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# Modelling, Analysis and Evaluation of a Metric System for the Quantification of Management Competitiveness in a System-of-Systems Complex Human Corporation

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Engineering* at the University of Pretoria

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## ABSTRACT

**Title:** Modelling, analysis and evaluation of a metric system for the quantification of management competitiveness in an SoSs complex human corporation.

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**Degree:** Master of Engineering in Industrial and Systems Engineering

**Keywords:** complex systems; heterogeneous system-of-systems; system-of-systems engineering management; measurement of management effort; measurement of competitiveness; hybrid structural interaction matrix; management index for competitiveness; global competitiveness management; agro-seed nurturing industry; grain South Africa

This research has quantified, through algorithmic sensing and metrication, the effective minimum management score required to attain competitiveness, otherwise known as the management index for competitiveness (MIC). The MIC is required by a System-of-Systems (SoSs) overseeing entity to competitively manage the complex network of systems that forms the heterogeneous SoSs cluster. Quantification of SoSs management is a scarcely researched field due to its extremely qualitative nature. This research has, however, presented an approach for quantifying the management effort. In a bid to bridge the research gap, a holistic and integrated framework depicting an SoSs network of 35 constituent systems in the agricultural grain industry was developed. The SoSs network was architected to show the complexities of the virtual and physical interactions between constituent systems. Furthermore, a quantitative mechanism via the Hybrid Structural Interaction Matrix (HSIM) concept was deployed. This was done so that instead of improving the overall management competitiveness through trial-and-error approaches, the priority systems can be identified and measured that will increase the overall competitiveness the most. From this, it was realised that the MIC herein is 0.50. The study also aimed to create specific rules that govern each level of competitiveness (by reflecting the necessary actions to be carried out and adhered to in order to maintain or enhance the competitiveness level). These governing rules are presented in a rules-like rubric format.

## CERTIFICATION

I declare that this dissertation, which I hereby submit for the Meng Industrial Engineering programme at the University of Pretoria, is my own work and has been carefully acknowledged and referenced in accordance with university requirements, I am aware of the University's policy and implications regarding plagiarism. I am aware that, should the dissertation be accepted, I must submit the additional copies, as well as a copy of the draft article before 7 February for the Autumn graduation, as required by the relevant regulations and that the degree will not be conferred if this requirement has not been fulfilled. I confirm that the Turnitin report is submitted together with the examination copy of the dissertation.

**Signed:** *MF Schoeman*

**Date:** 29 November 2024

## RESEARCH OUTPUTS

**Conference Paper**, for the Student Session at the 11th International Electronic Conference on Sensors and Applications:



*Proceeding Paper*

### **Design and development of an effective sensing and measurement procedure for tasks for System-of-Systems Engineering Management in the agro-seed nurturing industry <sup>†</sup>**

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**Abstract:** This research has quantified, through algorithmic sensing and metrication, the minimum management effort required by a System-of-Systems (SoSs) overseeing entity, to competitively manage the complex network of systems that forms the heterogenous SoSs cluster. In a bid to achieve this, a holistic and integrated framework depicting a SoSs network of 35 constituent systems in the agricultural grain industry was developed. Furthermore, a quantitative mechanism via the Hybrid Structural Interaction Matrix (HSIM) concept was deployed. From this, it was realized that the effective minimum management score required for the attainment of competitiveness in holistic management herein is 0.534067.

**Keywords:** systems-of-systems engineering management; sensing of management effort; agro-seed nurturing industry; measurement of management effort; measurement of competitiveness; hybrid structure interaction matrix; heterogenous systems-of-systems.

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## LIST OF ABBREVIATIONS

AFASA	African Farmers Association of South Africa
AFMA	Animal Feed Manufacturers Association of South Africa
Agbiz Grain	Grain Silo Industry Agribusinesses
AgriSA	Agriculture South Africa
AgriSETA	Agriculture Sector Education and Training Authority
AHP	Analytical Hierarchy Process
ARC	Agricultural Research Council
AWSA	Agricultural Writers South Africa
BFAP	Bureau for Food and Agricultural Policy
BFS	Blended Finance Scheme
BIM	Binary Interaction Matrix
CELC	Crop Estimates Liaison Committee
CPD	Continuing Professional Development
CQ	Contextual Question
DALRRD	Department of Agriculture, Land Reform and Rural Development
dtic	Department of Trade, Industry and Competition
Fertasa	Fertilizer Association of Southern Africa
GDP	Gross Domestic Product
GSA	Grain South Africa
GST	General Systems Theory

HSIM	Hybrid Structural Interaction Matrix
HTSD	Hierarchical Tree Structure Diagram
IIRF	Intensity of Importance Rating for Factor <i>i</i>
ITAC	International Trade Administration Commission of South Africa
JSE	Johannesburg Stock Exchange
LandBank	Land and Agricultural Development Bank of South Africa
MIC	Management Index for Competitiveness
MCDM	Multiple Criteria Decision Making
NAMC	National Agricultural Marketing Council
NCM	National Chamber of Milling
NT	National Treasury
OPDT	Oil and Protein Seed Development Trust
PPECB	Perishable Products Export Control Board
PRF	Protein Research Foundation
QA	Quality Assurance
S1...S35	System 1 ... System 35
SAAMA	South African Agricultural Machinery Association
SAAU	South African Agricultural Union
SACB	South African Chamber of Baking
SACOTA	South African Cereals and Oilseeds Traders Association
SACTA	South African Cultivar and Technology Agency
SACU	Southern African Customs Union
SADC	Southern African Development Community

Safex	South African Futures Exchange
SAGIS	South African Grain Information Service
SAGL	Southern African Grain Laboratory
SAGMA	South African Grain Milling Academy
SAGOS	Purchase and sale of grain, pulses and oilseeds and products contract
SAIIE	Southern African Institute for Industrial Engineering
SANSOR	South African National Seed Organization
SARS	South African Revenue Service
SAWCIT	South African Winter Cereal Industry Trust
SIM	Structural Interaction Matrix
SoS	System-of-Systems
SoSubs	System-of-Sub-systems
SoSE	System-of-Systems Engineering
SoSEM	System-of-Systems Engineering Management
TAU-SA	Transvaal Agricultural Union of South Africa
TLU-SA	Transvaal Landbou Unie van Suid-Afrika
US DoD	United States Department of Defence
VAT	Value-Added Tax
XML	Extensive Markup Language

# CHAPTER ONE: INTRODUCTION

This chapter provides the background of the study and introduces the problem, research questions, aim and objectives of the study. The rationale and motivation for the study, as well as the scope, limitations and delimitations of the study, are also explained. This chapter concludes with the layout of the dissertation.

## 1.1 Background to the Study

Due to globalisation, organisations of today are intertwined and interdependent, resulting in a critical need for cross-organisational collaboration for organisations of all sectors [1]. Operational and managerial silos should be eliminated to achieve efficiency, effectiveness and competitiveness — on both a national and a global level [2]. The fast-changing environment in which these business organisations operate creates new complexities that require a concurrent change in the management approach [3]. The Management Index for Competitiveness (MIC) approach stands as the focus point of this study.

Most industries still rely on traditional silo management approaches due to the deep societal entrenchment thereof, leading to a mismatch between the management approaches and the complex challenges faced by organisations today [4, 5]. The concept of Systems Thinking has since been identified as a source of competitiveness in management approaches [3]. Systems thinking can be applied to model an industry as a system comprising a set of multiple diverse and interrelated complex organisations, which can also be modelled as systems. Thus, the industry can be seen as a complex system, otherwise known as a System-of-Systems (SoS). The management of complex systems, irrespective of the human corporate they belong to, spanning across sectors such as manufacturing, agriculture, education, transportation and a host of others [6], needs to be investigated to compute the MIC. Providing a historical development of complex systems engineering management and its systems architecture are therefore critical to investigating the MIC.

In systems thinking terms, complex SoSs often consist of multiple operational, managerial and geographically independent systems that collaborate to create a new integrated network capable of fulfilling a purpose that cannot be achieved by any one individual constituent system in the network [7, 8]. Due to the independent nature of these constituent systems, the holistic management of the SoS impacts the overall competitiveness and risk management thereof [9, 10]. The holistic management of a system is pivotal since the forces of innovation

and competition do not only apply to the parts and relationships between the parts, but to the SoS as a whole [11]. The measurement of competitiveness of SoSs achieved through tasks and activities perception and metrification, results in the management effort of the interrelated constituent systems. This is also referred to as System-of-Systems Engineering Management (SoSEM).

There is no set framework for SoSEM [12-15] and creating such a framework can be a daunting task without any form of procedural sensing and measurement strategies or benchmarks aimed at quantifying the management effort required across the chain of tasks and activities of the systemic entities [16]. In this study, the quantification of management effort is derived from the application of decision-making models, as presented in the literature study. These models make use of hierarchical prioritisation and pairwise comparisons to provide a framework for quantifying decision-making, *i.e.* management. Therefore, by quantifying the management effort, the MIC can be computed.

The competitiveness of a country is strongly linked to the effectiveness with which its complex interconnected systems are managed. Consequently, this study is aimed at the development of the MIC through quantitative metrics as a tool to enhance South Africa's global competitiveness. The MIC model was evaluated by using a heterogeneous case study premised on the grain development sector.

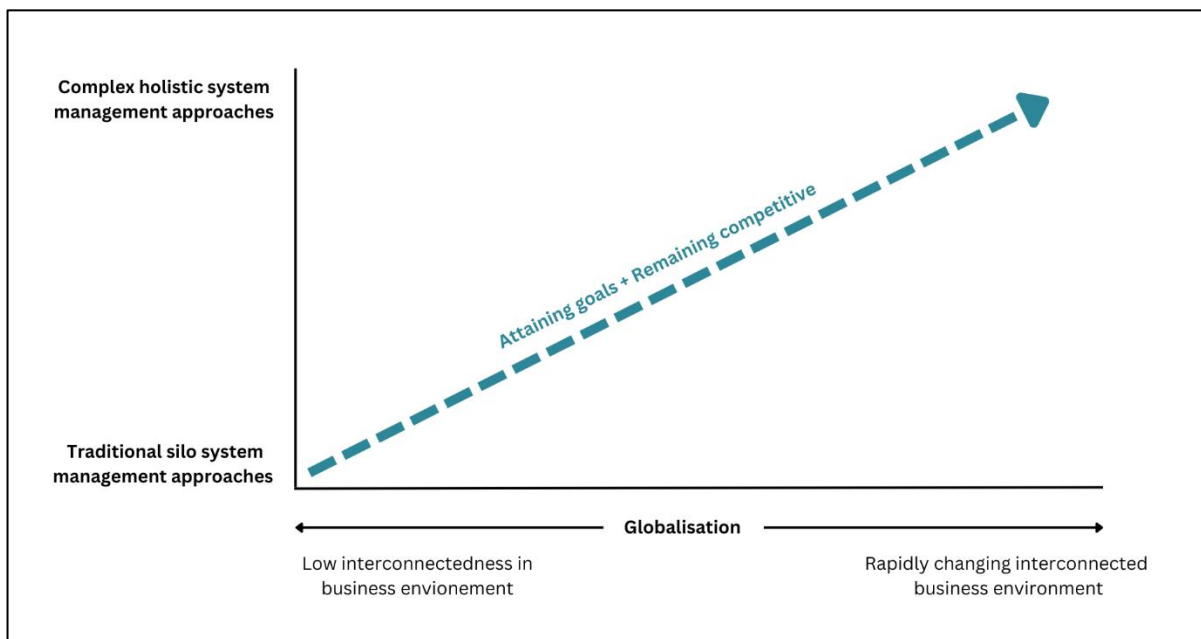
## 1.2 Problem Statement

While the research on SoSs has shown significant development in studies and experimental applications, a review of the relevant recent literature reveals that the research on System-of-Systems Engineering (SoSE) is still in an embryonic state in terms of the identification of an effective management methodology. Chapter 2 highlights the important lacuna in the existing literature on SoSEM. This underscores the problem of and need for this study.

Furthermore, the peculiarities and problem dimensions associated with an SoS network, be it a homogeneous or heterogeneous formation, are far too complex to be managed through traditional methods. Due to globalisation and the rapidly evolving systems environment, as mentioned above, traditional management tools are insufficient. This is a result of the inherent complex attributes of an SoS which spans across issues such as operational independence, managerial independence, geographic distribution, emergent behaviour and evolutionary development and more. In isolation or holistically, these attributes can impact negatively on the overall competitiveness of the diverse sectors of a country. This impact is caused by the

retrogression of desired goal attainment concerning behaviour predictability, performance, productivity and profitability if the concerned SoS is not properly managed. This can result in job losses, overbudgeting without any visible gains and poor synergy of outputs with other SoSs within a sector of the economy.

The prevalence of silo practices that persist in interconnected industries, forms part of the problem. SoSs that operate in silos are problematic in complex and dynamic environments like the grain development sector, which serves as the case study for this research. The core issue lies in the management of systems being part-focused and not holistic, due to the scarcity of information available on holistic SoSEM models. The lack of models for quantifying management makes it challenging for SoSs to maintain competitiveness amidst the evolving nature of SoSs. Ensuring that the SoSs in the various economic sectors remain competitive, given the rapidly changing business environment, is fundamental to positioning South Africa for global competitiveness. This is visually depicted in Figure 1.



**Figure 1.** Visual representation of competitiveness attainment.

### 1.3 Research Questions

Research questions play a critical role in conducting scientific research and should be the starting point for a well-executed research study [17]. The general and specific research questions of this study are listed in this section.

### **1.3.1 General Research Questions**

- What is systems engineering management?
- What is a system-of-systems?
- What is the difference between heterogeneous and homogeneous system-of-systems?
- How can systems thinking be applied to management?
- What impacts the competitiveness of a system?
- How does systems engineering management link to competitiveness?
- How does systems architecture link to systems engineering management?
- How can systems engineering management be quantified?
- How does a quantified management approach link to competitiveness?
- How does quantifying management for competitiveness influence South Africa's global competitiveness?

### **1.3.2 Specific Research Questions**

- How did systems engineering develop and what are the research gaps prevalent in the literature on the management of system-of-systems?
- How can the management interactions of a heterogeneous system-of-systems be architected?
- How can the management interactions of a heterogeneous system-of-systems be quantified and modelled towards system competitiveness?
- How can the efficacy and effectiveness towards system competitiveness of the two previous questions be measured in a South African context?

## **1.4 Study Aim and Objectives**

This section details the aim and objectives of the study.

### **1.4.1 Aim**

The study aims to develop a model for quantifying System-of-Systems Engineering Management for competitiveness, particularly focused on a case study from the agricultural grain industry domain.

## 1.4.2 Objectives

To achieve this aim, the study is further guided by the following objectives:

1. Understand, define and describe the historical development of SoSEM and identify possible lacunae in the research of SoSEM.
2. Design a holistic network that describes a heterogeneous SoS.
3. Develop a metric system by adapting a model for quantifying decision-making through hierarchical prioritisation and pairwise comparisons of the SoS network.
4. Validate the outcomes of objectives 3 and 4, by using the agro-seed nurturing (grain) management industry as a case study, to test the efficacy, effectiveness and overall SoSEM towards industry competitiveness.

The realisation of these study objectives will provide valuable insights into filling the research gap in systems engineering management from a heterogeneous SoS point of view. The outcomes of this research will contribute to the enhancement of the overall competitiveness of the agro-seed nurturing (grain) management industry of South Africa.

These study objectives are in line with the specific research questions, presented in the previous chapter. The objectives also informed the choice of a research methodology, presented in Chapter 3.

## 1.5 Rationale of the Study

The ever-growing levels of integration and connectedness of functional activities and their corresponding physical entities in the human society have heightened the need to investigate, analyse and explore the merits and gains of quantifying SoSEM as an alternative management approach. This study provides a quantitative approach to competitiveness in a dynamic and evolving environment, which is essential to any industry.

The study also contributes to systems engineering management theory, particularly in the context of heterogeneous SoSs. Research must be conducted on phenomena not thoroughly investigated by previous researchers [18]. Hence, this study deals with the gaps in the systems engineering management literature. A model for the quantification of the holistic management effort of SoSs, provides insight into the management of complex systems challenges. The study stimulates holistic thinking that quantifies decision-making and management in an inherently qualitative field.

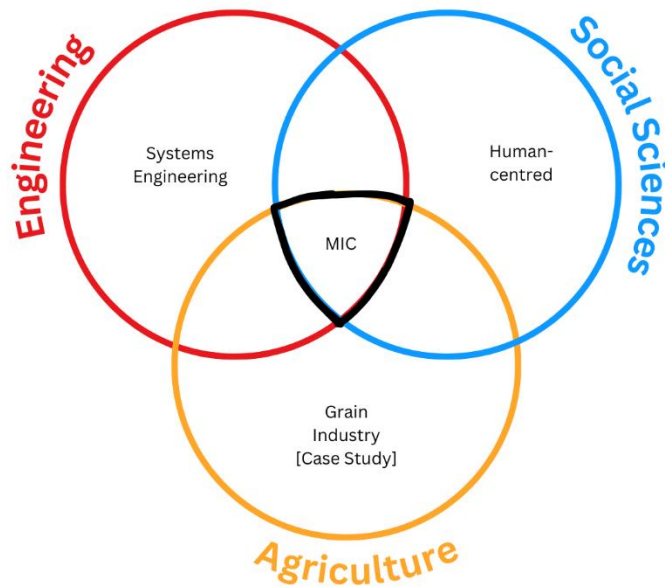
## 1.6 Motivation for the Study

At a Special Interest Group (SIG) event of the South African Institute for Industrial Engineering (SAIIE) on 10 April 2024 [19], the power of positive disruptors that challenge the generational approach of “this is how we have always been doing it, so it is best”, was discussed. The importance of contributing to the movement of crowd-solving through positive disruptions was emphasised. This approach shaped the direction of the study. Effectively responding to the complex challenges experienced in the field of systems engineering, through the adoption of a qualitative approach, is part of causing positive disruptions. Current management practices are informed by reductionist thinking, without regard to the holistic perspective. Investigating the novel approach of joining social science and engineering, to cause positive disruptions, served as a big motivation for the study.

Furthermore, the motivation for the use of the agricultural sector as a case study lies in the size of the impact that more effective management can bring about in this sector. Last year, the agricultural sector, which plays a significant role in providing food security in the country, recorded its first annual contraction in Gross Domestic Product (GDP) since 2019, shrinking by 12.2% [20]. To remain competitive as a country, it is therefore not enough to produce commodities, but to produce them in an economically viable and sustainable manner. Management practices play an essential role in the sustainable production of agriculture. Agriculture is a national asset, where the government is the custodian and we as citizens are stewards [19]. This was a big motivation for centralising the validation of the quantitative management model around agriculture, specifically the grain industry. Improving the agricultural industry, will in turn positively disrupt the performance of the other economic sectors in South Africa. It is important to not only approach agricultural improvements from a technological perspective (for example, precision irrigation and smart farming) but from a systems thinking perspective, focusing on the holistic interactions.

## 1.7 Scope of the Study

The project scope is represented graphically in Figure 2 by means of a Venn diagram. The quantitative engineering approach, specifically focused on systems engineering is represented in red. The qualitative social sciences approach, specifically focused on management towards competitiveness is represented in blue. Lastly, the yellow represents the agricultural sector, specifically focused on the grain industry as a case study.



**Figure 2.** Visual representation of the intersection that reveals the project scope.

Where these three sectors intersect, the intersection (indicated in black) represents the scope of the study. The intersection can be described as the point where selected systems engineering tools are applied to quantify management towards competitiveness, which results in positive disruptions in the grain industry. This intersection links to the four study objectives.

## 1.8 Limitations of the Study

The study aims to develop a model for quantifying management effort, thereby managing the complexities inherent in SoSs. Mathematical modelling, employed to develop the MIC model, as well as systems architecture modelling, used to create the SoS network, both have limitations. Because a model is a simplified representation of real-world occurrences, some of the information, depth and nuances are lost. This is a limitation of the study.

Furthermore, the SoS network architected from the case study data represents a set of interrelated constituent systems. SoSs can also be homogeneous, but this study only focused on a heterogeneous SoS.

The grain industry SoS network that is presented in this study, is also unable to adapt to changes in its constituent systems. This SoS network is designed for the interaction between the current role players (constituent systems) and under normal circumstances. The data from the SoS network were utilised in computing the MIC. Thus, if a new role player were to enter

the grain industry, the SoS network would need to change, and thereby the results obtained from the MIC model would also change. In addition, if a state of emergency (like a pandemic, drought or flood *etc.*) were to occur, the management towards competitiveness would be approached differently. In other words, the results obtained through the case study validation would not necessarily be able to be replicated at another point in time, due to the extremely evolving nature of the SoS environment. However, the generic approach could be adapted to include new entrants and external environmental changes.

## **1.9 Delimitations of the Study**

The study investigates the quantification of management effort in the context of an SoS. The quantitative MIC model is validated using a heterogeneous SoS case study. The intention was to focus the study on the exploration of SoSEM as a phenomenon and the conceptualisation behind quantifying SoSEM, which is a novel field of research. Therefore, different SoSs types, in terms of their nature (heterogeneous or homogeneous) and applicable domains (agriculture or other economic sectors) were not employed in validating the model, other than the grain industry case study. The reasoning behind selecting a heterogeneous agricultural SoS as the case study is stated in section 1.6.

## **1.10 Layout of the Dissertation**

This section discusses the division of the chapter presented in the dissertation. To ensure that there is a meaningful link between the research topic and objectives, methodology, findings and conclusion, a logical breakdown and proper planning of chapters are paramount [21]. The five main chapters are summarised below, each consisting of a chapter introduction and chapter summary to ensure a logical thread.

### *Chapter 1: Introduction*

The first chapter provides an overview of the study, elucidating the background, problem statement, aim, objectives, rationale and motivation for the study. Included in this chapter is an exposition of the scope, limitations and delimitations of the study. The goal of this chapter is to clarify the central topic of the study.

### *Chapter 2: Literature Review*

The second chapter presents the theoretical base of the study. The chapter starts by exploring the historical development of systems engineering as a basis for determining the gap in the literature on SoSEM. Thereafter, systems architecture and systems management are investigated, culminating in the exploration of quantitative models for modelling management towards competitiveness. This chapter provides further insight into the context of the study.

### *Chapter 3: Research Methodology*

The third chapter delineates the research methodology. The purpose of this chapter is to provide a detailed overview of the research paradigm and methods. A mixed methods approach is adopted, where qualitative research included the execution of the literature review and nested case study analysis, resulting in the architected SoS network. Thereafter, quantitative research is conducted via the HSI method, from which the MIC model is derived.

### *Chapter 4: Results and Discussion*

The fourth chapter presents the results obtained through algorithmic perception and measurement, aimed at enhancing the overall competitiveness of an SoS setup, such as the grain industry. The SoS network is architected to show the complexities of the interactions between constituent systems. Thereafter, the MIC is computed, employing priority ordering using normalised weight determination of the 35 constituent systems identified in the case study. These results are then interpreted to derive the research findings.

