
<td>2211 0.77 0.56 0.92 5160 5200</td>
</tr>
</tbody>
</table>

As \( t \) describes the main variability in the responses caused by the change of the oxygen content we conclude that a transition time of about 20 minutes is a reasonable estimate for the transition time of the described change in the oxygen content of the blast air.

3.2 Transition time when changing iron ore pellets

Another type of experiment common in the EBF is product development experiments, where raw materials (iron ore pellets, fluxes, and fuels/reactants such as coke) with differing compositions are tested. Here we investigate the transition time when changing iron ore pellets. The pellets, together with coke and fluxes, are charged at the top of the furnace, and the burden descends through the furnace shaft. Although many surface reactions occur already in the furnace shaft, most reactions are expected to take place when the burden reaches the reaction zone, in which the pellets are reduced and molten into hot metal. The hot metal and the slag are then tapped from the bottom of the furnace. The transition time between two types of pellets in the EBF can, therefore, be estimated by studying analyses of the pig iron and
the slag tapped from the furnace, which are available approximately once every hour, see Table 5.

We have studied data from past experiments in the EBF, where changes between two types of pellets had been made. When locating the appropriate historical data, we looked for a period of operation when the pellets type had been changed and the target levels for the other processing variables were the same as were planned for the upcoming experiment. Process variables such as the blast volume regulate the production rate and hence affect the transition time. To isolate the transition time due to the pellet change, it was also important that no other major disturbances had occurred that affected the processing variables during the period of operation in the EBF. We present the analysis of one change-over of pellets in this article. In this example, 99 observations, approximately one hour apart, on the variables in Table 5 were available and the change of pellets occurred just before observation 38.

PCA was conducted on the variables in Table 5. It was found that the three first PCs explain 71.6% of the variation in the data, see Table 6. The first PC mainly describes the thermal state in the bottom of the furnace, where lower values on the scores $t_1$ indicate a cooler state. The second PC seems to describe a chemical dimension that differentiates between the two pellets, see Figure 6. Figure 7 shows a time series plot of the 99 observations on $t_2$ and the time of the change of the pellets from type A to type B is indicated.

Table 5. Variables in the analysis of pig iron and slag from the EBF.

<table>
<thead>
<tr>
<th>Hot metal</th>
<th>Unit</th>
<th>Slag</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot metal temperature (Temp) °C</td>
<td></td>
<td>Iron content (Fe) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Carbon (C) Wt. %</td>
<td></td>
<td>Calcium oxide (CaO) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Silicon (Si) Wt. %</td>
<td></td>
<td>Silicon dioxide (SiO2) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Manganese (Mn) Wt. %</td>
<td></td>
<td>Manganese oxide (MnO) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Phosphorus (P) Wt. %</td>
<td></td>
<td>Sulfur in slag (S slag) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Sulfur (S) Wt. %</td>
<td></td>
<td>Aluminum oxide (Al2O3) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Nickel (Ni) Wt. %</td>
<td></td>
<td>Magnesium oxide (MgO) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Vanadium (V) Wt. %</td>
<td></td>
<td>Sodium oxide (Na2O) Wt. %</td>
<td></td>
</tr>
<tr>
<td>Titanium (Ti) Wt. %</td>
<td></td>
<td>Potassium oxide (K2O) Wt. %</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vanadium oxide (V2O5) Wt. %</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Titanium dioxide (TiO2) Wt. %</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phosphorus oxide (P2O5) Wt. %</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Results from the PCA on the 99 observations of pig iron and slag variables.

<table>
<thead>
<tr>
<th>PC</th>
<th>Explained variance [%]</th>
<th>Cum. explained variance [%]</th>
<th>Eigenvalue</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43.5</td>
<td>43.5</td>
<td>9.13</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>63.5</td>
<td>4.21</td>
</tr>
<tr>
<td>3</td>
<td>8.1</td>
<td>71.6</td>
<td>1.69</td>
</tr>
</tbody>
</table>
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Figure 6a. PC score scatter plot, \( t_1 \) vs. \( t_2 \) coded according to the pellets type.

Figure 6b. PC loading plot, \( p_1 \) vs. \( p_2 \). See Table 5 for the variable codes.

Figure 7. Time series plot of \( t_2 \). Observation 38 is the first after the change of iron ore pellets has occurred. The observations are approximately one hour apart.

By making a visual inspection of the time series in Figure 7 it seems reasonable to argue that the transition time is at least 6 hours. Fitting a time series model to \( t_2 \) will provide a more precise estimate.

**Intervention analysis**

Since the difference between the two iron ore pellets cannot be expressed quantitatively (the pellets may differ not only in chemistry, but also in processing conditions, production time, and production plant), the transition can instead be modeled by intervention analysis. Using intervention analysis, the change of pellets can be described by a step function, \( S^{(1)}(T) = 0 \) for pellets A, and \( S^{(2)}(T) = 1 \) for pellets B. It is not meaningful to use prewhitening to identify the structure of the transfer function in an intervention model. Instead, the structure of the transfer function must be estimated by viewing the time series in the light of the underlying mechanisms behind the change. When new pellets are charged at the top of the furnace, they will descend for a few hours before reaching the reaction zone. It is reasonable to assume that
the response will exhibit a pure delay during this descent. The newly molten material is then mixed with the remaining material from the previous burden mix in the bottom of the furnace, and it is thus likely that the chemistry of the melt will change gradually. A reasonable assumption is therefore the following transfer function (see also Figure 2)

$$\frac{\alpha_k}{1 - \delta k} S^{[T]} \zeta,$$

which emulates a first-order dynamic response to a step change, see Box et al. (2008).

Again, models of the time series in Figure 7 were developed in a stepwise manner and compared. First an ARIMA(0,1,1) model was fitted to the time series of \( t_2 \), where the differencing was needed to account for the nonstationary behavior (the shift in \( t_2 \)). Thereafter the intervention variable was introduced, testing different values of the pure delay (\( b \)). The intervention variable accounts for the shift in the time series and the remaining noise was described by an ARIMA(1,0,1) model. See Table 7 for a summary of the tested models.

Table 7 shows only minor differences among the fitted models for the model criteria. It can be concluded that the intervention variable can explain the shift in \( t_2 \) that otherwise warrants first differencing of the output time series. Model f) and g) in Table 7 perform similarly, and slightly better than model e) for all criteria except SIC and practically only differ in the choice of pure lag (\( b \)).

By testing other change-overs between pellet types at similar production rates in the EBF (not elaborated here) we conclude that \( b = 3 \) is probably the best choice. We chose model f) in Table 7 for calculation of the transition time.
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Table 7. Comparison of intervention models and a univariate ARIMA(0,1,1) model for the second principal component, $t_2$. The standard errors for the fitted parameters are given above or below the parameter values. The arrows next to the model criteria indicate if the corresponding criterion should be large (↑) or small (↓).

<table>
<thead>
<tr>
<th>Fitted model</th>
<th>d.f. ↑</th>
<th>s.d ↓</th>
<th>MAE ↓</th>
<th>$R^2_{adj}$ ↑</th>
<th>AIC ↓</th>
<th>SIC ↓</th>
</tr>
</thead>
<tbody>
<tr>
<td>e) ARIMA (0, 1, 1) $\Lambda t_2 (\ell) = \left( 1 - 0.41 B \right) \xi_\ell$</td>
<td>97</td>
<td>0.60</td>
<td>0.46</td>
<td>0.91</td>
<td>179</td>
<td>181</td>
</tr>
<tr>
<td>f) Intervention Noise ($b = 3$) $\quad t_2 (\ell) = 2.0 + \frac{0.27}{1 - 0.78 B} S^{(T)}<em>{-3} + \frac{0.12}{1 - 0.91 B} \xi</em>\ell$</td>
<td>91</td>
<td>0.58</td>
<td>0.43</td>
<td>0.92</td>
<td>173</td>
<td>186</td>
</tr>
<tr>
<td>g) Intervention Noise ($b = 4$) $\quad t_2 (\ell) = 1.98 + \frac{0.94}{1 - 0.72 B} S^{(T)}<em>{-3} + \frac{0.12}{1 - 0.92 B} \xi</em>\ell$</td>
<td>90</td>
<td>0.58</td>
<td>0.43</td>
<td>0.92</td>
<td>171</td>
<td>184</td>
</tr>
</tbody>
</table>

Notes: $\Lambda$ indicates that the first difference of the time series is modeled. d.f. = degrees of freedom; s.d = standard deviation of the residuals; MAE = Mean Absolute prediction Error; AIC = Akaike Information Criterion; SIC = Schwarz Information Criterion.

Transition time

Using model f) in Table 7 we assume a pure delay of three observations (about three hours) before the intervention starts to affect the chemistry in the pig iron and slag. According to Jenkins (1979, p. 62) the estimated ‘gain’, $\hat{g}$, the ultimate change of $t_2$ due to the intervention, can be calculated from the transfer function as:

$$\hat{g} = \frac{\hat{\delta}}{1 - \hat{\delta}} = \frac{-0.78}{1 - 0.78} = -3.54$$  \hspace{1cm} (19)

Hence, the change of pellets will eventually cause the average of $t_2$ to decrease by 3.54 units. An estimate of the percentage of the change that has occurred after each time period (with the start in period $b = 3$) can be calculated as:

$$\frac{\hat{\delta}^1}{\hat{g}}, \frac{\hat{\delta}^2}{\hat{g}}, \frac{\hat{\delta}^3}{\hat{g}}, \ldots, \frac{\hat{\delta}^n}{\hat{g}}$$  \hspace{1cm} (20)

Figure 8 presents the estimated cumulative percentage change realized in $t_2$, based on the fitted parameters of the transfer function, as a function of the time after the intervention. After about 10 hours, about 90 % of the total change has occurred which may be a reasonable cutoff to estimate the transition time. Hence we conclude that the experimenter needs to add a transition time of ten hours before measuring effects of a pellets change and probably a similar time for other raw materials charged at the top of the blast furnace, given that the same production rate is used in the EBF.
Validation of the transition time for the change of pellets