### *Chapter 5: Conclusion and Recommendations*

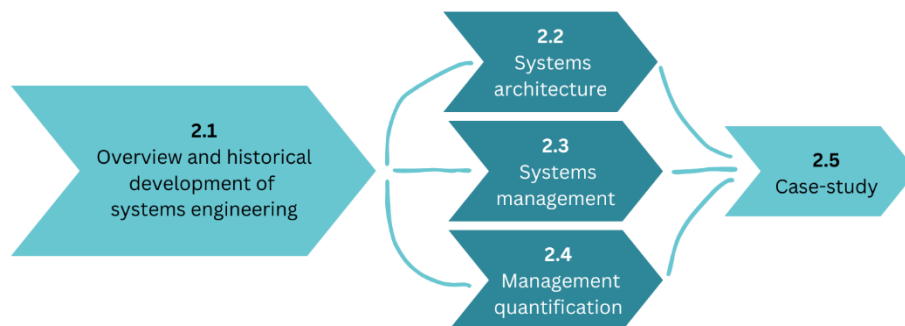
The last chapter summarises the research findings used to conclude the study, contributing to the existing knowledge in the field of SoSEM. The chapter evaluates whether the study objectives have been successfully achieved and discusses recommendations for future work. The recommendations offer guidance for future studies in this field.

## **1.11 Chapter Summary**

This chapter serves as an introduction to the study. It provided context on why the study was conducted. The problem, research questions, aim and objectives of the study, along with the scope, limitations and delimitations were discussed. The chapter also outlined the breakdown of the chapters of the dissertation. The rationale and motivation behind the study were also explicated in this chapter. The next chapter focuses on the theoretical framework underpinning this study, flowing from the topics discussed in Chapter 1.

## CHAPTER TWO: LITERATURE REVIEW

This chapter provides an overview of the methods and concepts pertaining to systems engineering in general and quantifies the management effort required for effective and competitive management of systems. The literature review process is crucial for critically analysing, synthesising and understanding existing knowledge relevant to the phenomenon under research [22]. The aim of the study and objectives of the study, specifically towards understanding SoSE in-depth, have provided a framework for the management thereof and shaped the layout of the literature study, as depicted in Figure 3.



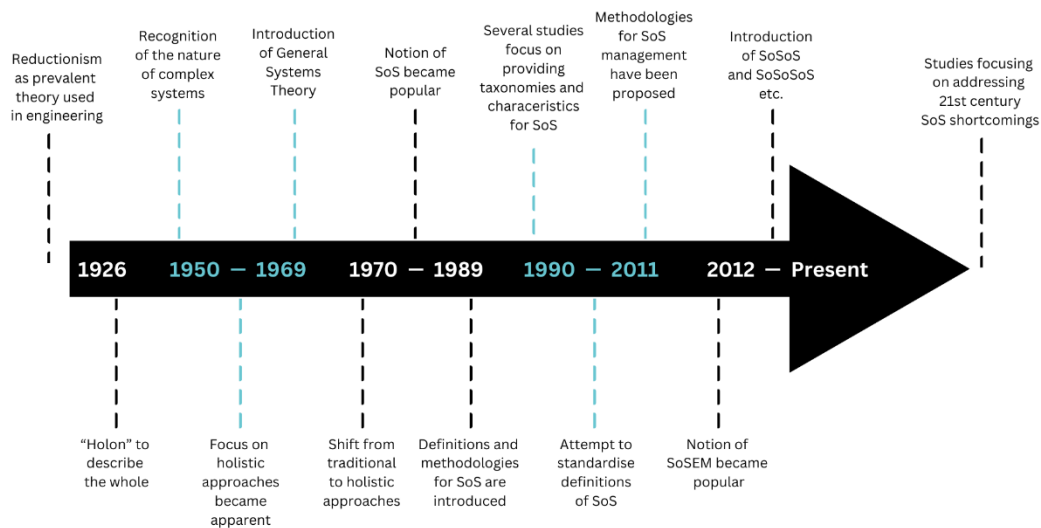
**Figure 3.** Layout of the literature study.

By conducting the literature review, the phenomenon of systems thinking in engineering was analysed. An in-depth understanding of **systems engineering** was achieved by investigating the **historical development** thereof. This investigation led to the realisation of the research gap in the field of systems management literature. The main challenge identified and also the rationale for this study, is the lack of framework for the management of SoSs. To create a framework for quantifying the SoSs management effort, **systems architecture** and **systems engineering management** needed to be understood. Models for **quantifying management** towards system competitiveness were also researched. To analyse the quantification framework, an SoSs **case study** was presented. Demonstrating the link between the research aim and the literature review is essential, hence this chapter illustrates that connection.

## 2.1 Overview and Historical Development of Systems Engineering

A system is expounded as “a collection of entities and their interrelationships gathered together to form a whole greater than the sum of the parts” [23]. In other words, the focus is on the entities, the interrelationships between these entities, and the whole. Alternatively, if the whole is described as a network, the entities would be the nodes and the interrelationships would be the links between the nodes [23]. The word “system” or “holon” (Greek word for system) was first mentioned by Smuts in 1926 [24]. This marked the start of the development of systems thinking in engineering, otherwise referred to as systems engineering, which is still a prevalent topic of academic research today. To have a comprehensive understanding of a research topic under investigation, it is important to explore the history and development thereof [22].

The investigation into the history of systems engineering highlights when, why and how the concept was developed. The eras of the development of systems engineering are visually depicted in Figure 4.



**Figure 4.** Historical development of systems engineering (adapted from [25]).

The different eras of the historical development, summarised in Figure 4 and listed below, are further elaborated on in section 2.1.1 to section 2.1.5:

- **Pre-1950**, when reductionism, as opposed to systems thinking, was the prevalent theory used in engineering [25].

- **1950 to 1969**, when the complexity of systems was realised and the concept of General Systems Theory (GST) was developed [25]. The research was largely driven by the United States Department of Defence (US DoD) [26].
- **1970 to 1989**, when the concept of a holistic view of complex systems was explored and the idea of SoSE was recognised [25].
- **1990 to 2011**, when the focus was on standardising the concept of SoSE [25].
- **2012 to present**, when the focus was on standardising the modelling framework for the concept of SoSE [27].

### **2.1.1 Reductionism**

The concept of reductionism was first used in science (specifically, molecular biology and genetics) to analyse complex systems [28]. Pre-1950, reductionism, as opposed to systems thinking, was the prevalent theory used in engineering. Reductionism is focused on breaking down a phenomenon into its independent components and studying them individually [29, 30]. This is based on the assumption that any phenomenon (complex system) can be reduced into its components (constituent systems), thereby breaking down the complexity of the system [31]. Therefore, reductionism promotes specialisation and fragmentation, whilst ignoring the interdependency and interrelationship between the constituent systems [4]. This reductionist approach limits the understanding of the complexity of a system to the understanding of the cause-and-effect between the individual components. This led to the shift from reductionism to traditional systems engineering, a new approach from where the concept of holistic systems thinking in engineering developed [30].

### **2.1.2 General Systems Theory**

During this era, the difference in complexity levels of systems was realised, which subsequently highlighted the limited capabilities of the traditional systems engineering approach to high-complexity systems [25]. Von Bertalanffy is considered one of the leaders towards a systems theory approach, as an efficient and effective alternative to reductionism. He highlighted the inability of reductionism and mathematical models to capture the nature of wholeness and the control of complex systems and, therefore, developed the general systems theory approach [32]. During the early years of this era (just after World War II), the research was largely driven by the US DoD. This was due to the fundamental operational transformation the war brought about, which highlighted the need to apply systems thinking to operations

[33]. Systems thinking evolved as a new paradigm to counteract the complexities associated with the emerging systems [15], which largely resulted from the war operations. Simultaneously, in other research fields such as cybernetics, additional theories focusing on addressing complex systems holistically emerged [34-36]. These additional theories were consistent with the tenets of the GST. In summary, research between 1950 and 1969 was primarily focused on recognising the need for a holistic view of the whole system, as opposed to analysing the parts of the system only. The idea of “systems within systems” was introduced towards the end of the era [37], which led to the development of the concept of SoS.

### **2.1.3 Recognition of System-of-Systems Engineering**

Between 1970 and 1989, several researchers started building on Von Bertalanffy’s idea of the GST, asserting the need to move from traditional systems engineering to more holistic approaches [38-42]. Furthermore, differentiation between single complex systems and larger complex systems took place. Terms such as “integrated set” [38] and “metasystem” [40] acknowledged the concept of large complex systems, today known as SoSs, although the concept was not formally recognised at that time. Single complex systems, today referred to as System-of-Sub-systems (SoSubs), recognise the wholeness of the system (holistic view), but are inflexible to respond to disruptions, otherwise, SoSubs do not constitute emergent behaviour.

### **2.1.4 Standardisation of System-of-Systems Engineering**

Between 1990 and 2011, emergent behaviour was introduced along with the concept of an SoS. Once the concept of an SoS was understood, it was found that SoSs can also be found everywhere [43]. The development of SoSE was still mostly driven by the fields of defence and aerospace during this era [44-46].

The National Council on Systems Engineering (NCOSE) grew from the development of systems engineering, which highlighted the need for formally trained systems engineers [47]. Meetings regarding the idea of NCOSE between representatives of various industry and academic organisations in the United States started in 1989 [47]. A year later, in 1990, NCOSE was founded. This marked the date on which systems thinking transitioned into systems engineering as a full-blown discipline. Later, it was rebranded as the International Council on Systems Engineering (INCOSE) [47].

The first version of INCOSE's *Systems Engineering Handbook* appeared in 1997 [47]. This gave way to multiple domain-specific definitions, characteristics, types, approaches and systems principles of SoSE being introduced. The need for standardisation across domains was therefore evident. Some of the most renowned researchers of SoSE of the time included Maier [48], Delaurentis [44], Boardman and Sauser [23] and Jamshidi [49]. The pursuit of achieving a standard definition of an SoS led to the existence of numerous, slightly varying definitions [27, 44]. Among many descriptions of an SoS, Maier [48] defined an SoS as a “collaborative network-centric assemblage” and Delaurentis added “trans-domain networks of heterogeneous systems” as a potential definition.

On a basic level, all definitions are in agreement that an SoS can be defined as a “super system” that differs from a system in its ability to achieve a common, “greater than sum” purpose through the collaboration of the constituent systems and emergent behaviour [23, 27, 43, 44]. The new integrated network capable of fulfilling the “greater than sum” purpose cannot be achieved by any one individual constituent system in the network [8]. In other words, SoSs have both “legacy”, from the coming together of the constituent systems (also referred to as legacy systems) and “mystery”, from the emergent behaviour of the system due to the unknowable environment in which an SoS operates [23]. In 2005, the International Standards Organization (ISO) published the first standard that defined systems engineering application and management.

In addition, the most widely accepted characteristics of SoSs were introduced by Boardman and Sauser and include [23]:

- **Autonomy:** The ability of the constituent systems of an SoS to have their purpose and function independently, despite being part of the SoS and contributing to achieving the purpose of the SoS.
- **Belonging:** The strive of the constituent system to achieve its purpose will lead to a higher likelihood of the SoS's “supra” purpose being achieved. Simultaneously, the existence of an SoS enhances the value of the constituent system's purpose. Therefore, belonging emphasises the simultaneous “partness” and “wholeness” of an SoS.
- **Connectivity:** The ability of an SoS to dynamically form and withdraw links between constituent systems, as the need arises, aiming to fulfil the “supra” purpose.

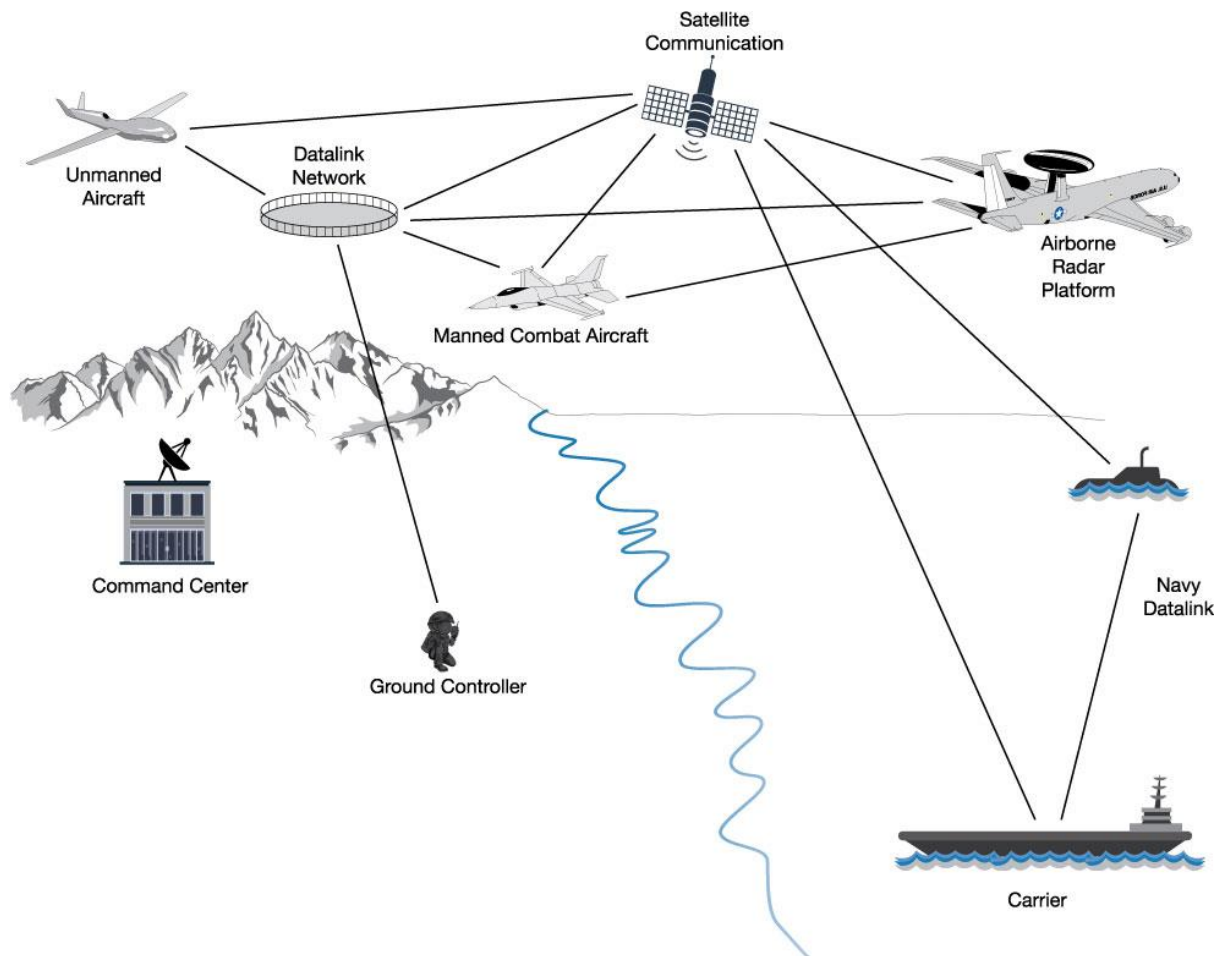
- **Diversity:** The ability of an SoS to be a simple whole with diverse capabilities. This characteristic is easiest explained by using the brain as an example: the neurons of the brain represent the constituent systems that are largely identical, requirement-driven and have limited capability. Similarly, the chemical interactions (representing the interrelationships) are limited in scope. The brain (representing the SoS) is a simple whole. But when the neurons work together, through chemical interactions, the brain is capable of high-level functions, such as a variety of thought, consciousness and perspective.
- **Emergence:** The ability of an SoS to have unforeseen capabilities. This characteristic is easiest explained by using a jury as an example. If every juror had to vote in isolation, the final verdict would be the sum of the guilty and innocent votes and thus a foreseen outcome. For example, 11-1 for guilty, meaning 10. But, when a jury gathers to discuss the verdict, there is an opportunity for the “original” votes to be overturned, thus making the final verdict an unforeseen outcome. For example, the original 11-1 for guilty can be swung to 12-0 for innocent through interdependent critical thinking. Thus, the synergy of the parts (jurors) can change the system outcome (verdict).

Another accepted list of characteristics was developed by Maier [7]. These include **operational independence and managerial independence** (which links to Boardman and Sauser’s autonomy and belonging characteristics [23]), **evolutionary development** (which links to Boardman and Sauser’s connectivity characteristic [23]), **emergent behaviour** (which links somewhat to Boardman and Sauser’s emergence characteristic [23]) and **geographic distribution** (which links somewhat to Boardman and Sauser’s diversity characteristic [23], but here more focused on the geographic extent of the constituent systems).

Furthermore, four general types of SoSE management approaches were identified in the research, including virtual [7], collaborative [7], acknowledged [50] and directed SoSs [7]. These approaches are based on the difference in the level of authority and responsibility overseeing the development of the SoSs. In addition, SoSE approaches to the modelling and managing of SoSs are yet to be standardised and applied in industries other than defence and aerospace.

## 2.1.5 Modelling Management of System-of-Systems Engineering

From 2012 until the present, the research was focused on the improvement, modification and standardisation of SoSEM modelling. As an example, with the advanced technology available today, the US DoD procures complex integrated SoSs [26]. This is depicted in Figure 5, where various systems in the battle space (tanks, ships, aircraft, satellites *etc.*) need to collect, process and distribute real-time data to the military decision-makers.



**Figure 5.** Complex SoS example in the military [26].

The interoperability requirements, as depicted in Figure 3, reinforce the need for a disciplined approach to SoSEM modelling across a wide range of domains, other than the military. SoSEM modelling is one of the 21<sup>st</sup>-century challenges in systems engineering which includes focusing on the architecture of SoS and the integration of SoS for performance optimisation, robustness and reliability of the heterogeneous or homogeneous constituent systems [27].

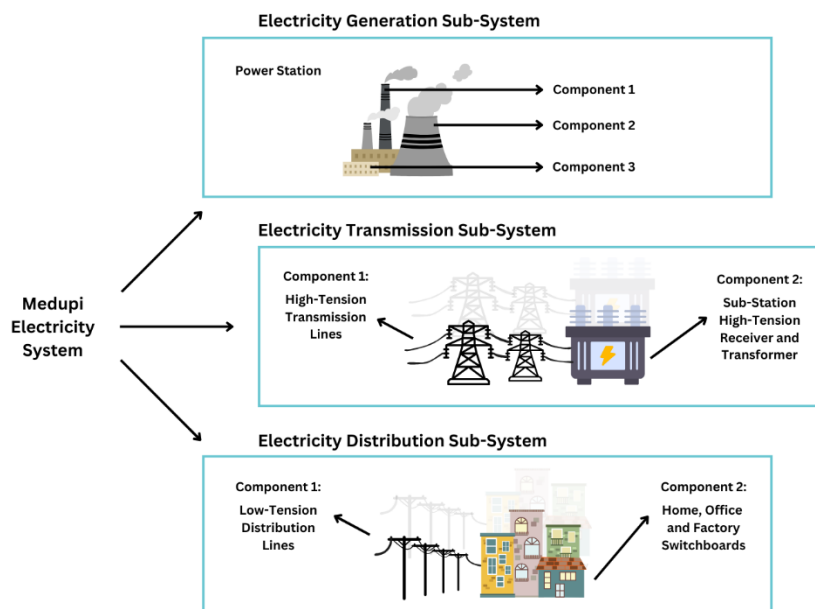
Furthermore, once the existence of SoSs was recognised, it gave way to the development of the concepts of System-of-Systems-of-Systems (SoSoS), System-of-Systems-of-Systems-of-Systems (SoSoSoS) *etc.* From studying SoSs literature, it was determined that the urgent problems faced by researchers of this era are:

- Developing an integrated methodology for engineering adaptable, sustainable and interoperable SoSs, by using the **open systems strategies** [27]. These strategies are premised on the principle that open systems have external interactions, sharing information, energy and material through the system boundary [51].
- **Engineering** SoSs where each constituent system has its human, technological and organisational purpose that is also evolutionary and adaptive over time. Therefore, the engineering thereof needs to be continuously adapted [27].
- **Standardising** the definitions and perspectives of SoSs which remains an issue due to the diversity of SoSs domains [27].
- Due to the global shift towards a networked society, creating a framework for SoS **architecting** becomes crucial in the face of generating meta-architectures from a collection of different systems [27].
- **Simulating** SoS architecture based on Extensible Markup Language (XML) to give useful information on the SoSs capabilities [27].
- Modelling **integration** of SoSs becomes increasingly important as the constituent systems become more technologically advanced making smooth communication more difficult. The need for a common language for signalling information, energy or material is evident [27].
- Studying the property of **emergence** in SoSs [27].
- Understanding the **management** paradox of SoSs, where the focus is both on the simpler holistic view of the system and the complexities that this wholeness brings about [27].
- Maintaining SoSs **performance** as both the constituent systems and the system as a whole grow in size and complexity over time [43].

This study aims to speak to the challenges of architecting systems, managing systems and maintaining system performance. These are further discussed in the sections 2.2 to 2.4 that follow. Open systems strategies are mentioned in the case study presented in section 2.5.

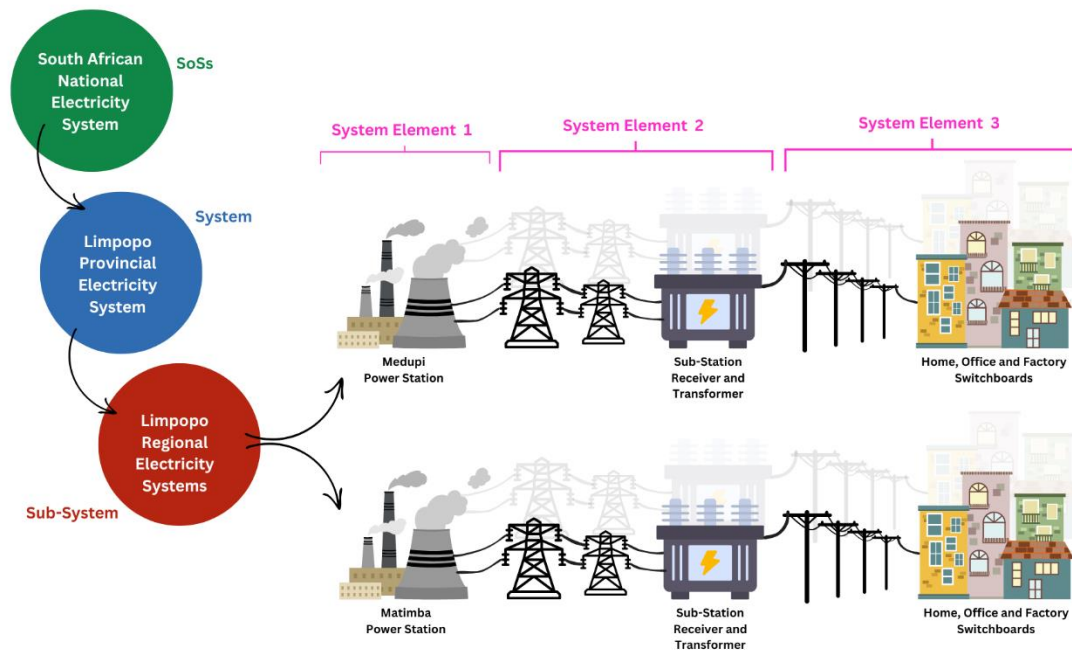
## 2.2 Systems Architecture

The word “system” can be applied to different levels of aggregation of complex interacting elements [52]. For example, a regional electricity system (for example, Medupi) can be seen as a system, where the sub-systems include the generation, transmission and distribution of electricity. Each sub-system has specific capabilities, which serve as the functional elements of the system. The generation sub-system will include the power station components. The transmission sub-system will include components such as the high-tension transmission lines and the sub-station high-tension receiver and transformer. Likewise, the distribution sub-system will include components such as the low-tension distribution lines and the home, office or factory main switchboards. Each component herein has its sub-components and parts. This example is depicted in Figure 6.



**Figure 6.** Visual depiction of an electricity system example (adapted from [53]).

Coincidentally, the regional electricity systems (for example, Medupi and Matimba) may be seen as sub-systems of the provincial electricity system (for example, Limpopo) which, in turn, is seen as a system in the national electricity SoS (for example, South Africa). Then, in turn, the sub-systems of the Medupi and Matimba regional electricity stations become system elements of the greater South African electricity SoS. This example is depicted in Figure 7. In essence, it can be deduced that most systems are also sub-systems of a higher-level system and most sub-systems can be regarded as systems on a lower level [52]. This gave rise to the term SoSubs, to distinguish between the term “system” on a lower and higher level.



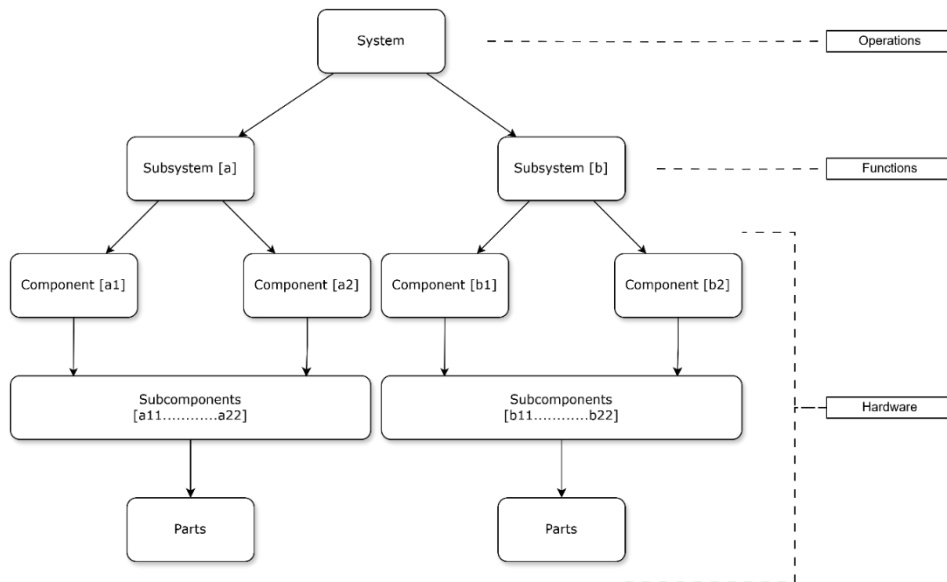
**Figure 7.** Visual depiction of an electricity SoS example (adapted from [53]).

To standardise the systems structure for SoSubs and SoSs, systems architecture is deployed, which forms part of modelling SoSEM. Architecture frameworks use models to represent the building blocks and views of the system [52]. One such model is the standard block diagramming technique, which was formally coined as the structured analysis and design (SAAD) model. This traditional model is function-based, relying on the top-down breakdown of a system and the hierarchical organisation of system elements according to their attributes. The degree of detail increases from the top level to the bottom level. These traditional hierarchical system modelling methods provide a common language for communicating system principles.

### 2.2.1 System-of-Sub-Systems Architecture

SoSubs is the term used to distinguish conventional single complex systems from higher-level complex systems. At the top level (the **systemic level**) of an SoSubs architecture, activities include the definition of operational tasks which entails the definition of the needs, problems and objectives of the system. On a **sub-systemic level**, activities include the transformation of the needs, problems and objectives into functions. Each sub-system can be complex in itself, possessing many properties of a system, except the capacity to perform its function without the support of its partner sub-systems [44]. On a component, sub-component and part level, the entities represent the hardware or physical embodiment of functions. The

**component** entities focus on functional facilitation. **Sub-components** focus on synchronising the sub-functions on an elementary level to work together for the actualisation of a specific component-level function. The lowest level (the **part level**) represents parts that cannot perform functional capabilities. The parts provide physical support only, in combination with other parts. Most parts are standardised concerning size and type and can therefore be obtained off the shelf [52]. The systems structure for SoSubs is depicted in Figure 8.



**Figure 8.** SoSubs structure (adapted from [52]).

## 2.2.2 System-of-Systems Architecture

SoS is the term used for higher-level complex systems, where the system comprises many sub-systems which are also systems and can function autonomously. The systems structure for an SoS (or supra system) is depicted in Figure 9. As evident from Figures 8 and 9, both SoSubs and SoSs conform to the definition of a system, as stated in section 2.2. In other words, both SoSubs and SoSs have in their structure different entities, interrelationships and the whole. The distinction, therefore comes, not from the structure *per se*, but from how the system entities come together and interact. The interactions between the constituent systems of the SoS, can be virtual or physical. Coincidentally, these interactions can occur between constituent systems of the supra systems or between the sub-systems of two different constituent systems, as indicated by the blue dotted lines in Figure 9. The SoS interactions create the capability of emergence for the whole, which does not occur in SoSubs. As previously mentioned, SoSs have both legacy and mystery, which are unique SoSs attributes.

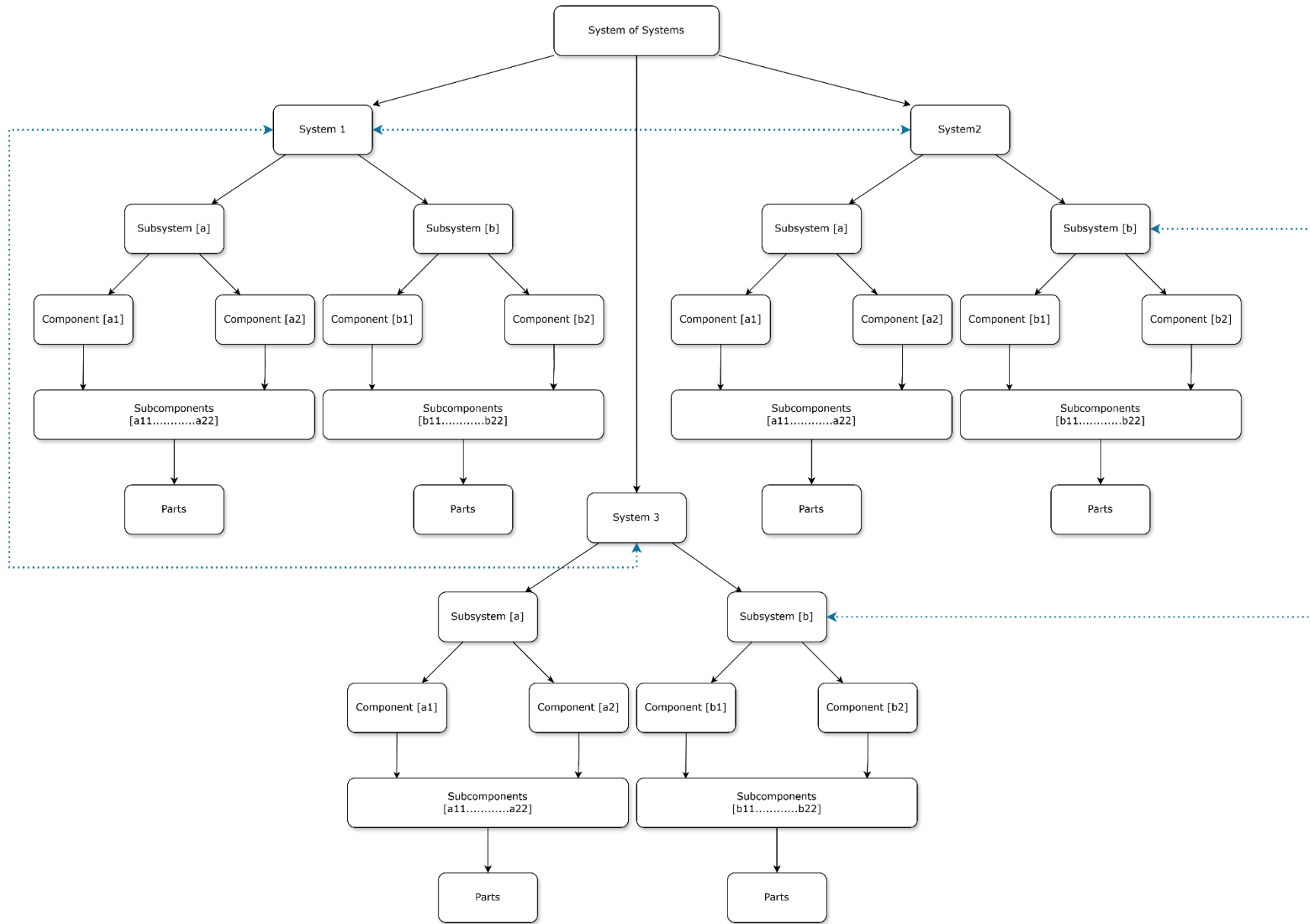


Figure 9. SoS structure (adapted from [52]).

### 2.2.3 System-of-Sub-Systems versus System-of-Systems

In this section, the distinction between SoSubs and SoSs is further explicated. Previously, the difference was shown through the architected structure. In Table 1, the difference is discussed with reference to the characteristics of an SoS, as mentioned in section 2.1.4.

**Table 1.** Differences between SoSubs and SoSs (adapted from [52]).

Characteristic	SoSubs	SoSs
<b>Autonomy</b>	Autonomy is ceded by the parts (the sub-systems, components, sub-components and parts) in order to grant autonomy to the system as a whole.	All constituent systems exercise autonomy in order to fulfil the purpose of the SoSs.
<b>Belonging</b>	Parts function as members of a family where it is in their nature to belong to a “parent” on a higher systemic level, i.e. sub-components belong to their component “parents” and did not choose to form part of the system.	Constituent systems choose to belong on a benefits basis. By belonging constituent systems cause greater fulfilment of their own purposes and belief in the SoSs’ supra purpose.
<b>Connectivity</b>	Prescient design, where there is a high connectivity hidden inside sub-systems (i.e. each sub-system has components, sub-components and parts) but minimum connectivity among the partner sub-systems.	SoSs is dynamically supplied by constituent systems, each with a myriad of interactions with the other constituent systems, like a network to enhance SoSs capability.
<b>Diversity</b>	The diversity of parts is limited to modular hierarchy, and thus encapsulated to create discrete modules whose nature is to project simplicity into the next level of the hierarchy.	Constituent systems possess increased diversity in SoSs. The capability is achieved by the inherited autonomy, belonging and connectivity.
<b>Emergence</b>	Emergence is designed in the system and therefore foreseen (both good and bad behaviour).	Emergence is enhanced by deliberately being unforeseen, which ensures early detection and possible elimination of bad behaviours.

## 2.3 Systems Engineering Management

Other than understanding systems architecture, understanding the management paradox of SoSs also forms part of the pursuit of modelling SoSEM. The focus of SoSEM needs to be on both the simpler holistic view of the system and the complexities that this wholeness brings about [27]. However, the management of complex systems, irrespective of the human corporate they belong to, spanning across sectors such as manufacturing, agriculture, education, transportation and a host of others [6], require an effective, structured yet simplified approach [12, 13]. While efforts were made to address the research gaps in the complex SoSs field, up until now there is no set framework for the management of SoSs [12-15]. Creating such a framework can be a daunting task without any form of procedural sensing and measurement strategies or benchmarks aimed at quantifying the management effort required across the chain of tasks and activities of the systemic entities [16]. In the above light, the concept of SoSEM for effectiveness and competitiveness was researched to categorise the nature of the complex system being addressed in this research.

### 2.3.1 What is System-of-Systems Engineering Management?

SoSEM is defined as “the design, development, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results” [54]. The management of SoSs is about designing for influence rather than control. Designing for influence refers to the ability to manage (or influence) constituent systems such that the interoperations of the SoSs achieve the supra purpose thereof [55]. Focusing on influencing the supra purpose is challenging, because the systems structure is focused on the individual constituent systems and their purpose rather than the holistic view. SoSEM opposes this traditional reductionist manner of promoting the competitiveness and effectiveness of the constituent systems [55].

SoSEM from a project management point of view is achieved by integrating three major activities, namely development phasing, systems engineering process and life cycle integration [56]. Development phasing refers to the baseline for coordinating SoS design. The systems engineering process refers to the structure for the SoS design and tracking requirement throughout. Life cycle integration is applied to ensure the designed SoS is viable throughout its life.

The four key types of SoSEM approaches, as mentioned in section 2.1.4, are:

- **Virtual SoSs:** There is no centralised management authority over the constituent systems, meaning no set interactions between these constituent systems towards a common purpose. The SoS's emergent behaviour relies on relatively invisible mechanisms to maintain management and network performance [57-61]. The internet is an example of a virtual SoS.
- **Collaborative SoSs:** The constituent systems interact voluntarily towards fulfilling agreed-upon purposes. The mechanisms to maintain management and network performance are decided upon collectively by these constituent systems [57-61]. The intelligent transport system is an example of a collaborative SoS.
- **Acknowledged SoSs:** There is a recognised manager and common purpose for the SoSs [60]. The resources, objectives and specific plans are decided on at the top level by the management team [58]. The military command (defence) system is an example of an acknowledged SoS.
- **Directed SoSs:** There is a centralised management authority over the constituent systems, which are being managed for a specific common purpose [59, 60]. Future combat systems are an example of a directed SoS.

Gunawan *et al.* [62] proposed a flexible framework for SoS management to continuously evaluate a complex system. This framework encompasses five aspects, namely:

- **SoS:** Brief description of the complex system.
- **External factors:** Brief description of the external factors on the SoS.
- **Governing body:** Brief description of the body responsible for the governance of the SoS.
- **Constraints:** Brief description of the constraints that could affect the governance of the SoS.
- **Feedback process between the governing body and the SoS:** The governing body provides governance to the SoS and, in turn, the SoS provides feedback on how the management plays out.

The development and management of an SoS necessitate smooth integration across many interdisciplinary tasks and activities of the systemic entities, as well as maintaining connectivity between the constituent systems and the external environment as the SoS evolves [63].

### 2.3.2 Benefits of System-of-Systems Engineering Management

Applying systems thinking to the management efforts of an SoS has become more popular, as the level of complexity and integration of SoSs increased [63]. However, acquiring the knowledge and framework necessary for such SoS management has still some room for enhancement, which would subsequently increase the benefits of implementing SoSEM. The key benefit to be gained by approaching management from a systems engineering perspective is its ability to holistically view, conceptualise and understand all relevant system entities playing a role in a given environment [64]. SoSEM is a skill for better planning for the future [65] and ensuring the purpose of the SoS is fulfilled [66]. This is emphasised by Vargas *et al.* [63], stating that a well-defined SoSEM process results in the achievement of the purpose of the SoS, which in turn is advantageous for attaining and maintaining the competitiveness of the SoS. This is the top-most mentioned advantage of SoSEM in the literature. The benefits of SoSEM are listed in Table 2.

**Table 2.** Advantages of System-of-Systems Engineering Management [63].

<b>Advantages of System of Systems Engineering Management</b>
Guides the SoSs towards the achievement of its goals.
Supports decision-making.
Facilitates analyses of interdependent constituent systems.
Supports SoSs evolution.
Enables more effective integration and use of systems engineering resources.
Facilitates consideration of emergent properties.
Facilitates achievement of more sophisticated functionalities.
Facilitates consideration of autonomous constituent systems.
Facilitates bottom-up investigation approaches.

From Table 2, it can be seen that a good SoSEM process can support decision-making (second most mentioned advantage in the literature) and facilitate analyses of interdependent constituents (third most mentioned advantage in the literature). Overall, it is evident that SoSEM aims to strengthen the ability of the SoS to handle unforeseen and evolving challenges [63].

To ensure optimal management of SoSs, a shift towards interoperability and systems thinking needs to be made and constituent systems functioning as operational silos need to be eliminated [2]. The cornerstone of enhancing SoSEM is the ability of the constituent systems to operate autonomously, but in deep-grounded co-existence [67]. This leads to the promotion of the sustainability of an SoS [68].

### 2.3.3 Quantification of System-of-Systems Engineering Management

Management efforts required to sustain the existence of complex systems are hardly expressed from a metricate point of view due to their extreme qualitative nature. The need for an approach for quantifying the management effort required to sustain complex systems is therefore evident. A model utilising algorithmic perception, measurement, effective planning and decision-making, all aimed at enhancing the overall competitiveness of an SoS setup, is required to quantify the management of complex systems.

Although there is no model presented in the literature for quantifying SoSEM from a holistic perspective, there are models available for decision-making management. Since SoSs follow a hierarchical structure, models that manage complexities by structuring the problem hierarchically and then prioritising a set criterion through pairwise comparisons, can be adapted in a bid to quantify SoSEM.

## 2.4 Quantification of Systems Management for Global Competitiveness

There are several Multiple Criteria Decision-Making (MCDM) approaches presented in the literature, such as the methods depicted in Table 3.

**Table 3.** Multiple Criteria Decision-Making methods [69].

Method	Description
AHP	Pairwise comparison of hierarchical criteria considering different information.
FUZZY AHP	AHP with the fuzzy evaluation of the alternatives.
TOPSIS	Evaluating based on the distance of alternative to the ideal solution.
FUZZY TOPSIS	Based on TOPSIS under a fuzzy environment.
VIKOR	A compensatory version of TOPSIS that is based on minimising the distance to the ideal solution using a linear normalisation approach.
ELECTRE	Outranking the relationship of the alternatives and using pairwise comparison.
PROMETHEE	Outranking method (such as ELECTRE) including several iterations.
PRAGMA	Comparing partial profiles of alternatives considering all the possible criteria pairs.
SAW	Involving a simple addition of scores that represents the goal achievements considering all criteria that is multiplied by the criteria weights.
SMART	Weighting the criteria based on their importance and converting importance weights into real numbers.

Some of these models make use of hierarchical prioritisation and pairwise comparisons to provide a framework for quantifying decision-making, of which one of the best-known tools in the research area of decision science is the Analytical Hierarchy Process (AHP) model.

The AHP model is briefly discussed in section 2.4.1, where its inherent limitations are highlighted. Furthermore, management competitiveness modelling has not been computed by using any of the above-mentioned models. These limitations led to the investigation of the Hybrid Structural Interaction Matrix (HSIM) model, as explicated in-depth in section 2.4.2. The measurement of SoS competitiveness achievement through tasks and activities perception and metrification, results in the management effort of the interrelated constituent systems, also referred to as SoSEM. The HSIM method can be used as the basis for modelling management competitiveness.

### **2.4.1 Analytical Hierarchy Process**

One of the best-known tools in the research area of decision science is the AHP method. This method is regularly used in scientific investigations, evoking analysis centred around process improvement. Although AHP is seen as a traditional prioritisation model, other decision science tools and models have emerged from recent studies [70]. These models aim to address the inherent limitations of the AHP method.

One limitation of the AHP method is that the allocation of “intensity of importance” to factors has no scientific basis [70]. In addition, in AHP, the assignment of ratings to the factors under investigation is done by experts in the relevant field and not via a computerised model. This places a limit on the applicability of the AHP model. Utilising a weighted factor approach is one way to combat this inherent limitation. The weighted factor computational process offers a simplified and cost-effective alternative to acquiring an expert to assign ratings. This further alleviates the problem of not having access to experts (especially in specialised fields in under-developed countries of the world) or experts not agreeing on the performance ratings which results in a re-evaluation and time wasted) [70]. Eliminating the requirement of experts will result in the reduction of expenses incurred during the implementation process and the time needed to reach a consensus on an appropriate rating.

This is a strong justification for the adoption of another model in decision science. One such model that addresses the prioritisation limitation of the AHP method, is the HSIM model. The HSIM model was developed as an improvement to the structural interaction matrix (SIM) framework coined in 1980 [71]. This model makes use of the integration of a weighting model into the prioritisation procedure.

## 2.4.2 Hybrid Structural Interaction Matrix

The HSIM model serves as a problem-solving tool premised on systems thinking [72]. The model is matrix-orientated, using pair-wise comparisons to present all factors and prioritising these factors through the application of the principle of subordination. It also has embedded some features of the hierarchical tree structure diagram (HTSD) to streamline the separate factors hierarchy into a consolidated hierarchical diagram [70].

The HSIM methodology actively studies the interdependencies and interactions amongst the myriads of factors under investigation. The process for executing the steps of the HSIM method involves developing a SIM. A SIM has both orientation and direction associated with it [73]. Well-defined contextual questions are used to drive the pair-wise comparisons to form a SIM. Thereafter, it expands on the SIM, which is limited to the principle of subordination and the HTSD, to also integrate weight assignment. Mathematical equations are deployed in the HSIM method to determine the weights of the individual factors for numeric quantification [72].