To examine if the estimated transition time for pellet changes in the EBF can be considered stable, another change-over between two pellets types was analyzed. The same chemical variables of the pig iron and the slag and the same analysis procedure as described above was used to analyze the new data set. The same model form of the transfer function (18) was used in the validation model, but the parameters of the transfer function were estimated using the new data set. The transition pattern produced by the final model from the validation test is given in Figure 8 together with the transition pattern given by model f) in Table 7. We see that both models produce a similar transition pattern, which is expected using the same model form of the transfer function. We note that the change rate is comparable for the two examples of pellet changes in the furnace, and hence seem to be stable. However, for the estimated transition time for changes of pellets in the EBF is based on the assumption that the production rate is kept at the same level as in the two analyzed examples.

Figure 8. The estimated cumulative percent of change after the change of pellets in the EBF as a function of time based on estimated intervention models for two pellet changes. Model f) is given in Table 7.

4. Conclusions and discussion

In this article we propose a formal method to determine the needed transition time between experimental runs in a continuous process. Since we often encounter a multitude of responses in a continuous process we first use PCA to create a few new, independent, linear combinations of the original variables that together summarize the main variability in the response space. We then investigate if the PCs seem to be dependent on the changes in the input time series. If this is the case, a crude estimate of the transition time can often be made by visual inspection of the PC time series. For a more precise estimate we use transfer function-noise models or intervention analysis to model the dynamic relation between an
input time series $x_i$ and the output time series in form of PC scores. The transition time is estimated from the fitted dynamic models. The proposed method is summarized in Figure 9.

![Figure 9. A summary of the proposed procedure to estimate the transition time.](image)

The proposed method is developed to determine the transition times \textit{a priori} during planning of the experiment. In addition, it would be attractive if the transition time could be determined on-line during an ongoing experiment. However, it is difficult to use the proposed method on-line. One concern is that time series analysis and transfer function-noise models require enough observations for stable estimation of the parameters. Furthermore, to estimate the true transfer function and the corresponding transition times, the process needs to have stabilized and require a number of observations at the new level. We argue that our proposed method to help determine the transition time \textit{a priori} is an important aid to the experimenter. With that said, future work to find an effective method to determine transition times on-line would be very valuable.

We illustrate the proposed method using data from an experimental blast furnace where two types of transitions were studied. The transition time after a change of a quantitative variable was determined through transfer function-noise modeling while the change of a qualitative raw material variable was analyzed by intervention analysis. The results show that the estimated transition time for the material variable is substantially longer than for the process variable, which is important information for the experimental planning, but also for the analysis phase. The results differed compared to the prevailing understanding among the engineers at the EBF. Previously, changes of pellets were thought to be noticeable after four hours, while changes in blast parameters were considered to take even longer time, which also affected decisions in the planning phase of experiments in the EBF. The complete transition times in the EBF for these changes were not fully known.

The estimation of the transition time using PCs provides a summarized and manageable overview of the course of events in a multivariate response situation. However, if the change
of the input affects the process in several ways with different time lags, we have to be careful. Assume a situation where our change affects response $Y_i$ more slowly than the other responses. Then $Y_i$ will probably be uncorrelated with most other responses and have loadings of small magnitude in the first number of PCs. That is, $Y_i$ is correlated with the change of the input but not to the other responses due to the different lag structure. Indeed, transfer function-noise models and intervention models for single-output variables like $Y_i$ may be needed to complement models using PCs to get the complete picture of the transition time. The experimenter may check that responses of special interest have loadings of significant magnitude in the PCs. Otherwise, single-output models should be considered.

By knowledge of the transition time we can establish the needed length of each experimental run. Each run requires enough time to include the transition time and an additional time during which responses can be sampled at the new state. Furthermore, knowing the transition time between runs is important when selecting representative data for each run to include in the analysis of the experiment. Usually the responses during the transition time are excluded from the analysis, which further stresses the importance to correctly determine the transition time. In addition, good estimates of the transition time are useful to achieve better traceability in dynamic processes. For example, the transition time can measure the dynamic propagation of a disturbance or product change in the output. The transition time can also be of importance for process control strategies and design of engineering control systems.

After changes of some input variables the estimated transition may be gradual and slow (see, for example, Figure 8) and the experimenter may need to decide a reasonable cutoff. In such cases, the transition time can, for example, be defined as the time required to reach 90 percent of the total change modeled by the transfer function.

If the transition time for different experimental factors differs significantly, the experimenter may consider randomization restrictions for factors with longer transition times. Hence, split-plot designs can be arranged based on information about the transition time for the factors to minimize the required length of the whole experiment. Further descriptions about split-plot designs are given in, for example, Box and Jones (1992) and Kowalski et al. (2007). Factors with longer transition times can be natural choices for whole-plots while those with shorter transition times are potential sub-plot factors. The transition time is by no means the only consideration when deciding on the appropriate experimental design, such as a split-plot design, but since the experimental time in continuous processes normally is limited and costly the transition time is an important issue.

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References


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