Thus, to develop the SIM, the following ten steps are executed [74]:

- **Step 1:** List all the factors and number them serially.
- **Step 2:** Establish a contextual relationship for these factors. Each factor can interact in several ways, but for the SIM, only an interaction based on the established contextual relationship is considered. The contextual relationship used to conduct the pair-wise comparison is determined by answering a contextual question, for example, “Does factor  $i$  depend on factor  $j$  for actualisation?”.
- **Step 3:** Draw a square matrix of dimension  $(n+1)$ , where  $n$  is the total number of factors considered.
- **Step 4:** Divide the first elemental box diagonally and assign “ $i$ ” to the rows and “ $j$ ” to the columns of the matrix drawn in Step 3.
- **Step 5:** Serially number all the factors considered in the study, for both the rows and columns, *i.e.* 1 to  $n$ , for the rows  $i$  and 1 to  $n$ , for the columns  $j$ .
- **Step 6:** Carry out the pair-wise comparison between all the numbered factors, thereby filling up the matrix.
- **Step 7-9:** To fill up these matrix spaces, the contextual relation of the factors, as presented in Step 2, is used to fill up the elemental spaces,  $e_{ij}$ . If the response to the

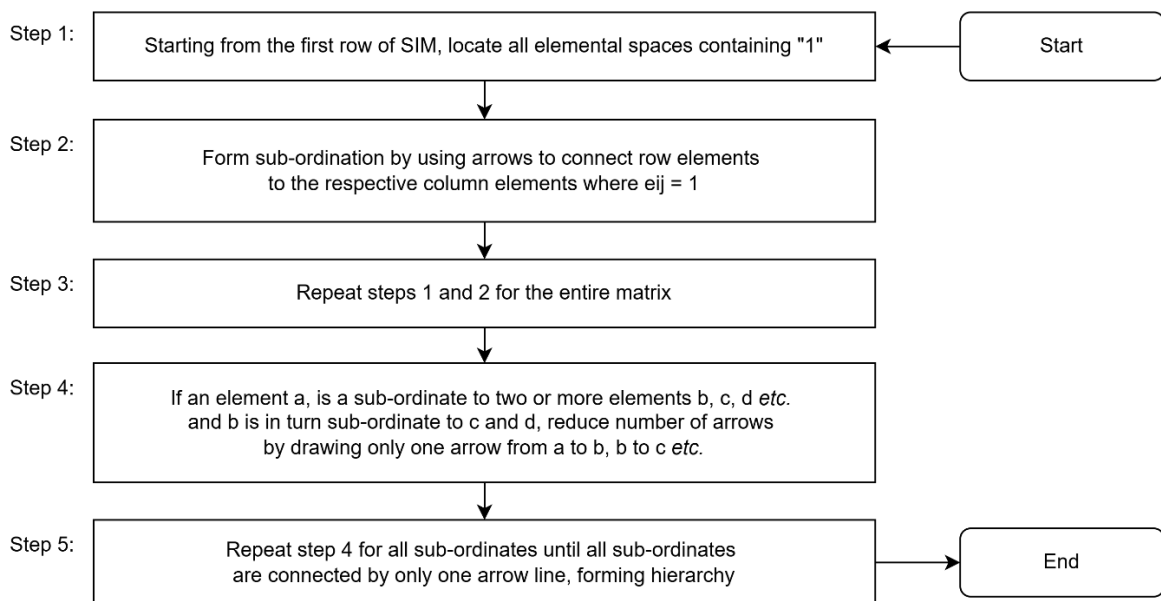
contextual question relating factors “ $i$ ” and “ $j$ ” is valid, “1” is assigned to the elemental space,  $e_{ij}$ . In other words, the answer to the contextual question was “yes”. Likewise, if the response to the contextual question relating factors “ $i$ ” and “ $j$ ” is not valid, “0” is assigned to the elemental space,  $e_{ij}$ . In other words, the answer to the contextual question was “no”.

Mathematically, the generalised form of the contextual relationship can be expressed as:

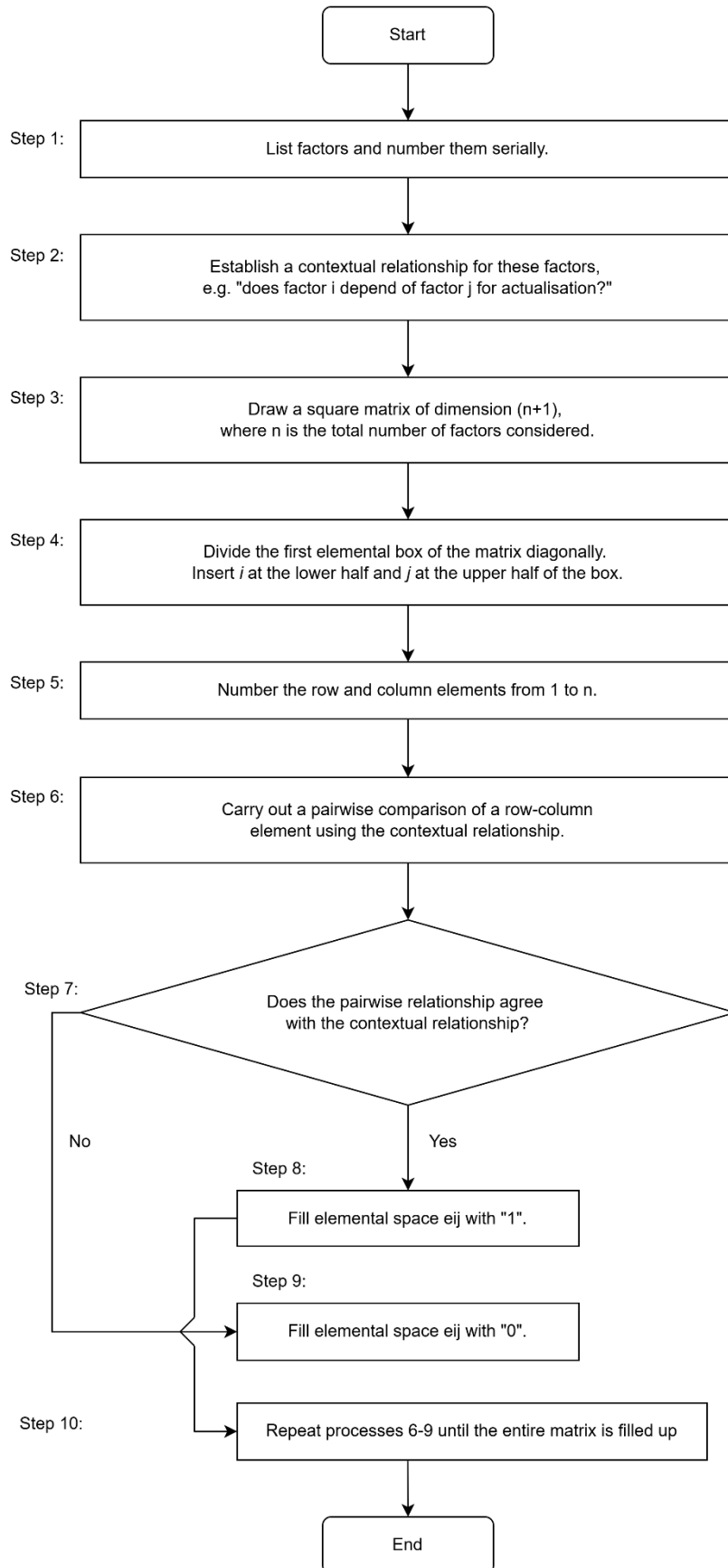
- If  $i \rightarrow j = 1$  then  $j \rightarrow i = 0$  however, if  $i \rightarrow j = 0$  then  $j \rightarrow i = 0$  or  $j \rightarrow i = 1$ .
- Also, if  $i \rightarrow j = 0$  then  $j \rightarrow i \neq 1$ , thus bidirectional actualisation is not allowed.

- **Step 10:** Repeat Steps 6 to 9 until the whole matrix is filled up.

It is important to note that mapping factors “ $i$ ” to “ $j$ ” implies the reading of the SIM would be read across the columns and vice versa for a mapping of “ $j$ ” to “ $i$ ”. The HTSD is required to integrate the interacting factors into a hierarchical order. The most prioritised factor (the row with fewer zeros in the SIM) is seated at the top-most position and vice versa [72]. The steps for creating the HTSD are visually summarised in a flow diagram in Figure 10. In addition, the flow diagram of the steps of the SIM framework is depicted in Figure 11.



**Figure 10.** Flow diagram of the steps of the HTSD framework [74].



**Figure 11.** Flow diagram of the steps of the SIM framework [74].

Apart from the ten-step process described above for the implementation of SIM steps, a computational system for the determination and normalisation of the weights for the prioritised factors is also adopted as part of the HSIM model. This introduces the “intensity of importance” of the different factors considered — a feature lacking in the AHP model. This is done by rating factors on a scale from 0 to 9. It is dependent on the number of subordinate factors obtained from the SIM. The model for calculating weight assignment is as follows:

$$IIRF_i = \left( \frac{N_{SF_i}}{T_{NF}} \cdot M_{SR} \right) + \left( \frac{b}{T_{NF}} \right) (M_{SR} - C),$$

$$C = \frac{M_{PSF} \cdot M_{SR}}{T_{NF}},$$

$$B = N_{SF_i} + 1,$$

where  $IIRF_i$  is the intensity of factor  $i$ 's significance rating,  $N_{SF_i}$  is the number of subordinate factors to a particular factor  $i$ ,  $M_{PSF}$  is the maximum number of subordinate factors that can be considered,  $C$  is constant,  $B$  is the proportion of variations,  $T_{NF}$  is the number of factors in total and  $M_{SR}$  is the maximum possible scale rating.

Additionally, the following technique was used to normalise the ratings:

1. Organise the  $IIRF_i$ -ratings per matrix into a column matrix;
2. Calculate each rating's  $n$ th root, where  $n$  denotes the total number of factors considered;
3. Calculate the sum of the results obtained in Step 2;
4. Divide Step 2's  $n$ th root for each factor by Step 3's summation.

These steps can be transcribed into the following model:

$$N_{Wi} = \frac{(x_i)^{1/n}}{\sum_{i=1}^n (x_i)^{1/n}},$$

where  $N_{Wi}$  is the factor's normalised weight  $i$ ,  $n$  is the number of factors and  $x_i$  is the original rate of factor  $i$  before normalisation.

In conclusion, the normalised weights obtained for each factor through the application of the HSIM model are used to make informed decisions. Thereby fulfilling the purpose of the HSIM model to serve as a decision science tool.

## **2.5 Management for Global Competitiveness of a Case Study SoSs in the Agricultural Systems Domain**

Positioning South Africa for global competitiveness is strongly linked to the country's ability to effectively manage its complex interconnected systems. Agriculture in South Africa contributes significantly to the nation's economic growth [75] and therefore influences the global competitiveness of South Africa. Based on this, the agricultural sector, specifically, the grain industry, was used as a case study to investigate SoSEM competitiveness.

### **2.5.1 Agricultural Sector of South Africa**

The agricultural sector in South Africa is extremely diverse compared to other countries in the sub-Saharan African region [76]. This is largely due to the range in the country's climate. The variety of farming products yielded include all major grains, oilseeds, deciduous and subtropical fruits, sugar, citrus, nuts, wine, flowers, vegetables and livestock [76]. In South Africa, the agricultural sector is one of the biggest contributors to the country's gross domestic product (GDP). This is supported by the 2023 statistics, where the total GDP grew by 0.6%, quarter-on-quarter, and the agricultural GDP grew by 4.2% over the same period, making it the fastest-growing sector of the South African economy [77].

### **2.5.2 Grain Industry of South Africa**

From section 1.1 and section 2.5.1, it is evident that the agricultural sector is an important determinant of the competitiveness of South Africa. Subsequently, the biggest contributor to agriculture is field crops (39%), of which the biggest contributing crop is grain (30%), comprising larger commercial and smaller subsistence farms [78].

The South African agro-seed processing industry (in short, the grain industry) is responsible for the nurturing, development and trade of grains. Its value chain is a complex system involving producers (farmers), input providers, storers (silos) and handlers, distributors, millers, bakers, traders and transporters. The performance of the grain industry is not only dependent on the cooperation and communication between the above-mentioned role players but also on external factors like exchange rates, oil prices and climate change [79]. Additionally, the grain industry is connected to the animal feed industry, which also has an impact on their economic performance [80].

The grain industry is a crucial component in South African economic growth, leading to [75]:

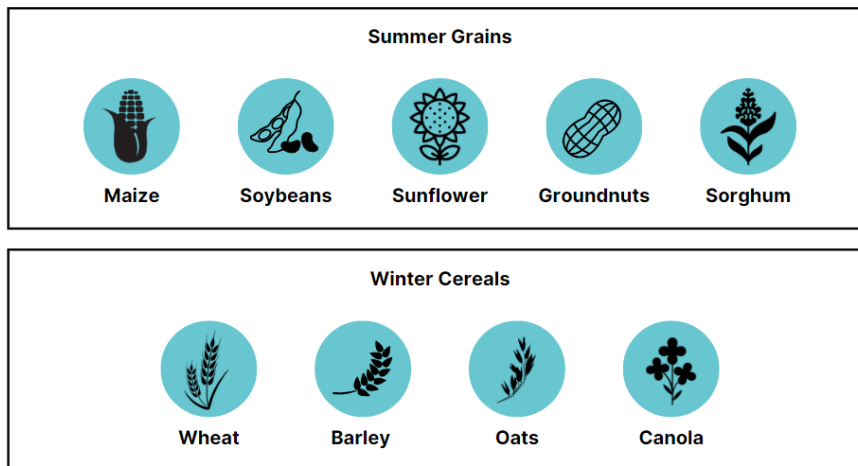
- the improvement of food security.
- providing numerous employment opportunities.
- contributing to the export earnings (South Africa is ranked among the top 10 global exporters of maize).

Despite the grain industry's importance, the earnings in this sector remain low compared to its potential contribution [81]. It is therefore evident that to improve the sector's performance, the interconnected nature of the grain industry must be investigated [80, 81].

What, however, complicates this investigation, is the grain industry's largely non-objective nature due to the chain of embedded and interconnected non-metric qualitative tasks and activities. Therefore, traditionally, the procedures available for the measurement of the grain industry's performance are often limited to verbal articulations, physical observations and benchmarking of tasks with desired targets, amongst others. Therefore, the need to improve competitiveness in the management of this sector is evident. To improve competitiveness, grain industry organisations aiming at bettering the management of the grain value chain, were formed [82]. This occurred with the advent of the free market system in 1994 [82]. Thus, on 19 June 1999, Grain South Africa (GSA) was established as the sole grain commodity organisation [78]. GSA was formed through merging NAMPO (former maize organisation), NOPO (former soybeans, sunflower and groundnuts organisation), WPO (former wheat, barley and oats organisation) and the SPO (former sorghum organisation) [78].

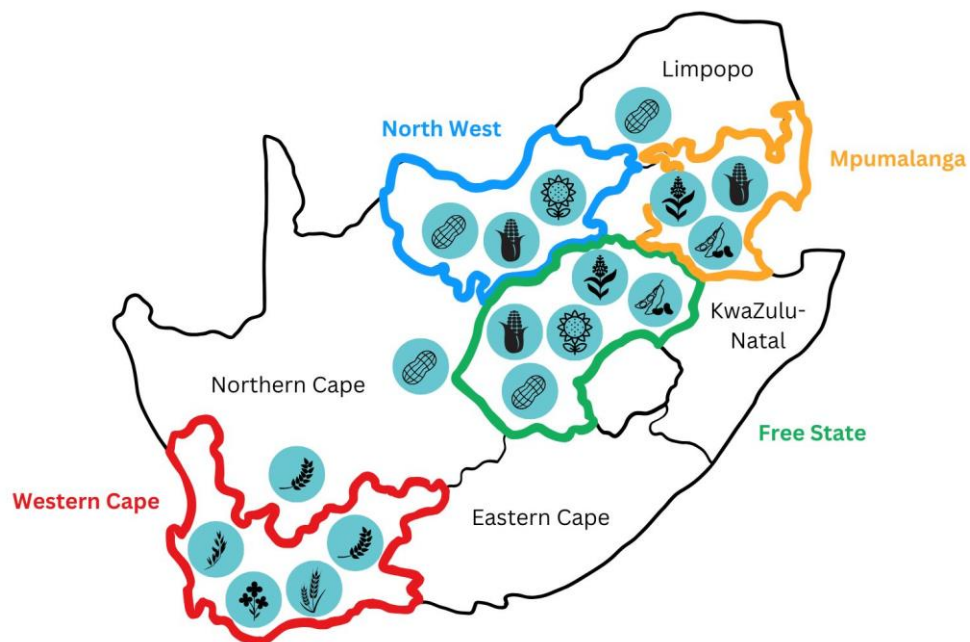
### **2.5.3 GSA as a Case Study**

Commercial grain commodities in South Africa include maize, soybeans, sunflowers, groundnuts, wheat, barley, oats and sorghum. Grain is used as the common term for these above-mentioned commodities, but on a technical level, these grains can be classified as either grains or cereals. Grains usually refer to summer grains, *i.e.* grains that are harvested in the summer season. Cereals usually refer to winter grains, *i.e.* grains that are harvested in the winter season. This is depicted in Figure 12.



**Figure 12.** Grain commodities of South Africa [78].

In addition, some grains or cereals are also categorised as oilseeds. Oilseeds refer to grains or cereals that are also valuable for the oil content they produce, like for example sunflowers, groundnuts, sorghum and canola. These grain commodities are farmed by commercial and subsistence farmers across the country. Even though most grain crops can be farmed in all the South African provinces, some provinces contribute more to the total grain production of the country [76]. Figure 13 maps the distribution of grain farming in South Africa, focusing on the provinces contributing the highest number of tonnes for each commodity. As is evident in Figure 13, Western Cape, Free State, North West and Mpumalanga are responsible for the majority of the grain production.



**Key:** Refer to Figure 12 above for an explanation of the grain symbols.

**Figure 13.** Distribution of grain farming in South Africa.

GSA is responsible for managing the interests of these South African grain producers (farmers). GSA was formed as an autonomous and voluntary industry organisation that acts collectively in the economic interest of South African grain producers [78]. The organisation addresses industry matters with all the grain role players to support sustainability. These grain role players can be classified as research entities, supply chain entities, economy and market information entities, government entities, interest representative entities and producer development entities.

Comparing the grain industry to an SoS, as discussed in section 2.2, these grain role players can be seen as constituent system entities. For this case study, GSA serves as the centric system that conducts oversight in the agro-seed processing industry. GSA is denoted as System 15 (S15). Furthermore, 34 other grain role players were identified as external, standalone constituent systems and categorised according to the above-mentioned types of role players. All the system entities are listed in Table 4.

**Table 4.** List of constituent system entities.

Si	System Name		Description
S1	SACTA	South African Cultivar and Technology Agency	<b>Research</b> Responsible for the ongoing innovation in plant breeding and technology development of crop cultivars [83].
S2	SAGL	Southern African Grain Laboratory	<b>Research</b> A reference laboratory for grain and oilseeds, which delivers market-driven analytical laboratory services for the following grains: maize, wheat, sorghum, sunflower and soybeans [84].
S3	PRF	Protein Research Foundation	<b>Research</b> Responsible for researching better protein utilisation and technology transfers to replace imported protein for animal use with locally produced protein [85].
S4	ARC	Agricultural Research Council	<b>Research</b> Reports to DALRRD (S20) and is a science institution that fosters innovation to develop the agricultural sector means of several research campuses, which are predominantly commodity-based [86].
S5	Fertasa	Fertilizer Association of Southern Africa	<b>Supply Chain Player (Input Provider)</b> Represents the fertiliser industry and its members [87].

**Table 4 (Continued).**

S6	SANSOR	South African National Seed Organization	<b>Supply Chain Player (Input Provider)</b> The National Designated Authority (NDA) which certifies that seed was produced, inspected and graded according to the legislated standards and systems [88].
S7	SAAMA	South African Agricultural Machinery Association	<b>Supply Chain Player (Input Provider)</b> The official body representing the interest of agricultural machinery manufacturers, importers and builders [89].
S8	NCM	National Chamber of Milling	<b>Supply Chain Player (Processor)</b> A non-profit trade organisation representing the interest of the South African flour and maize milling industry and its members [90].
S9	SACB	South African Chamber of Baking	<b>Supply Chain Player (Processor)</b> A non-profit trade organisation representing the interest of the South African baking industry and its members [91].
S10	AFMA	Animal Feed Manufacturers Association of South Africa	<b>Supply Chain Player (Processor)</b> A non-profit trade organisation representing the interest of the South African animal feed industry and its members [92].
S11	Agbiz Grain	Grain Silo Industry Agribusinesses	<b>Supply Chain Player (Storage)</b> A non-profit trade organisation representing the interest of the South African grain storage and handling industry and its members [93].
S12	SACOTA	South African Cereals and Oilseeds Traders Association	<b>Supply Chain Player (Trader)</b> Represents the interest of the South African grain traders' industry and its members [94].
S13	PPECB	Perishable Products Export Control Board	<b>Supply Chain Player (Trader)</b> Mandated by DALRRD (S20) and reports to dtic (S21). It is South Africa's official independent certification agency that delivers all end-point inspection services on all perishable products destined for export [95].
S14	ITAC	International Trade Administration Commission of South Africa	<b>Supply Chain Player (Trader)</b> Reports to dtic (S21) and is responsible for the administration of international trade to foster economic growth and development in South Africa [96].
S15	GSA	Grain South Africa	-
S16	BFAP	Bureau for Food and Agricultural Policy	<b>Economy/Market Information</b> A non-profit organisation responsible for providing unbiased, research-based market and policy insights to inform sound decision-making by stakeholders in the agricultural, agro-processing and food sectors across Africa [77].

**Table 4 (Continued).**

S17	SAGIS	South African Grain Information Service	<b>Economy/Market Information</b> A non-profit company responsible for providing the grain industry with essential market information by verifying submitted data from co-workers [97].
S18	NAMC	National Agricultural Marketing Council	<b>Economy/Market Information</b> Reports to DALRRD (S20) and is responsible for providing marketing advisory services to key stakeholders in support of a vibrant agricultural marketing system in South Africa [98].
S19	CEC/ CELC	Crop Estimates (Liaison) Committee	<b>Economy/Market Information</b> An independent committee providing accurate, timely and credible crop estimates to stakeholders in the grain industry [99].
S20	DALRRD	Department of Agriculture, Land Reform and Rural Development	<b>Government</b> A government department with reporting entities that include ARC (S4), PPECB (S13) and NAMC (S18) [100].
S21	dtic	Department of Trade, Industry and Competition	<b>Government</b> A government department with reporting entities that include PPECB (S13) ITAC (S14) and the Competition Commission in NAMC (S18) [101].
S22	TLU-SA/ TAU-SA	Transvaal Agricultural Union of South Africa	<b>Interest Representative</b> A farmer's union representing predominantly Afrikaans farmers [102].
S23	AFASA	African Farmers Association of South Africa	<b>Interest Representative</b> A farmer's union representing predominantly African farmers [103].
S24	Maize Trust	Maize Trust	<b>Interest Representative</b> A trust that provides funding for the benefit of the maize industry — in particular for maize research and development projects and the maintenance of market information required by the industry [104].
S25	Sorghum Trust	Sorghum Trust	<b>Interest Representative</b> A trust that provides funding for the benefit of the sorghum industry — in particular for sorghum research and development projects and the maintenance of market information required by the industry [105].
S26	SAWCIT	South African Winter Cereal Industry Trust	<b>Interest Representative</b> A trust that provides funding for the benefit of the winter cereal industry — in particular for winter cereal research and development projects and the maintenance of market information required by the industry [106].

**Table 4 (Continued).**

S27	OPOT/ OPDT	Oil & Protein Seed Development Trust	<b>Interest Representative</b> A trust that provides funding for the benefit of the oilseeds industry — in particular for oilseed research and development projects and the maintenance of market information required by the industry [107].
S28	AWSA	Agricultural Writers South Africa	<b>Economy/Market Information</b> A voluntary, non-profit, professional association promoting the image and standards of agricultural journalism in South Africa through magazines, newspapers, radio and television [108].
S29	AgriSA	Agriculture South Africa	<b>Interest Representative</b> A federation of agricultural organisations with member organisations representing different provincial agricultural unions, agribusinesses and commodity organisations [109].
S30	CropLife	CropLife	<b>Development</b> A non-profit association that provides plant health crop protection and plant biotechnology solutions in South Africa via research and training [110].
S31	AgriSETA	Agriculture Sector Education and Training Authority	<b>Development</b> Funded by the NT (S32) and provides learning programmes and education, as well as conducts research in the agricultural sector [111].
S32	NT	National Treasury	<b>Government</b> A government department with reporting entities including LandBank (S33) and SARS (S24) [112].
S33	LandBank	Land and Agricultural Development Bank of South Africa	<b>Development</b> A specialist agricultural development finance institution that provides financial services and products to the commercial farming sector and agri-businesses. Blended Finance Scheme with DALRRD (S20) [113].
S34	SARS	South African Revenue Service	<b>Economy/Market Information</b> Responsible for the collection of all revenues due, ensuring optimal compliance with tax and customs legislation, and providing a customs and excise service that will facilitate legitimate trade, as well as protect the economy and society [114].
S35	JSE Safex	South African Futures Exchange	<b>Economy/Market Information</b> A futures exchange subsidiary of Johannesburg Stock Exchange (JSE) Limited, that provides a platform for price discovery and efficient price risk management for the grains market in South and Southern Africa [115].

## 2.6 Chapter Summary

In this chapter, a literature review was conducted to comprehensively understand systems engineering and to identify the research gap in the field of systems engineering. It also summarised the theory of SoSEM and different models for the quantification thereof. Lastly, GSA was introduced as the case study. The connection between the literature review and the research deliverables is evident throughout the chapter, emphasising the critical evaluation of the existing literature in the context of the study. The knowledge gained through the literature study led to the development of the research methodology, as presented in the Chapter 3.

## CHAPTER THREE: RESEARCH METHODOLOGY

This chapter begins by defining the research paradigm, followed by a comprehensive discussion of the methodology and methods selected to conduct the study. To achieve the objectives and answer the research questions of the study, it is important to choose the appropriate research methodology and methods. According to Fox and Bayat [116], the choice of research methodology is premised on personal preference and should be influenced by the nature of the study or research phenomenon's existence, as well as the researcher's field of knowledge or expertise. Therefore, the reasons for choosing the specific research methodology that influenced the choice of methods are also elaborated on in this chapter.

More specifically, from the normalised HSIM data, the MIC is determined and a generalised model for computing the MIC was developed. Lastly, a process flowchart describing the research methodology was designed.

### 3.1 What is a Research Paradigm?

A research paradigm is defined as “a basic belief system or worldview that guides the investigator” [117]. It includes components such as ontology (the nature of the research phenomenon's existence), epistemology (the approach to how knowledge is uncovered based on the ontology of the phenomenon), methodology (the general strategy to uncover the knowledge) and methods (the specific modes of collecting data to uncover the knowledge) [118].

Guba and Lincoln [117] introduced a typology of research paradigms including positivism and constructivism. Positivism takes on a quantitative approach and focuses on “hard, generalisable data”, whereas constructivism takes on a qualitative approach and focuses on “rich, observational data” [119]. A third research paradigm later introduced is that of pragmatism [120], which aims to combine the epistemological and methodological differences of quantitative and qualitative research [119]. This paradigm takes on a multi-method or mixed-method approach [121]. The multi-method approach combines the quantitative and qualitative approaches in parallel, to provide a stronger conclusion for the study through the convergence and triangulation of the different quantitative and qualitative findings [122]. In contrast, the mixed-methods approach applies quantitative and qualitative approaches in sequential phases of the research study to better understand the research problem [123]. Creswell [124] formally defines the mixed-method approach as “research in which the investigator collects

and analyses data, integrates the findings, and draws conclusions using both qualitative and quantitative approaches or methods in a single study”. According to Sekaran [125], a mixed-method approach assists the research in answering research questions that cannot be answered by using pure quantitative or pure qualitative approaches. The nature (ontology) of the research context of the study may require that, for example, a qualitative data set is supplemented by a quantitative data set, to achieve the goal of the study [3].

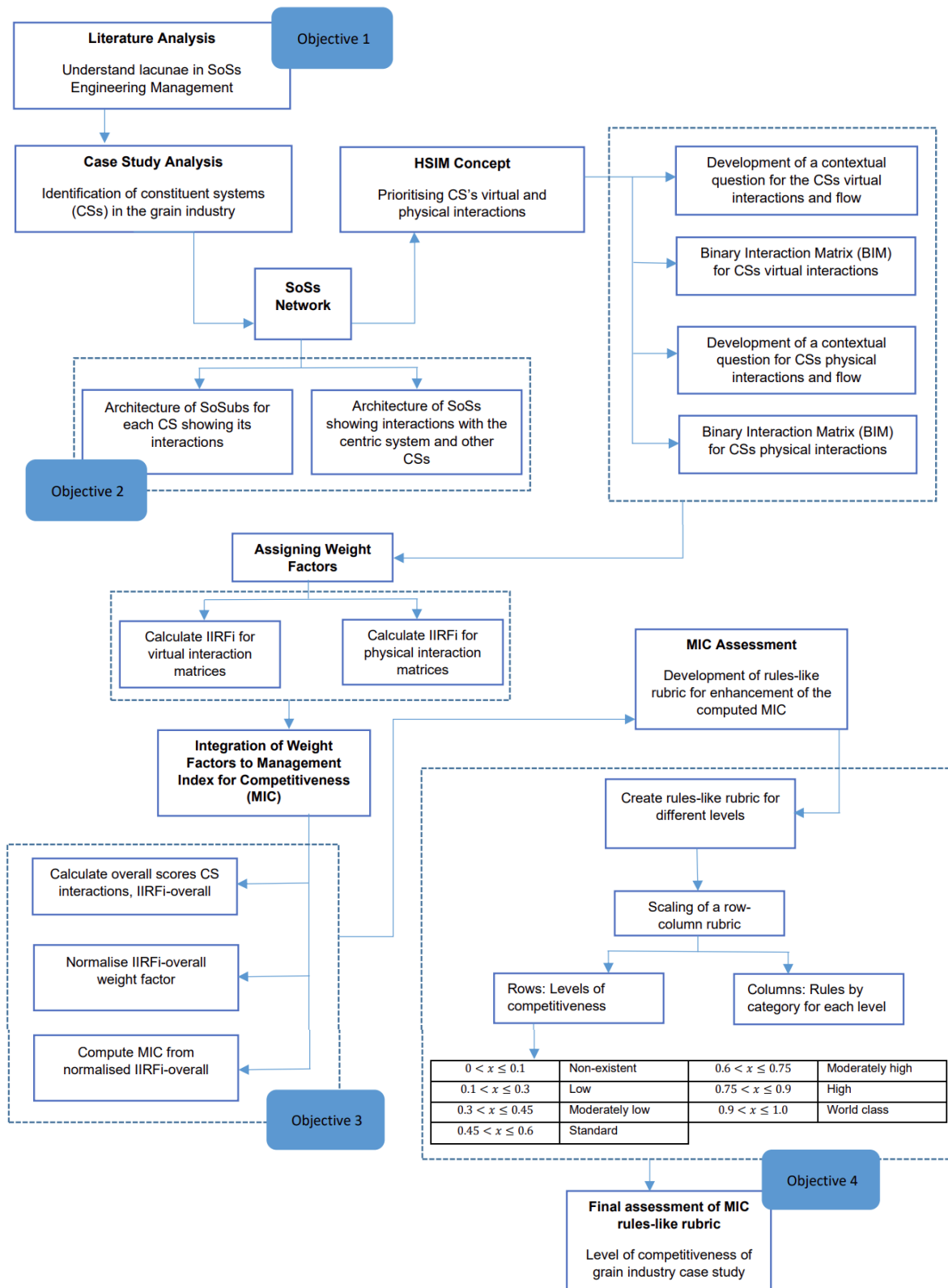
### 3.2 Research Methodology and Conceptual Framework

Given that the primary goal of this study is to quantify management effort based on the qualitative interrelationships between system entities, the ontology of the study naturally aligns itself with the **mixed-method approach** (epistemology). This influenced the choice of the methodology adopted in this study.

Research methodology is the general strategy or procedures that outline how research will be conducted for a specific study [126]. It is a blueprint for how data are collected, measured and analysed to answer the research questions and thereby achieve the aim and objectives of the study [127]. In short, the research methodology provides the **conceptual framework** for the study. Thereby, this study is divided into three stages, satisfying the research objectives.

The initial stage includes an extensive literature review discussing the phenomenon of systems engineering and the management thereof, as presented in Chapter 2. The product of this stage was two-fold, comprising the in-depth explication of SoSEM, as well as a summary of the system entities identified in the grain industry case study. The second stage takes on a **qualitative approach** and includes constructing a holistic framework that depicts a heterogeneous SoS network of the system entities in the grain industry case study (Objectives 1 and 2). The research methods applied in this stage include multiple nested case studies and systems architecture. These methods are described in more detail in section 3.3. The last stage takes on a **quantitative approach**. In this stage, the qualitative results derived from the second stage were converted into quantitative data and used to determine the management effort towards competitiveness. The research methods applied in the third stage were the HSI method and the computation of the MIC (Objectives 3 and 4). A comprehensive, systematic description of these methods is given in section 3.4 to section 3.6.

The conceptual framework that shows the flow of tasks and activities across the research, as well as the link between the research approaches and the objectives, is depicted in Figure 14.



**Figure 14.** Conceptual research framework.

### 3.3 Qualitative Studies

For the second stage of this study, qualitative research was conducted. In a qualitative research study, non-numerical data are collected [128] and aim to deduce insights from the data based on observations and interpretations [129]. According to Mohajan [130], there are different types of qualitative research methods, such as phenomenology, ethnography, narrative approach, grounded theory, content analysis, action research, historical research and **case study**. The case study qualitative research method can be a study of either a single case or multiple cases, for which there are various subtypes of each [130]. The benefits of using case studies as a research method include their potential to attain stronger conceptual validity, their usefulness in analysing the contributing and causal role in the context of individual cases and their capacity to convey this causal complexity [131]. Additionally, there are three ways of collecting data for qualitative research, namely interviewing people (communicating with the entities), carrying out observations or using existing documents [132].

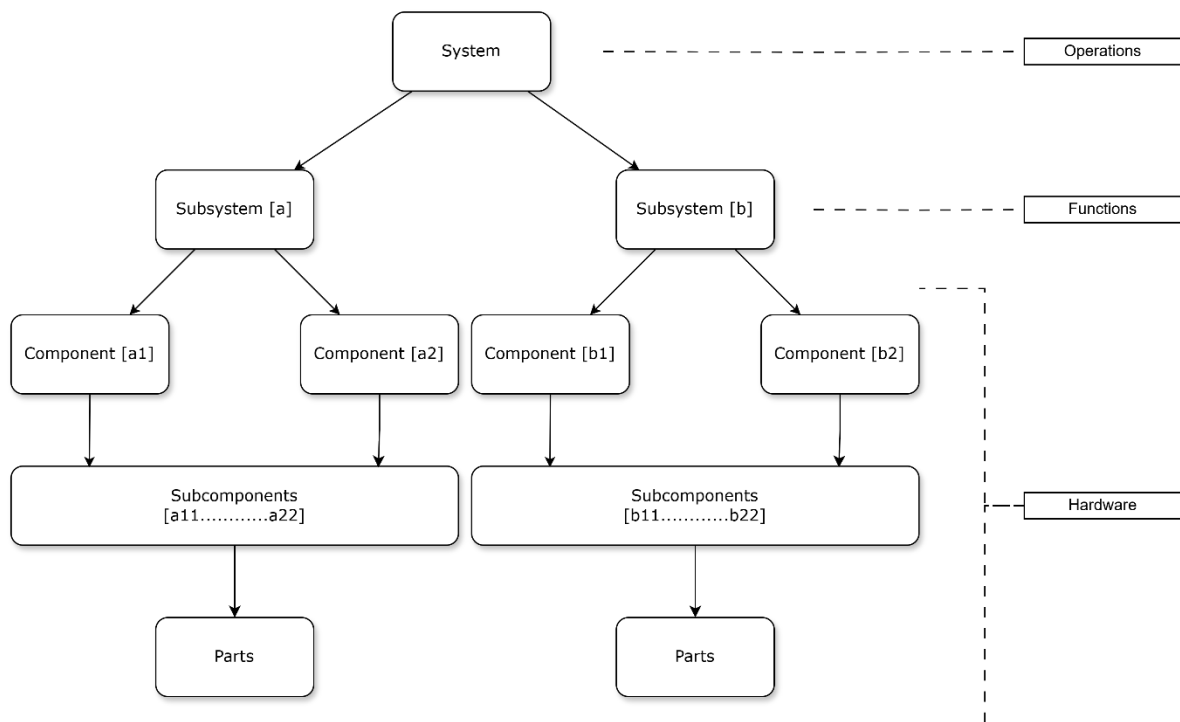
In this study, **nested studies**, which is a subtype of multiple case studies were applied. For nested studies, non-random sampling was used to conduct case study investigations, to portray a limited number of cases in detail [133]. Nested studies are different from other multiple case studies in the sense that they obtain their wholeness from a wider case [130]. In other words, all the single cases investigated are linked to an umbrella case. In the context of this study, the single cases refer to the individual grain constituent system entities, whereas the umbrella case study is the grain industry SoS.

The 35 individual grain constituent system entities, as presented in Chapter 2, served as the individual cases. The data were obtained via communicating with the management of the centric system entity, GSA, as well as investigating existing documents (such as annual reports) from the other constituent entities. For the nested case study analysis, these individual cases were investigated and compared according to the following elements:

- The level of propagation of information (**or** communication of signals **or** sharing of data) between the individual cases.
- The level of significance of the propagation of information (**or** communication of signals **or** sharing of data) between the individual cases.
- The number, complexity and critical nature of the hardware of the individual cases.
- The number, complexity and critical nature of the software of the individual cases.
- The human resource capabilities of the individual cases.

Using the qualitative data obtained from the above-mentioned elements in the context of the 35 individual cases, the method of systems architecting was used to model the causal complexity of the constituent system entities in the wider case of the SoS network. The SoS network originates from an SoSubs network determined by the comparison of the above-mentioned elements. The steps involved in architecting the network are [52]:

1. Define the centric system and develop its sub-systems according to the systems structure, as depicted in Figure 15;
2. Define all external entities interacting with the centric system;
3. Develop the sub-systems for each external entity, according to the systems structure architecture, similar to Step 1;
4. Determine the interrelationships between the entities (centric and external) by defining the interrelationships between the external entity sub-systems relating to the sub-systems of the centric entity;
5. Draw an SoS network showing the systems and their interrelationships.



**Figure 15.** Architecture template for the structure of a system [52].

### 3.4 Quantitative Model for System Elements Interaction

For the third stage of this study, quantitative research was conducted. Qualitative research deals with the collection and analysis of numerical data to identify trends and relationships [134]. Quantitative research comprises a range of methods [135], where the methods process data by following three consecutive phases, namely **data management, data analysis and data interpretation** [136]. One such quantitative method is the HSIM comparative model [70], which was adopted in this study. The HSIM comparative approach is premised on the theory of subordination and makes use of a binary weight assignment scheme which over time, translates into a continuous weight assignment mechanism [70, 73, 74].

The qualitative data from the second stage, obtained from the wider grain industry case study and depicted in an SoS network, were used to generate the quantitative data. This was done in the **data management phase**, where the SoS network diagram was used to identify, prioritise and rank constituent systems based on the SoS network in order of significance using the principle of subordination. Unlike the conventional HSIM method, an SoS network diagram was used to achieve this, rather than a HTSD.

For the quantification of the data, using the HSIM method, the focus is on the interactions between constituent systems. A given systems pair can interact in a variety of ways, in accordance with the HSIM principle. Using the Binary Interaction Matrix (BIM) concept of the HSIM method, the systems' interactions based on a specific contextual relationship were used to construct an inter-systems pairwise matrix.

For the wider grain industry case study, the focus was on the virtual and physical interactions between the constituent systems. Virtual interactions include the propagation of information/signals/data and the criticality of the propagation of information/signals/data. Subsequently, physical interactions include the effort required to manage the hardware, software and people of constituent systems. For each interaction mentioned, a contextual question (CQ) was developed. The CQs link to the investigated elements of the individual cases and are as follows:

- Does system  $i$  propagate information, communicate signals or share data with system  $j$ ?
- Does system  $i$  propagate information, communicate signals or share data that is considered to be more critical or significant than that of system  $j$ ?
- Does system  $i$  have in its custody more hardware to manage in terms of their numbers, complexity and critical nature in comparison to system  $j$ ?

- Does system  $i$  have in its custody more software to manage in terms of their numbers, complexity and critical nature in comparison to system  $j$ ?
- Does system  $i$  have more human resources in its custody to manage in comparison with system  $j$ ?

The CQs were used to determine the inter-systems pairwise matrix. This was done by allocating either the number 0 or 1 to the interaction between system  $i$  and system  $j$ , such that:

$$S_{ij} = \begin{cases} 0, & \text{no interaction, i. e. answer to CQ is "no"} \\ 1, & \text{unidirectional interaction, i. e. answer to CQ is "yes"} \\ S_{ji} = 1, & \text{bidirectional interaction, i. e. answer to CQ is neutral/equal,} \end{cases}$$

where  $S_{ij}$  denotes the constituent systems of row  $i$  and column  $j$ . As can be seen in the third instance,  $S_{ij}$  and  $S_{ji}$  can both be "1" since the deployment of the HSIM approach herein is not about prioritisation but relates to the sharing of resources between any two constituent systems.

The step-by-step procedure for establishing the HSIM for a given conglomeration of heterogeneous constituent systems (factors) is depicted in Figure 16 and was applied in the **data analysis phase** of the quantitative research studies.

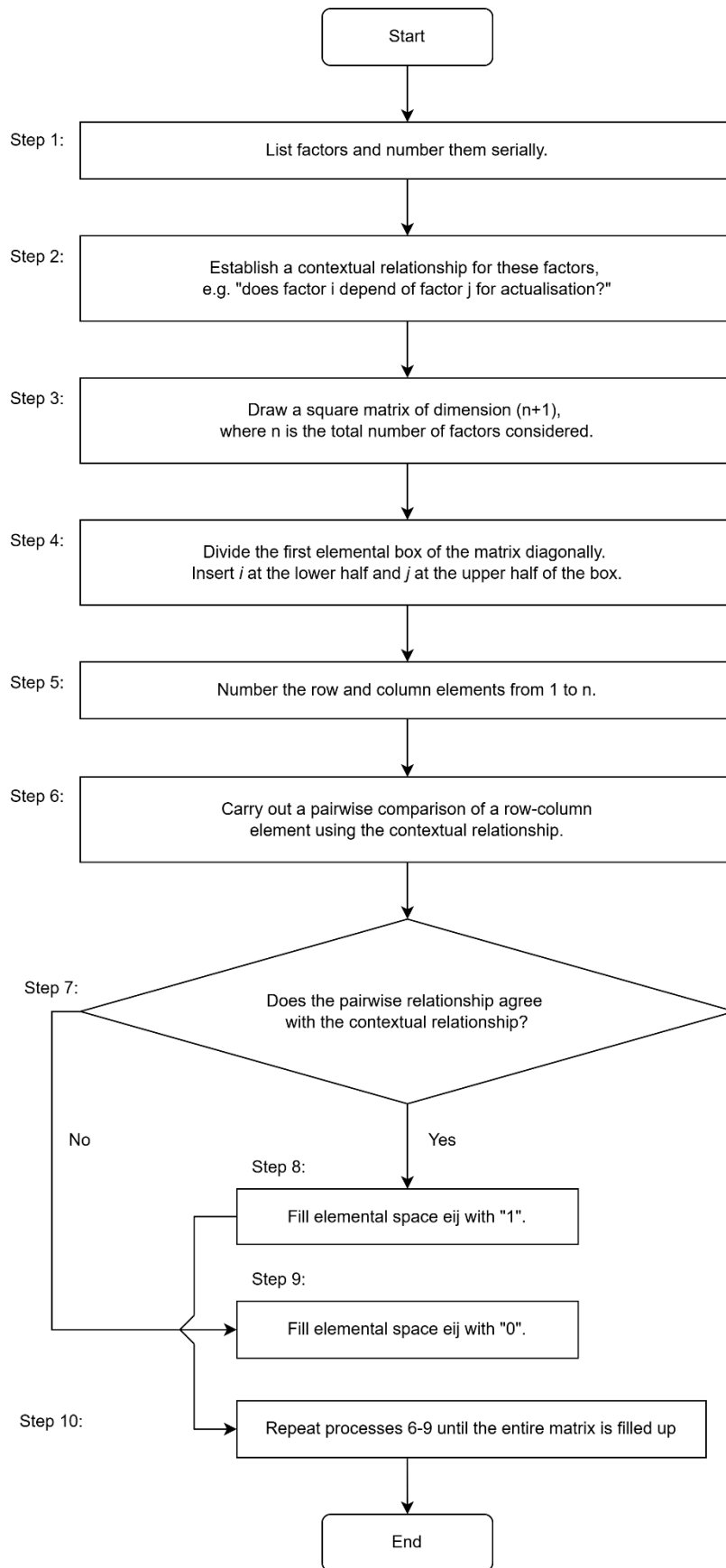
Weight assignment was used to do numerical analyses of the constituent systems in the SoS network. The model for calculating weight assignment is as follows:

$$IIRF_i = \left( \frac{N_{SF_i}}{T_{NF}} \cdot M_{SR} \right) + \left( \frac{B}{T_{NF}} \right) (M_{SR} - C),$$

$$\text{where } C = \frac{M_{PSF} \cdot M_{SR}}{T_{NF}},$$

$$\text{and } B = N_{SF_i} + 1,$$

where  $IIRF_i$  is the intensity of system  $i$ 's significance rating,  $N_{SF_i}$  is the number of subordinate systems to a particular system  $i$ ,  $M_{PSF}$  is the maximum number of subordinate systems that can be considered,  $C$  is constant,  $B$  is the proportion of variations,  $T_{NF}$  is the number of systems in total and  $M_{SR}$  is the maximum possible scale rating.



**Figure 16.** Diagram of the HSIM development process [73].

The actual normalised weight of each constituent system was then determined based on the estimated normalised weight of each constituent system. The following technique was used to normalise the ratings:

1. For each constituent system identified in the case study, organise the  $IIRF_i$ -ratings per matrix into a column matrix;
2. Determine the overall  $IIRF_i$ -rating by averaging the  $IIRF_i$ -rating of the virtual interaction matrices and the  $IIRF_i$ -rating of the physical interaction matrices and add this to the column matrix from Step 1;
3. Calculate each rating's  $n$ th root, where  $n$  denotes the total number of constituent systems considered;
4. Add Step 3's findings together and calculate the sum;
5. Divide Step 3's  $n$ th root for each constituent system by Step 4's summation.

The steps are combined to create the following model:

$$N_{Wi} = \frac{(x_i)^{1/n}}{\sum_{i=1}^n (x_i)^{1/n}},$$

where  $N_{Wi}$  is the system's normalised weight  $i$ ,  $n$  is the number of systems and  $x_i$  is the original rate of system  $i$  before normalisation.

The following is a generalised version of the steps for determining the effective minimum management score required for competitiveness attainment (also known as the MIC):

1. Sort the normalised scores into a sequenced ascending order e.g. {0 to 1} for  $n$  system entities;
2. Obtain the average of the scores;
3. Separate the normalised scores into two clusters viz.:
  - a. below average scores should be in one cluster,
  - b. equal to or more than the average score should form another cluster;
4. Count how many scores are in each cluster;
5. Determine what percentage of the total number of scores ( $n$ ) are in each cluster;
6. Multiply the outcome of Step 5 by the sum of scores per cluster;
7. Sum the outcomes in Step 6 to determine the effective minimum management score required for competitiveness attainment.

Thus, the HSIM model converts the qualitative data from the second stage and applies a time-variant approach to offer a method for the quantification of the management effort required to maintain SoS competitiveness, which is the primary goal of the study. In other words, it offers a method for computing the MIC. This forms part of the **data interpretation phase** which includes generating the rules-like rubric for the computed MIC (minimum management score). The rules-like rubric entails specific rules that govern each level of competitiveness (by reflecting on the necessary actions to be carried out and adhered to in order to maintain or enhance the competitiveness level). This phase is important because evidence (data analysis) without interpretation is worthless [136].

### 3.5 Development of the Management Index Model for Competitiveness

The generalised version of the process for calculating the MIC is outlined in section 3.4. Although this process is understandable, it lacks mathematical accuracy. In addition, it is not possible to be performed by a computer or other mathematical-based mechanism. Converting the step-by-step process into a mathematical formula, using mathematical modelling, will make this process clearer. Mathematical modelling is described as the “process of formulating an abstract model in terms of mathematical language to describe the complex behaviour of a real system” [137]. It is a multi-disciplinary field which leads to a better understanding of the process under investigation [137]. According to Blum and Borromeo-Ferri [138], it is important to use mathematical modelling in solving tasks, because it facilitates a more accurate interpretation of the process.

Therefore, through the process of iteration testing, the above-mentioned steps were combined and transcribed to create the mathematical model for computing the MIC. The model makes use of a Heaviside step-function, called  $H(x)$ . The Heaviside step-function, otherwise known as the unit step-function, was introduced by Oliver Heaviside and is normally denoted with the letters  $H$  or  $u$  [139]. It is a discontinuous single-valued function, where the value of one is allocated for the positive argument and the value of zero for the negative argument [140]. A unique property of this function is that it can be displayed as either a piecewise constant function or a generalised function [140, 141]. Subsequently, this special function is useful for calculations addressing the conceptual design procedures from an engineering perspective [142].

Thus, the newly created model for computing the MIC is as follows:

$$MIC = \sum_{j=1}^2 C_j T_j \quad \leftarrow \text{Step 6's multiplication and Step 7}$$

where:

$$T_1 = \frac{\sum_{i=1}^n (H(N_{Wi} - N_{Wavg}) \times N_{Wi})}{n} \quad \leftarrow \text{Step 6's summation}$$

$$\text{and } T_2 = \sum_{i=1}^n N_{Wi} - T_1$$

$$C_1 = \frac{\sum_{i=1}^n H(N_{Wi} - N_{Wavg})}{n} \quad \leftarrow \text{Step 3, 4 and 5}$$

$$\text{and } C_2 = 1 - C_1$$

$$N_{Wavg} = \frac{\sum_{i=1}^n N_{Wi}}{n} \quad \leftarrow \text{Step 2}$$

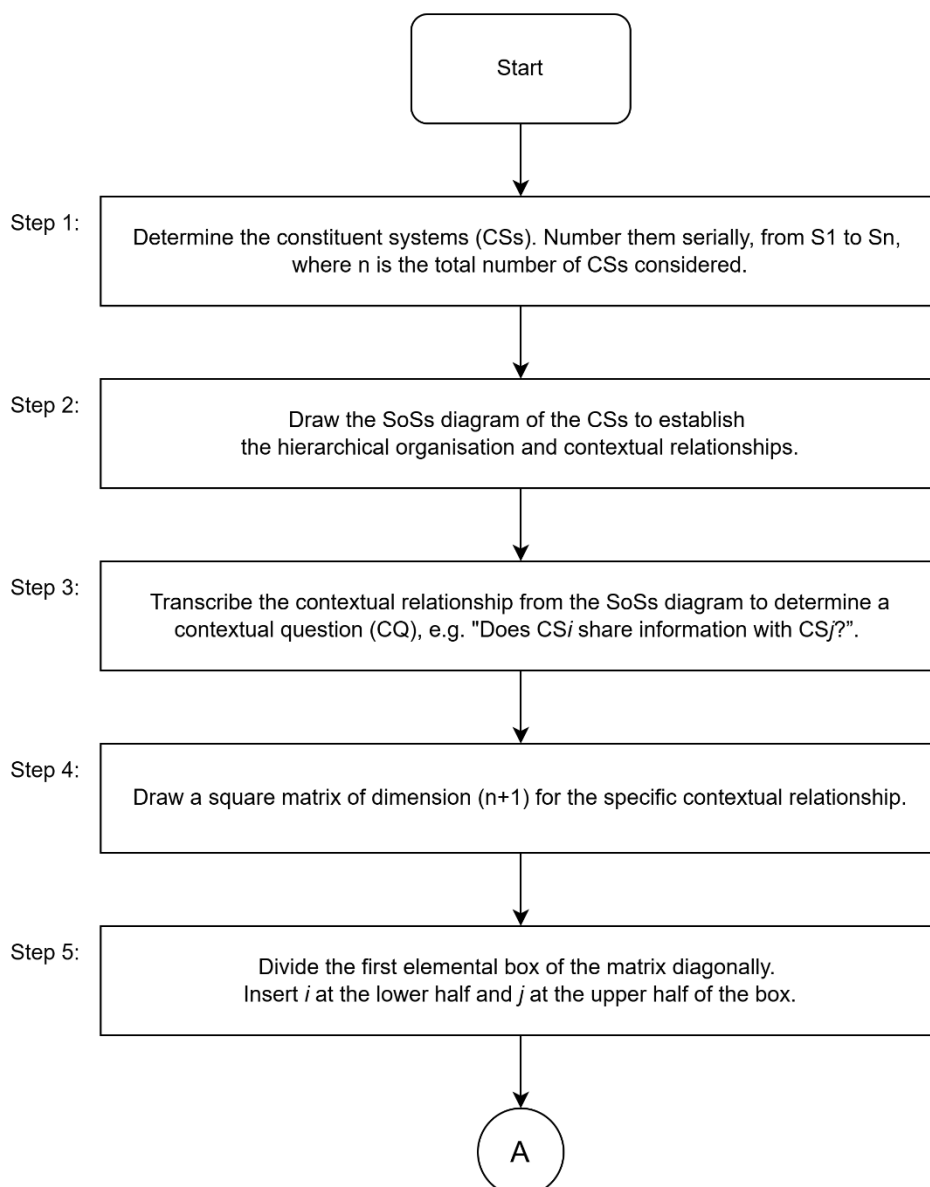
$$H(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases}$$

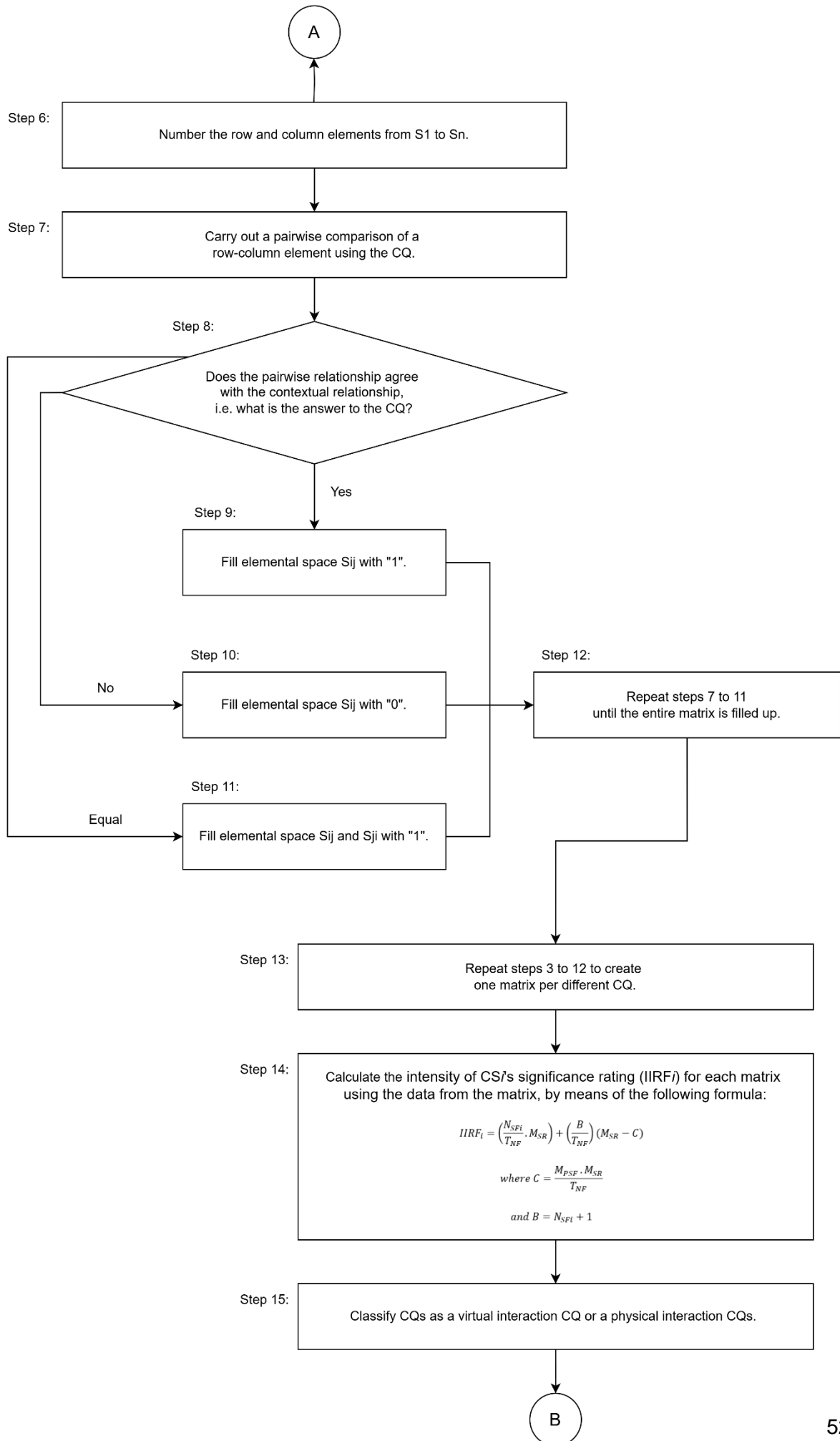
Where  $C_j$  is the cluster percentage of the total number of scores of cluster  $j$  and  $T_j$  is the sum of scores of cluster  $j$ , where  $j = 1$  represents the “equal to or more than the average score” cluster and  $j = 2$  represents the “below than the average score” cluster. In addition,  $N_{Wavg}$  is the average of the normalised weights,  $N_{Wi}$  is the normalised weight of system  $i$ ,  $n$  is the number of systems and  $H(x)$  represents the Heaviside step-function. The comments in blue indicate the specific step of the generalised version of the process (as described at the end of section 3.4) that relates to the specific mathematical equation. Step 1 is not expressed separately, because the Heaviside step-function already takes into account that the values are sorted in ascending order.

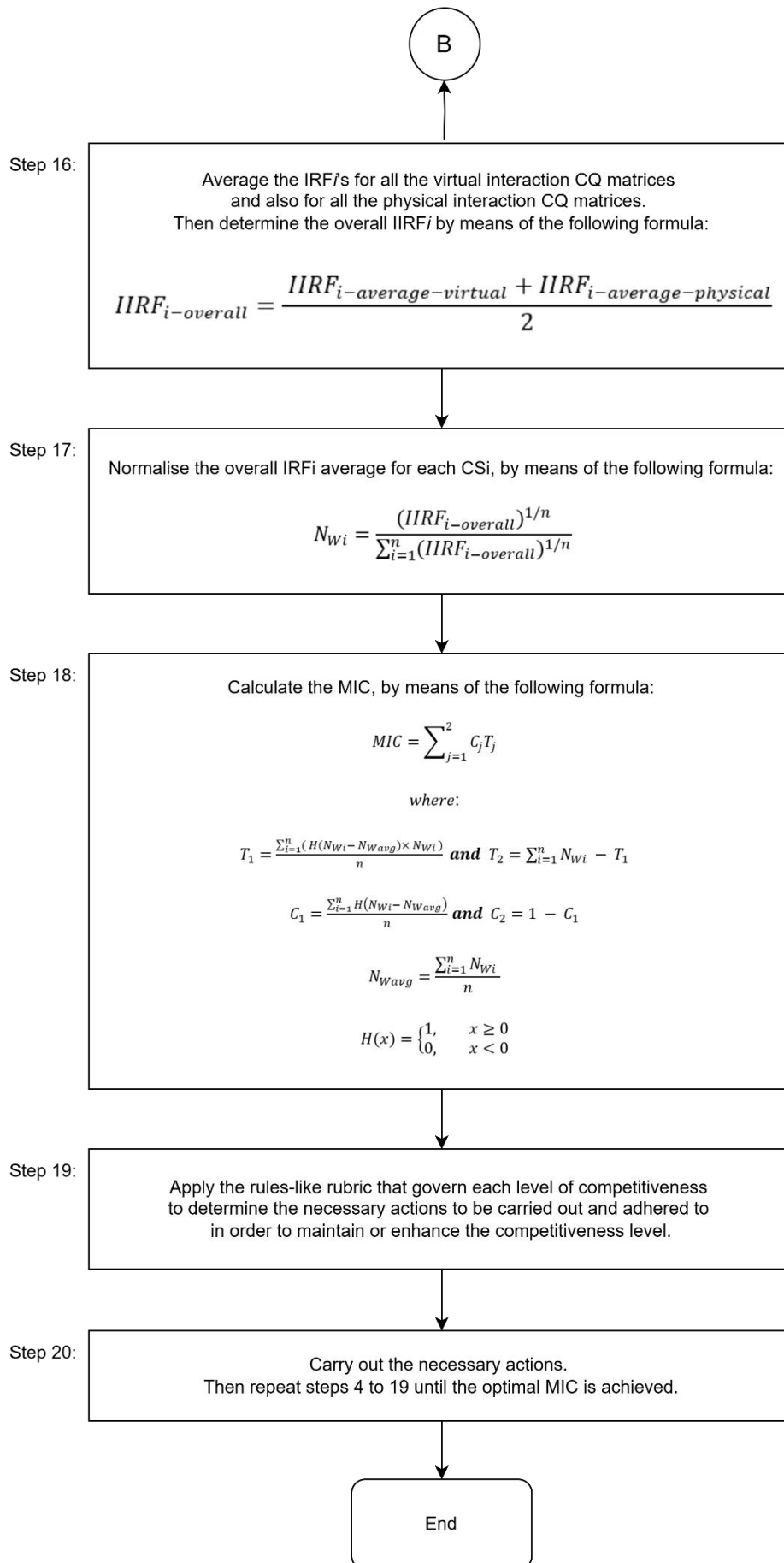
### 3.6 Process Flowchart of the Management Index of Competitiveness

Even though several researchers have tried to create one robust approach for combining qualitative and quantitative methods [143], one of the disadvantages of using the mixed methods approach remains the lack of a generalised approach [122]. Therefore, a generalised mathematical model for computing the MIC was developed and presented in section 3.5. Furthermore, a detailed flowchart depicting the process of obtaining the MIC from an SoS diagram is provided below. The flowchart provides a more detailed formula and guidance on how the research was conducted, to present replicable and generalisable findings right from the onset of the research process.

The flowchart of the step-by-step actions required to determine the MIC from the SoS diagram is depicted in Figure 17, stretching over three pages. This summarises all the steps executed in Chapter 4.







**Figure 17.** Flowchart for computing the MIC.

### 3.7 Chapter Summary

This chapter presented and discussed the research methodology and methods adopted to conduct this study. The choice of a research design and methodology was informed by several factors, mainly the aim and objectives of the study. A mixed methods approach is adopted to conduct this study, where qualitative and quantitative data are collected sequentially. The qualitative research method is applied to understand the complexities of the phenomenon and to provide context to the study. Subsequently, the quantitative research method intends to obtain accurate quantification of the phenomenon to allow for the analysis thereof [144]. The objectives and the research questions of this study were addressed by the adopted research methodology. The next chapter presents the findings of the study.

## CHAPTER FOUR: RESULTS AND DISCUSSION

Research results must address the research problem and answer the research questions of the study [145]. In this chapter, the research results are therefore outlined and discussed. This is done with reference to the qualitative research, conducted by means of multiple nested case studies and systems architecture. Grain South Africa is the umbrella case study or centric system of this study, with 34 nested case studies or constituent systems. The centric system and the other constituent systems are discussed in-depth in this chapter and further explicated by applying systems architecture. The quantitative research, conducted by means of the HSIM method, is also outlined. From the normalised HSIM data, the MIC is determined by applying the generalised model for computing the MIC, as developed in Chapter 3. The execution of this chapter was done using the process flowchart describing the research methodology, also described in Chapter 3

### 4.1 Nested Case Study Analysis of the SoSs Constituent Systems

The umbrella case study focusing on the grain industry in South Africa was introduced at the end of Chapter 2. There are 35 nested individual cases under the umbrella case study. More precisely, 1 centric system entity and 34 other constituent system entities of the SoSs (umbrella case). In this section, the 35 entities, as well as their interrelationships with each other are discussed in more detail. In this section, the different external system entities interacting with GSA are described in more depth.

#### 4.1.1 Centric System

The centric system is GSA, which has been discussed in detail in section 2.5.3. GSA has five divisions, focusing on grain research (Division 1), supply chain partners (Division 2), grain market and economy (Division 3), industry interest representatives (Division 4) and farmer development (Division 5) [78]. Figure 18 shows the systems architecture of GSA and how it links to all the system entities, including the government entities.

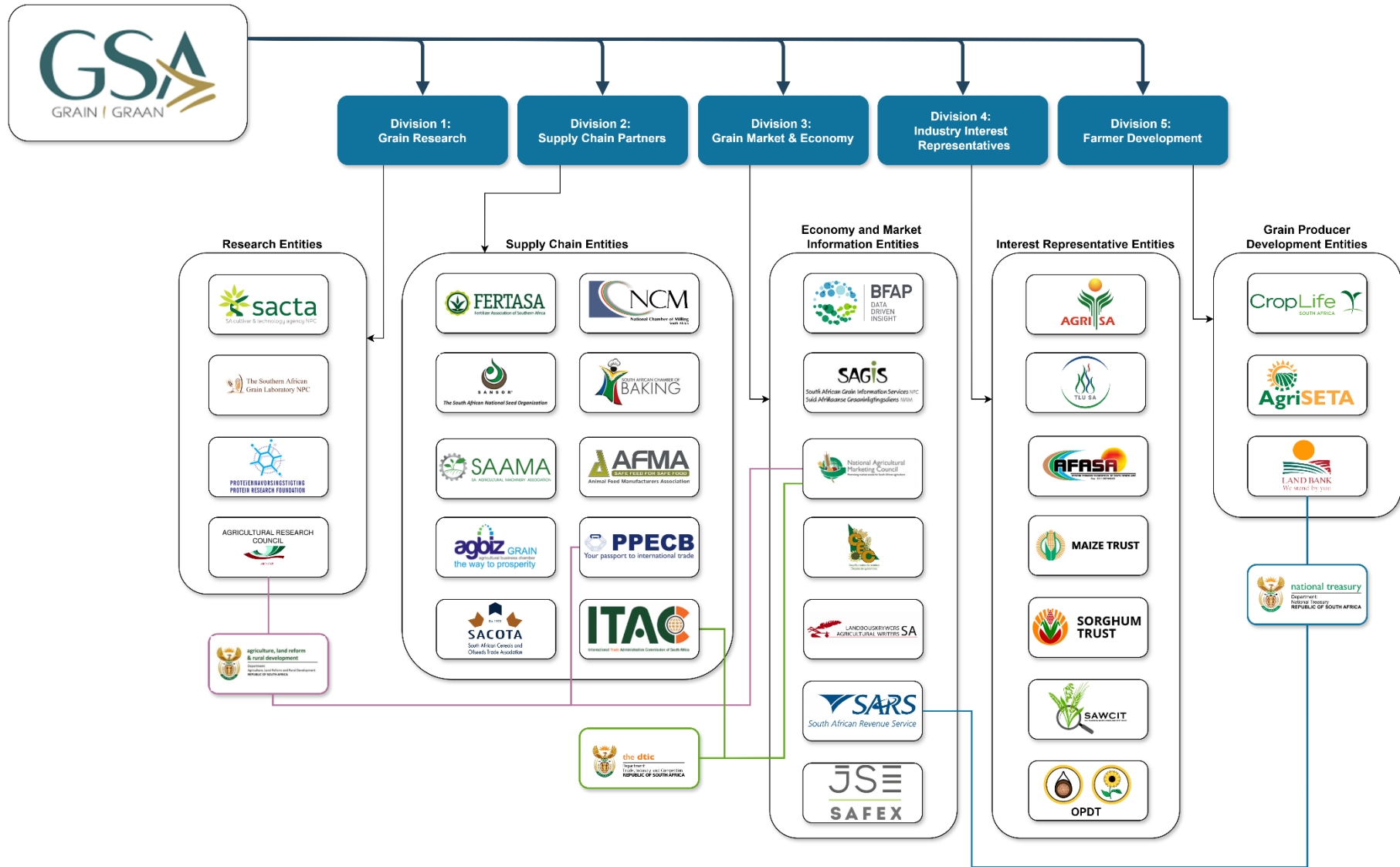


Figure 18. GSA systems architecture.

## 4.1.2 Research Entities

The research entities include mainly laboratories responsible for grain and grain-related research. Therefore, the system entities discussed in this section are SACTA, SAGL, PRF and ARC.

### 4.1.2.1 South African Cultivar and Technology Agency

SACTA was established in 2016 as a non-profit company responsible for ongoing innovation in plant breeding and technology development of self-pollinated (Division 1) and open-pollinated (Division 2) cultivars in South Africa [83]. For South Africa's grain industry, SACTA focuses on self-pollinating grain and oilseed crops, specifically wheat, barley, soybeans and some canola cultivars. The research is funded using breeding statutory levies. Figure 19 represents the systems architecture of SACTA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

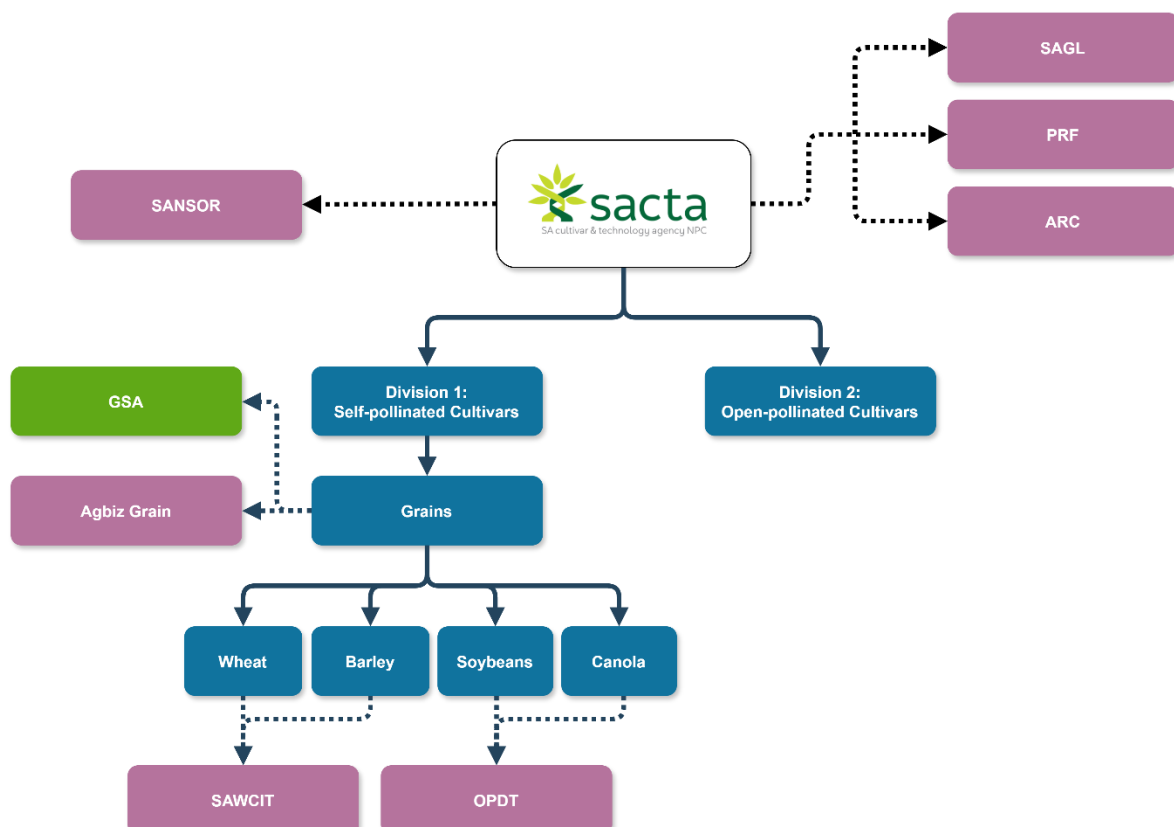


Figure 19. SACTA systems architecture.

#### 4.1.2.2 Southern African Grain Laboratory

SAGL was established in 1997 by the grain industry as an independent non-profit company to act as a reference laboratory for grain and oilseeds [84]. They deliver market-driven analytical laboratory services for maize, wheat, sorghum, sunflower and soybeans. SAGL has six divisions, namely [84]:

- **Division 1:** The Grading and Milling Laboratory is responsible for conducting studies related to the grading of wheat, maize and oilseeds, as well as conducting milling tests.
- **Division 2:** The Chemistry Laboratory is responsible for conducting studies on the pH, colour, fat, fibre, moisture, protein *etc.* of the grain cultivars.
- **Division 3:** The Rheology and Baking Laboratory is responsible for conducting numerous baking test studies.
- **Division 4:** The Nutrients and Toxins Laboratory is responsible for conducting studies on the vitamins, minerals, sodium, amino acids *etc.* needed for grain growth.
- **Division 5:** This division is responsible for SAGL’s Support services, Quality Assurance (QA) of tests and Management.
- **Division 6:** The Crop Protection Division has a flexible scope of studies which are conducted. This division’s work is largely market-driven by stakeholders who want to conduct specific grain research. One such organisation is GSA.

Figure 20 represents the systems architecture of SAGL in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

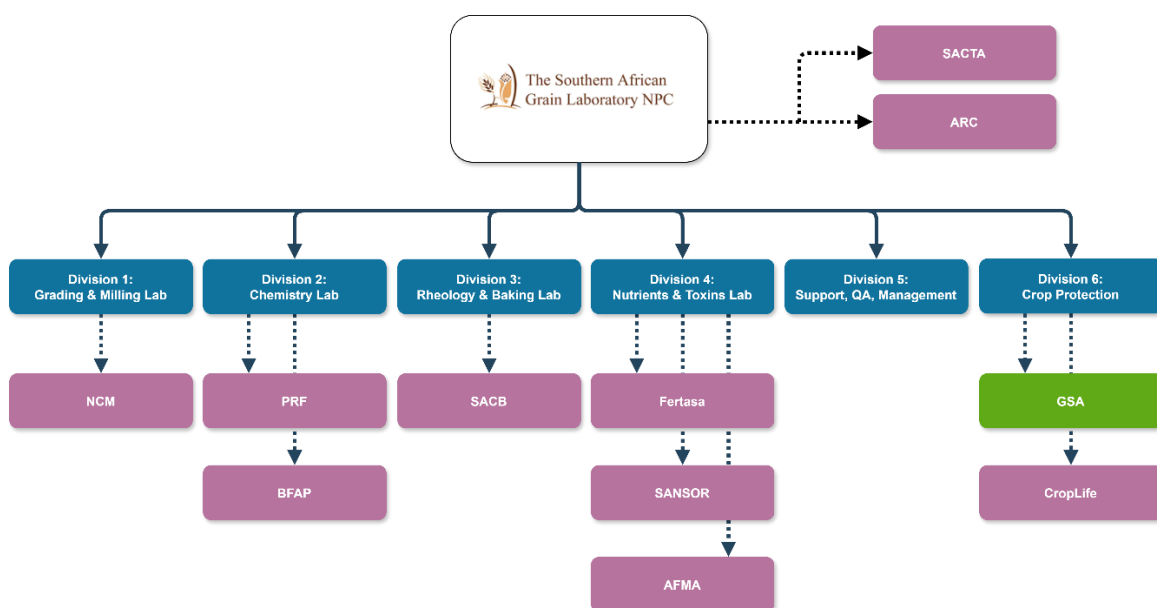


Figure 20. SAGL systems architecture.

### 4.1.2.3 Protein Research Foundation

The PRF was formally established in 1990. Even though certain objectives of the foundation date to 1973, it was restructured to focus on purely research and related matters from 1990 onwards [85]. PRF's main objective is to research better protein utilisation and technology transfers to replace imported protein for animal use with locally produced protein [85]. The research is funded and focused on crops (Division 1), oilseeds (Division 2) and fishmeal (Division 3) for animal use, and therefore provides information to AFMA. Figure 21 represents the systems architecture of PRF in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

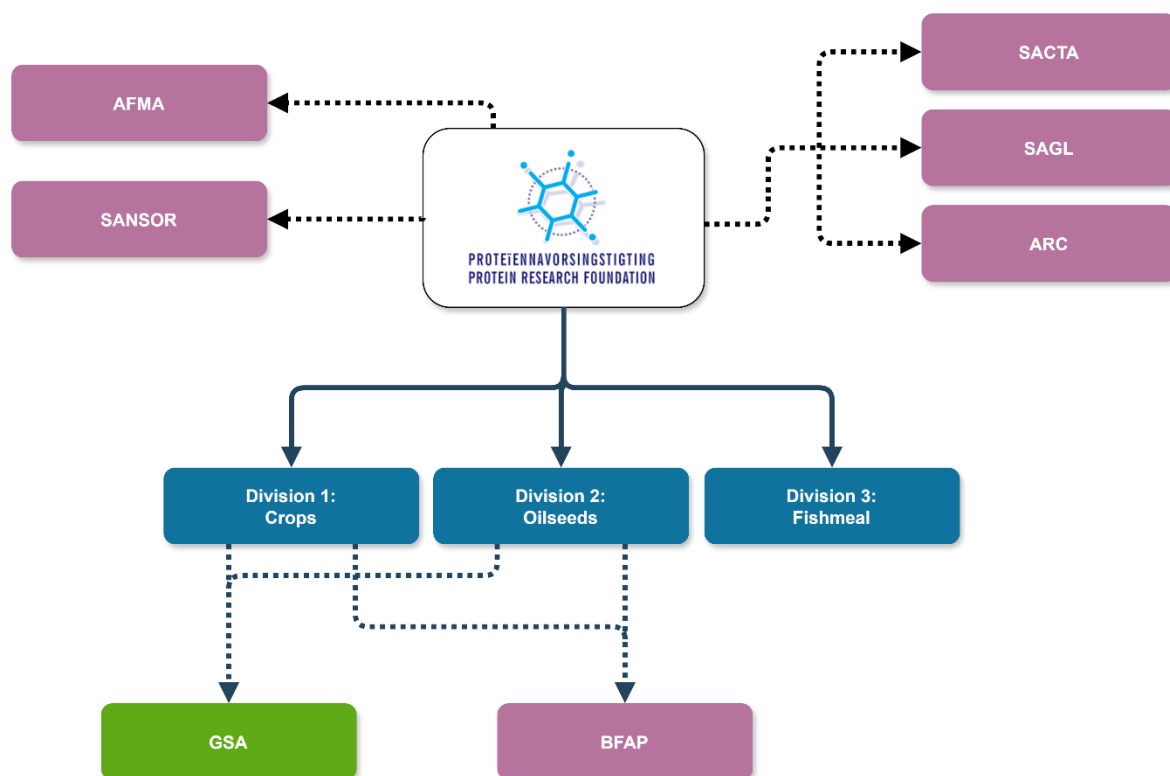


Figure 21. PRF systems architecture.

### 4.1.2.4 Agricultural Research Council

ARC is a state-owned enterprise reporting to DALRRD [146]. It was established according to the Agricultural Research Act 86 of 1990, as a science institution that fosters innovation to develop the agricultural sector.

ARC's main functions include [86]:

- Increase agricultural production and productivity,
- Sustain ecosystems and natural resources,
- Enhance nutritional value, quality and safety of agricultural products,
- Create a skilled and capable sector,
- Enhance agricultural resilience.

ARC performs its functions using several research campuses, strategically located throughout the country. These research campuses are predominantly commodity-based and therefore operate under either the Animal Sciences or Crop Sciences divisions. The Research and Innovation System division shares information with relevant parties, such as GSA, Agbiz Grain and NAMC. Figure 22 represents the systems architecture of ARC in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

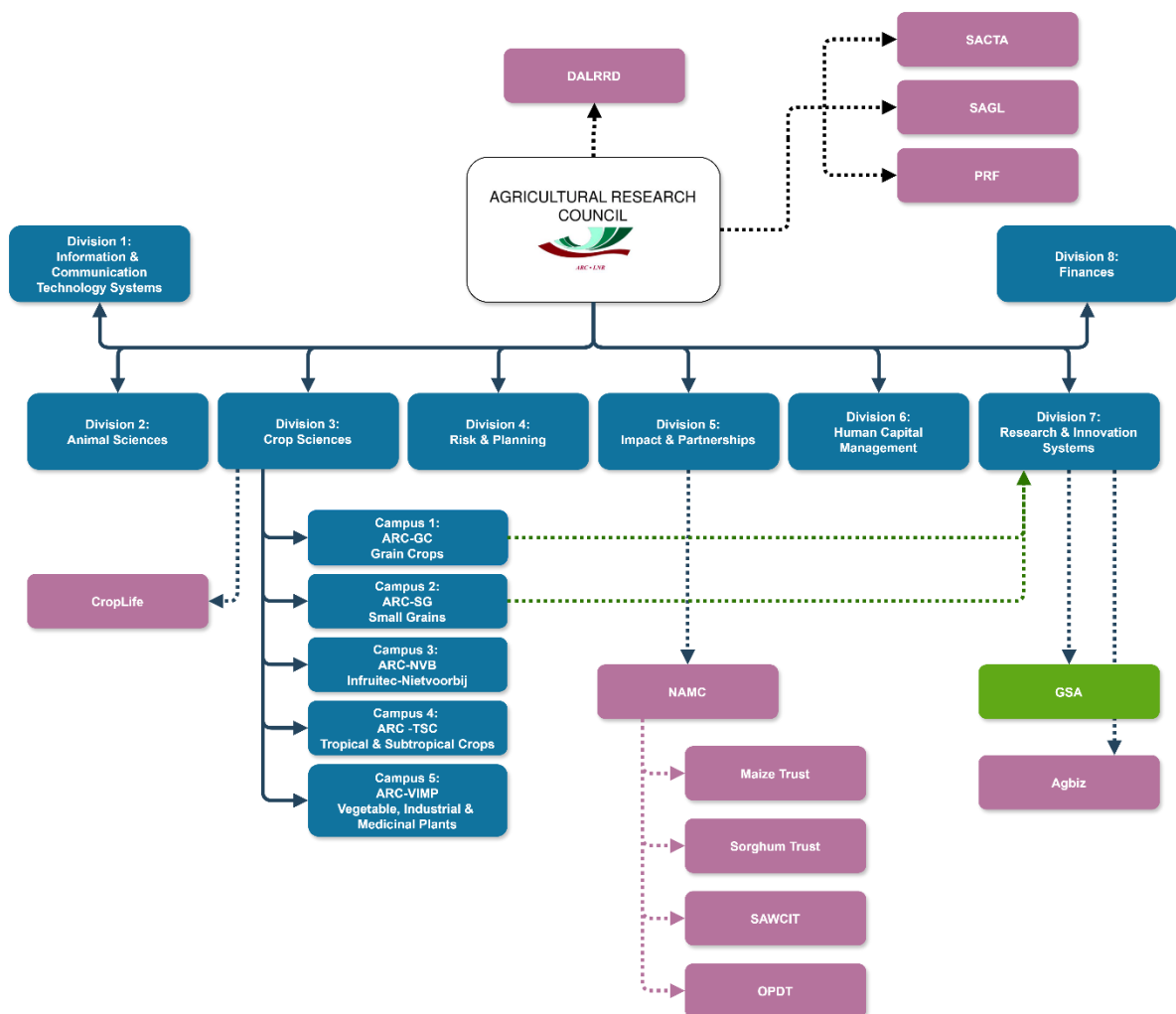


Figure 22. ARC systems architecture.

### 4.1.3 Supply Chain Entities

The supply chain representative entities include **input providers**, such as Fertasa (fertiliser), SANSOR (seed) and SAAMA (agricultural machinery); **grain processors**, such as AFMA (animal feed), NCM (milling) and SACB (baking); **grain storage and handling organisations**, such as Agbiz Grain and **grain traders**, such as SACOTA, PPECB and ITAC.

#### 4.1.3.1 Fertiliser Association of South Africa

The Fertiliser Society of South Africa was established in 1959 but restructured in 2014 when it was renamed the Fertiliser Association of South Africa, as it is still known today [87]. Fertasa is a non-profit company that represents the fertiliser industry and its members. The association comprises four divisions [87]:

- **Division 1:** The Members' Meeting represents the ordinary and affiliate members, who nominate representatives. This division is managed by the nominated Chief Executive Officer and other representatives who have the authority to approve budgets, fees, finances *etc.* Fertasa also initiates dialogue with the government and other industry supply chain role players.
- **Division 2:** The Technical Committee develops policies and guidelines for fertiliser use, to ensure sustainable soil fertility. Research needed to develop new guidelines is derived from SAGL.
- **Division 3:** The Regulatory Committee is responsible for developing, as well as interpreting regulations pertaining to the sustainable use of fertiliser products.
- **Division 4:** The Educational Committee is sub-divided into the Publications Committee (who publishes the Fertasa journal, handbook and other documents) and the Training Committee (who designs and implements training courses such as the “Fertiliser Advisors, Certification and Training Scheme”). These committees communicate with different divisions of GSA.

Figure 23 represents the systems architecture of Fertasa in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

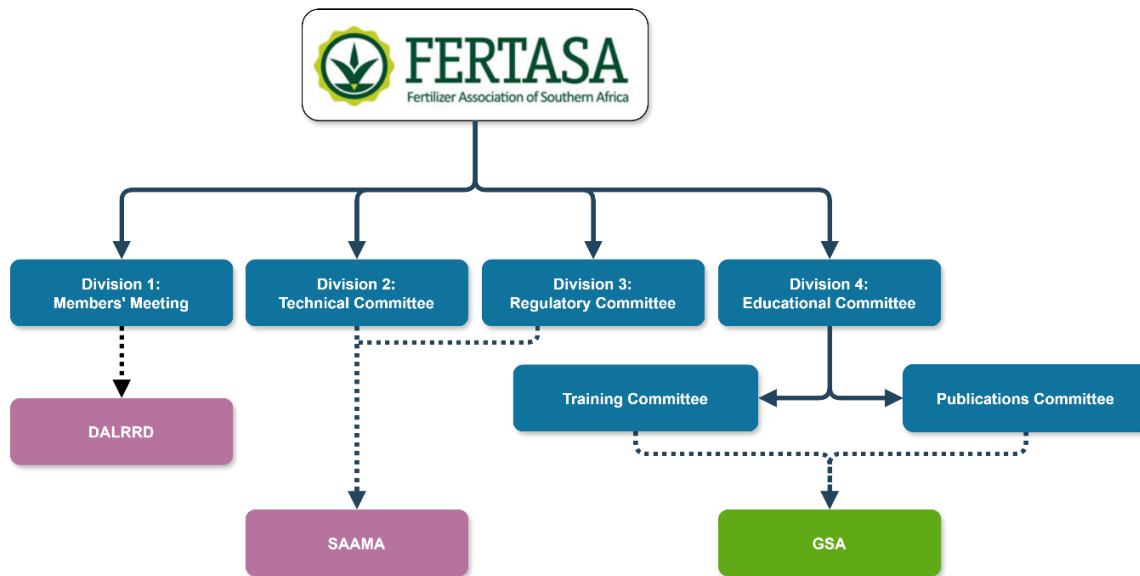


Figure 23. Fertasa systems architecture.

#### 4.1.3.2 South African National Seed Organisation

SANSOR was established in 1989 as the National Designated Authority to certify that seed was produced, inspected and graded according to the legislated standards and systems [88]. The organisation comprises two divisions [88]:

- **Division 1:** The Phytosanitary Division researches seed and plant health. Seed and plant health is an essential step for ensuring successful imports and exports. Members that assist with conducting research include universities, such as North-West University, University of Pretoria, Stellenbosch University and University of KwaZulu-Natal, as well as laboratories such as SACTA and ARC.
- **Division 2:** The Seed Certification Division ensures that quality assurance tests are conducted on the seeds supplied to local and international farmers and other growers. They control and verify that the supplied seeds are of high quality and in accordance with the requirements of the various National and International Seed Certification Schemes, as determined by, for example, DALRRD.

Figure 24 represents the systems architecture of SANSOR in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

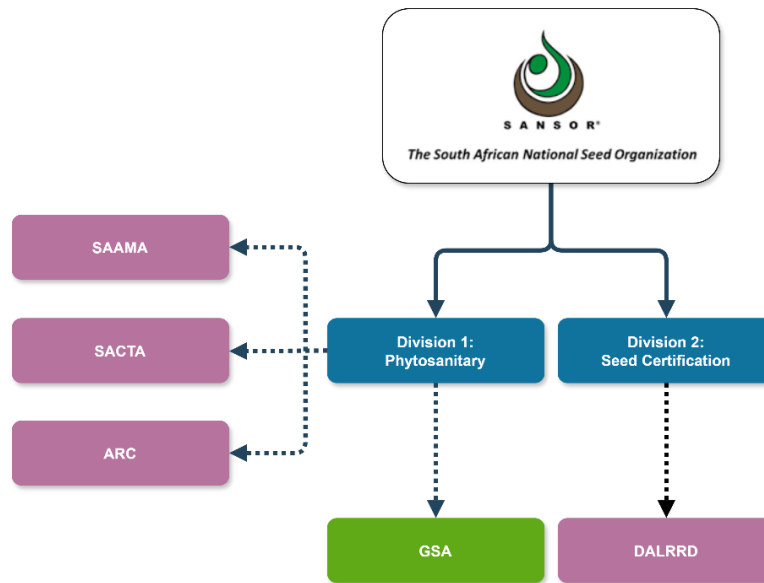


Figure 24. SANSOR systems architecture.

#### 4.1.3.3 South African Agricultural Machinery Association

SAAMA was established in 1985 as the official representative body for the interests of the agricultural machinery industry and its members [89]. Their members include machinery manufacturers, importers and builders. The organisation comprises three divisions [89]:

- **Division 1:** The Campaign and Promotion Committee is responsible for coordinating campaigns to address or mitigate common industry threats or challenges, as well as promoting consumer support for their members and the machinery industry. SAAMA also initiates dialogue and partnerships with the government and other industry supply chain role players.
- **Division 2:** The Technical Committee consists of qualified technicians and provides their members with direction and support regarding practical adherence to current and new machinery legislation.
- **Division 3:** The Sales Committee provides detailed information on sales registration areas as well as accurate information on equipment statistics. In addition, they also protect their members and the farmers from grey imports (imports through unauthorised channels) and unethical traders.

Figure 25 represents the systems architecture of SAAMA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

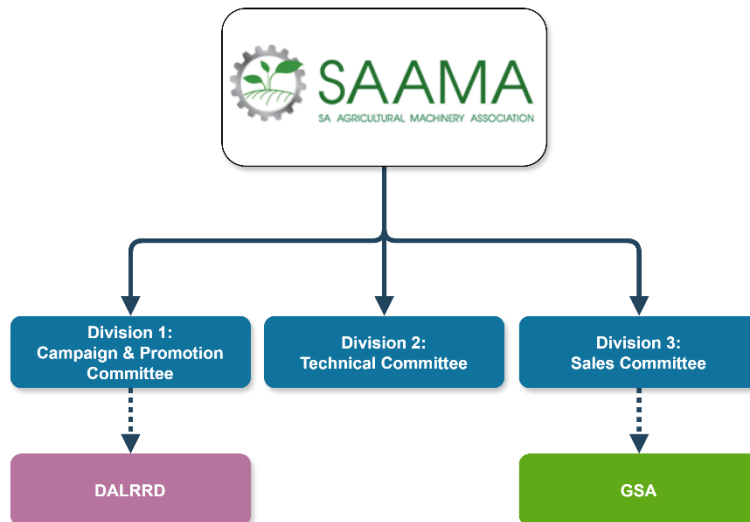


Figure 25. SAAMA systems architecture.

#### 4.1.3.4 National Chamber of Milling

NCM was established in 1936 as a non-profit organisation that acts as the sole representative body for the interests of the wheat and maize milling industry and its members [90]. The organisation's members include millers as well as the suppliers and traders of wheat and maize. The organisation comprises three divisions [90]:

- **Division 1:** The South African Grain Milling Academy (SAGMA) is an institution that provides high-quality training and education with regard to wheat and maize milling.
- **Division 2:** The Technical Committee consists of qualified technicians and deals with all technical milling matters. Research needed to develop new guidelines are derived from SAGL.
- **Division 3:** The Procurement Committee consists of procurement specialists and deals with all purchase, sale and transport matters related to grain procurement. This includes having Safex advisory meetings and setting up procurement agreements with other interest representative bodies, such as GSA, AFMA, Agbiz Grain and SACOTA.

Figure 26 represents the systems architecture of NCM in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

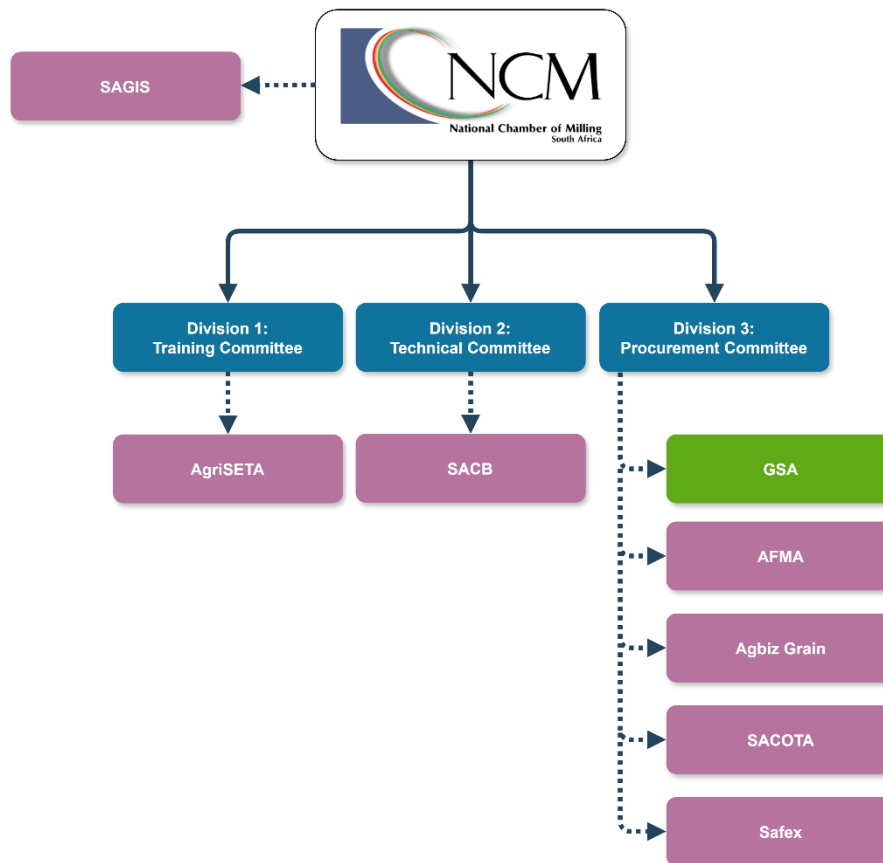


Figure 26. NCM systems architecture.

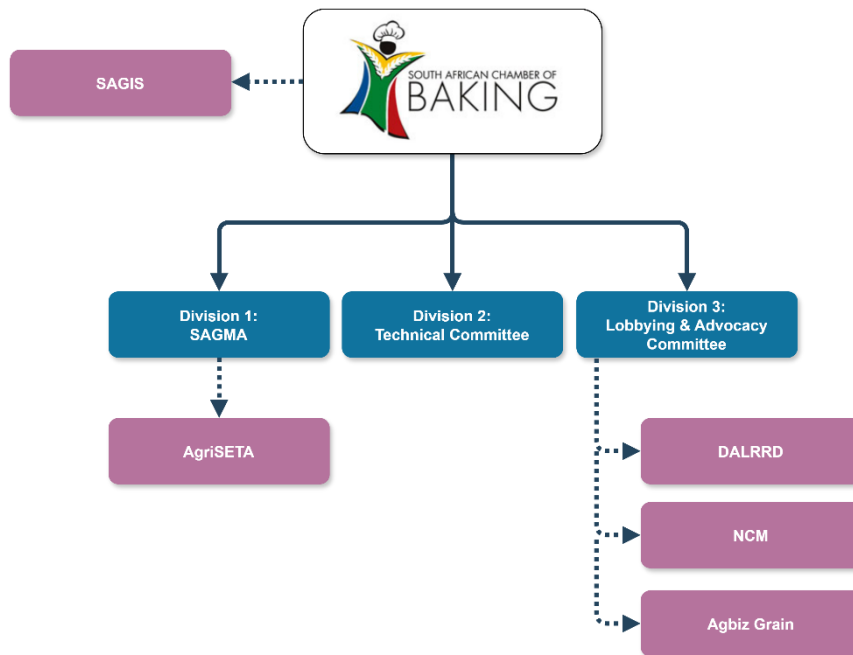
#### 4.1.3.5 South African Chamber of Baking

SACB was established in 1938 as a non-profit organisation and acts as the sole representative body for the interests of the baking industry and its members [91]. The organisation’s members include baking members (wholesale, retail, independent and emerging bakers), supplier members, associate members and honorary life members. SACB comprises three divisions [91]:

- **Division 1:** The Training Committee ensures that the baking industry has an up-to-standard and recognised training system that teaches the proper baking practices. This is done through offering two self-study courses with official examinations, namely the “basics of breadmaking” and the “theory of breadmaking (advanced)”.
- **Division 2:** The Technical Committee consists of qualified technicians and deals with all scientific and technical baking matters, including legislative matters. They provide their members with technical information (regarding food safety and labelling) and market research. Research needed to develop new guidelines is derived from SAGL.

- Division 3:** The Lobbying and Advocacy Committee initiates dialogue with and provides industry output to the government and other industry supply chain role players.

Figure 27 represents the systems architecture of SACB in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.



**Figure 27.** SACB systems architecture.

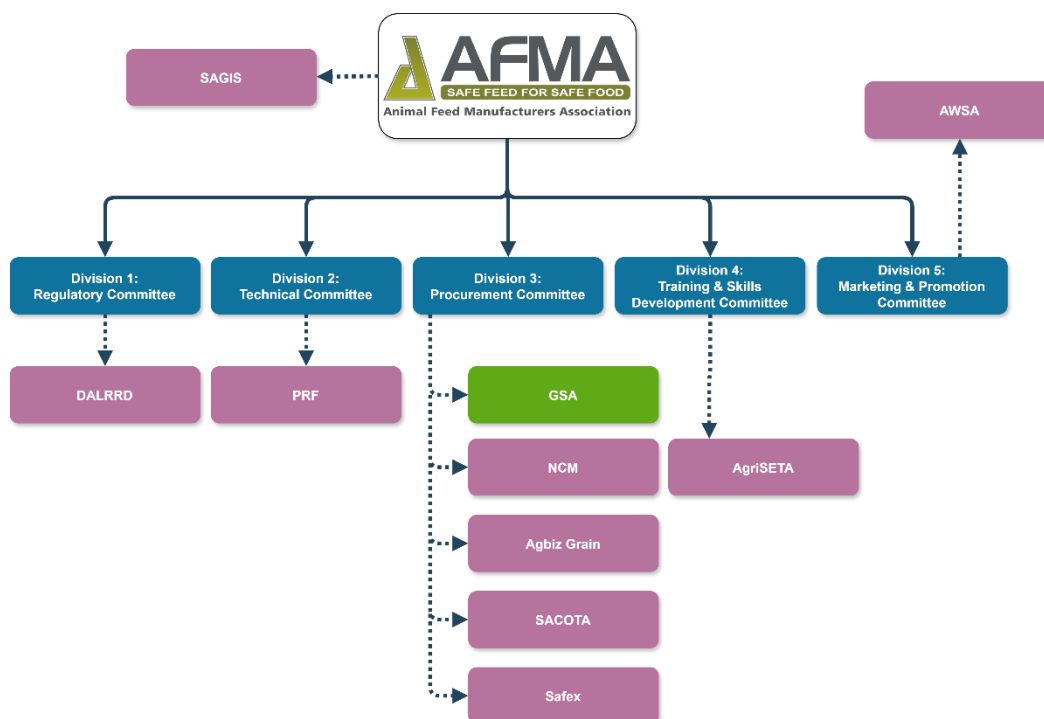
#### 4.1.3.6 Animal Feed Manufacturers Association of South Africa

AFMA was established in 1923 as a non-profit company and acts as the official representative body for the interests of the South African animal feed industry and its members [92]. It was previously known as OVK. AFMA’s members include millers as well as the suppliers and traders of wheat and maize. The organisation comprises five divisions [92]:

- Division 1:** The Regulatory Committee is an information and participation portal for all legislative and regulatory matters. The focus is on aligning the feed industry legislation and AFMA’s vision to the global standard. This committee also liaises with DALRRD on projects. Two advisory committees (ADCOM-FR on feed regulation and ADCOM-COC on the code of conduct) support this committee by means of feedback from industry professionals.

- Division 2:** The Technical Committee consists of qualified technicians and deals with all feed manufacturing, nutrition and feeding matters. It encompasses seven sub-committees, focusing on Salmonella, Dioxins and PCBs, Mycotoxins, Medicated feed, Sulphur, Nutritional Guidelines Revision Project (NGRP) and Laboratory Analyses. Research needed to develop new guidelines is derived from SAGL.
- Division 3:** The Trade Committee consists of procurement specialists and deals with all procurements and supply matters relating to feed ingredients and raw materials used in the feed industry. AFMA also initiates dialogue and negotiations with the government and other industry supply chain role players. This includes having Safex advisory meetings and setting up procurement agreements with other interest representative bodies, such as GSA, NCM, Agbiz Grain and SACOTA.
- Division 4:** The Training and Skills Development Committee focuses on facilitating feed training opportunities by means of vacation work, internships, short courses and outreaches.
- Division 5:** The Marketing and Promotion Committee deals with all advertising and promotional content including managing the social media platforms and the website, publishing the chairman's report and the magazine, as well as organising the events, workshops and symposiums.

Figure 28 represents the systems architecture of AFMA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.



**Figure 28.** AFMA systems architecture.

#### 4.1.3.7 Agricultural Business Chamber

In 2002, the Corporate Chamber of AgriSA decided to function independently and thus founded Agbiz. Agbiz is a voluntary association of agribusinesses that plays an important role in creating an environment where agribusinesses can expand and compete, ultimately ensuring economic growth for the country [147]. The association instituted two semi-autonomous desks or divisions, namely Agbiz Grain (established in 2014, when it replaced the Grain Silo Industry Organisation) and Agbiz Fruit (established in 2019).

Agbiz Grain is a non-profit trade organisation representing the interest of the South African grain storage and handling industry. They have fourteen members, namely AFGRI, AgriMark, BKB Grainco, GWK, NWK, TWK, OVK, VKB, Overberg Agri, Kaap Agri, Senwes, Schoeman Group and Silostrat [93]. Agbiz Grain promotes its members' interests through liaisons with the government and other supply chain role players, as well as representation on the industry trusts' boards. They are also involved with the development of AgriSETA's grain training and education programmes.

Figure 29 represents the systems architecture of Agbiz in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

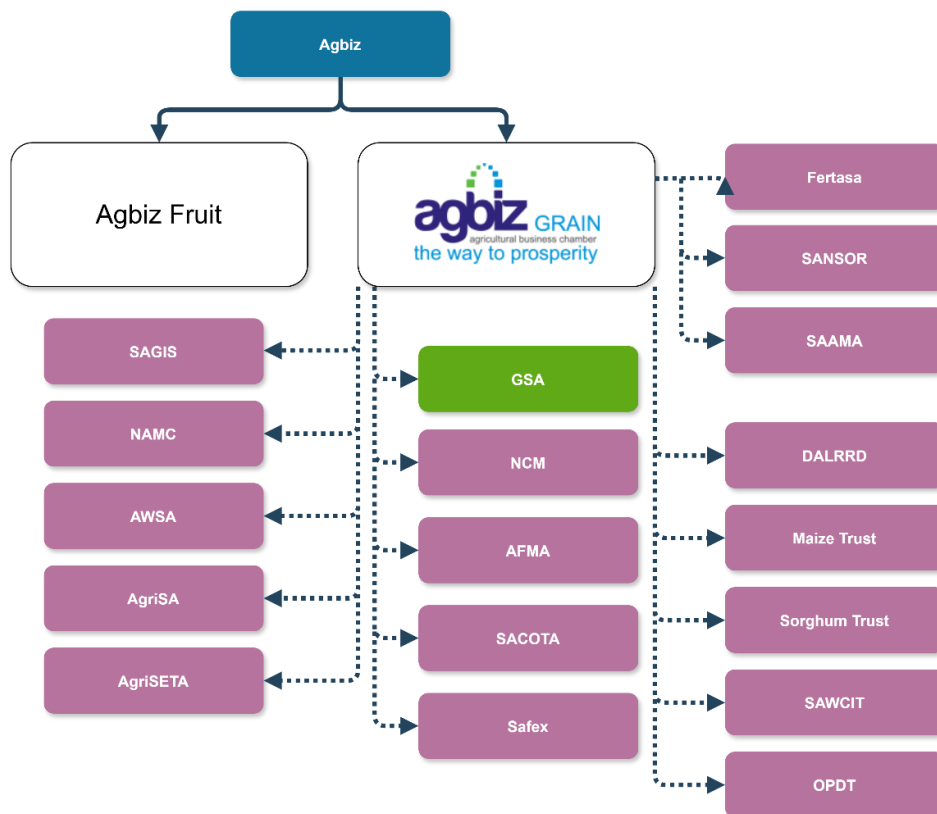


Figure 29. Agbiz Grain systems architecture.

#### 4.1.3.8 South African Cereals and Oilseeds Trade Association

SACOTA, which was established in 1930, is a leading association of trading members functioning within South Africa and the Southern African Development Community (SADC) region [94]. The association aims to increase its significance through expanding its activities and initiating dialogue with the government, other trade organisations and key supply chain role players. SACOTA comprises three divisions [94]:

- **Division 1:** The Grain Trade Division deals with all the grain trade-related activities including purchase, sale and transport, mostly focused on exports. This division provides information on trade contracts, such as the contract for the purchase and sale of grain, pulses and oilseeds and related products (SAGOS) and JSE Agri contract. In addition, it also provides the list of registered exporters and elevators for the different grain commodities. The focus is on ensuring that the grain industry meets the export standards and that exports operate smoothly.
- **Division 2:** The Animal Feed Division handles matters similar to that of Division 1, albeit with a focus on the trade of animal feed. It provides a list of transporters that are compliant with the AFMA transport protocol. The focus is on ensuring that the grain feed industry meets the standards and operates smoothly.
- **Division 3:** The Arbitration Division handles disputes and arbitrations, usually in a combined effort with the representative bodies which are part of the SAGOS contract. These bodies include AFMA, Agbiz Grain, GSA, NCM and the Arbitration Foundation of Southern Africa (AFSA). AFSA manages the technical part of the disputes. In contrast to the other two divisions, this division focuses less on the specific activities and more on the smooth operation of the activities by being proactive and resolving issues promptly.

Figure 30 represents the systems architecture of SACOTA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

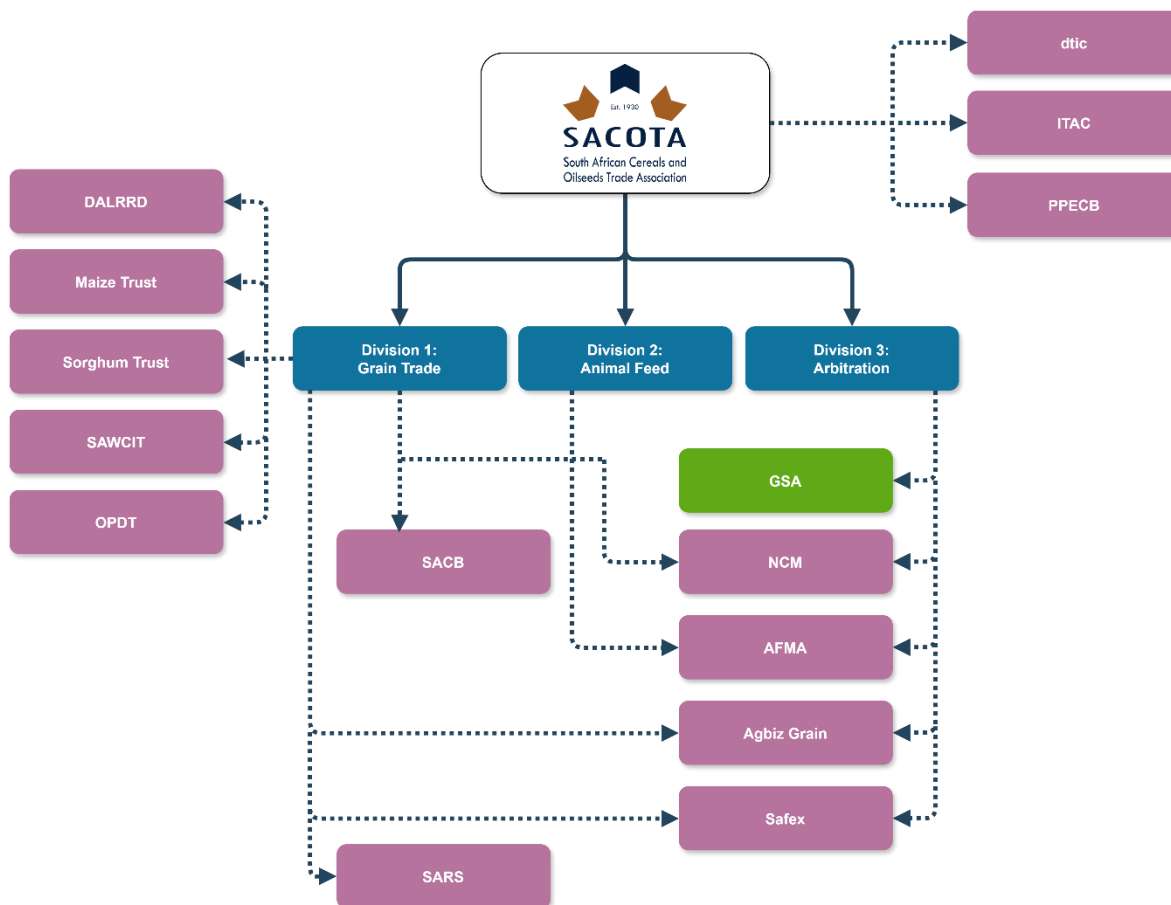


Figure 30. SACOTA systems architecture.

#### 4.1.3.9 Perishable Products Export Control Board

PPECB was established in 1926 as the official certification agency of South Africa [95]. The agency is mandated by DALRRD to conduct end-point inspections on perishable products under the Perishable Products Export Control Act (PPEC Act), No. 9 of 1983 and the Agricultural Product Standards Act (APS Act), No. 119 of 1990 [148]. PPECB operates as an independent and impartial service provider to ensure high-quality certification and to support export competitiveness. This, as well as the recognition by the European importing bodies, ensures smooth exports and reduced risk for producers [95].

PPECB conduct hazard analysis and critical control point inspections for over 200 product types across South Africa, including grain products. The three divisions of PPECB are called Exports (Division 1), Imports (Division 2) and Producers and Packhouses (Division 3) [95]. Therefore, producers, packhouses and grain silos that want to export their grain must register with PPECB under the grain subdivision of Division 3.

Figure 31 represents the systems architecture of PPECB in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

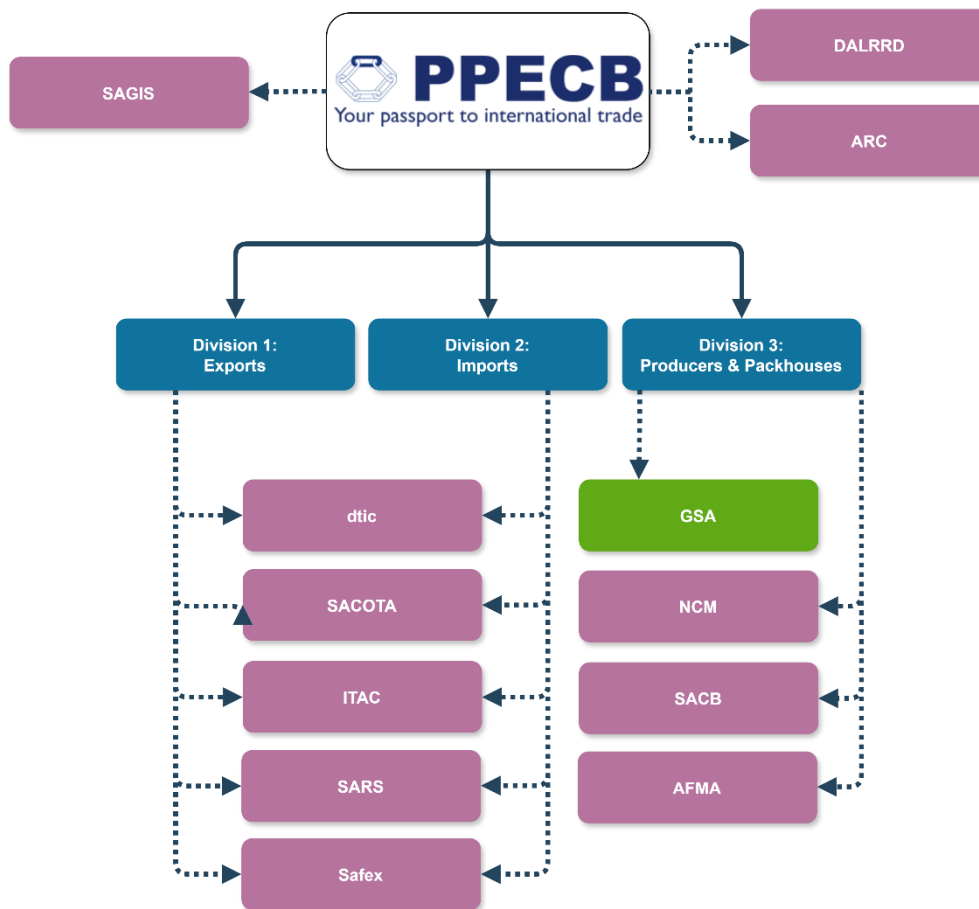


Figure 31. PPECB systems architecture.

#### 4.1.3.10 International Trade Administration Commission of South Africa

ITAC was established in 2003 when it replaced its predecessor, the Board on Trade and Industries (BTI). ITAC is a schedule 3A Public Entity constituted in terms of the International Trade Administration Act, No 71 of 2002 and the Southern African Customs Union (SACU) Agreement [149]. This commission aims to promote economic growth and development to increase South Africa's investability and employment rate [96]. ITAC comprises four divisions, in line with the commission's four core functions [96]:

- **Division 1:** The Trade Remedies Unit applies trade remedy instruments through the investigation of reported dumping and subsidized imports amongst other matters.

- **Division 2:** The Tariff Investigations Unit deals with tariff amendments that include the increase and reduction in ordinary customs duties, as well as the creation of rebate and drawback provisions.
- **Division 3:** The Import Control Unit ensures that health, environmental, security, safety and technical standards are enforced on all imports.
- **Division 4:** The Export Control Unit ensures that health, environmental, security, safety and technical standards are enforced on all exports.

Figure 32 represents the systems architecture of ITAC in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

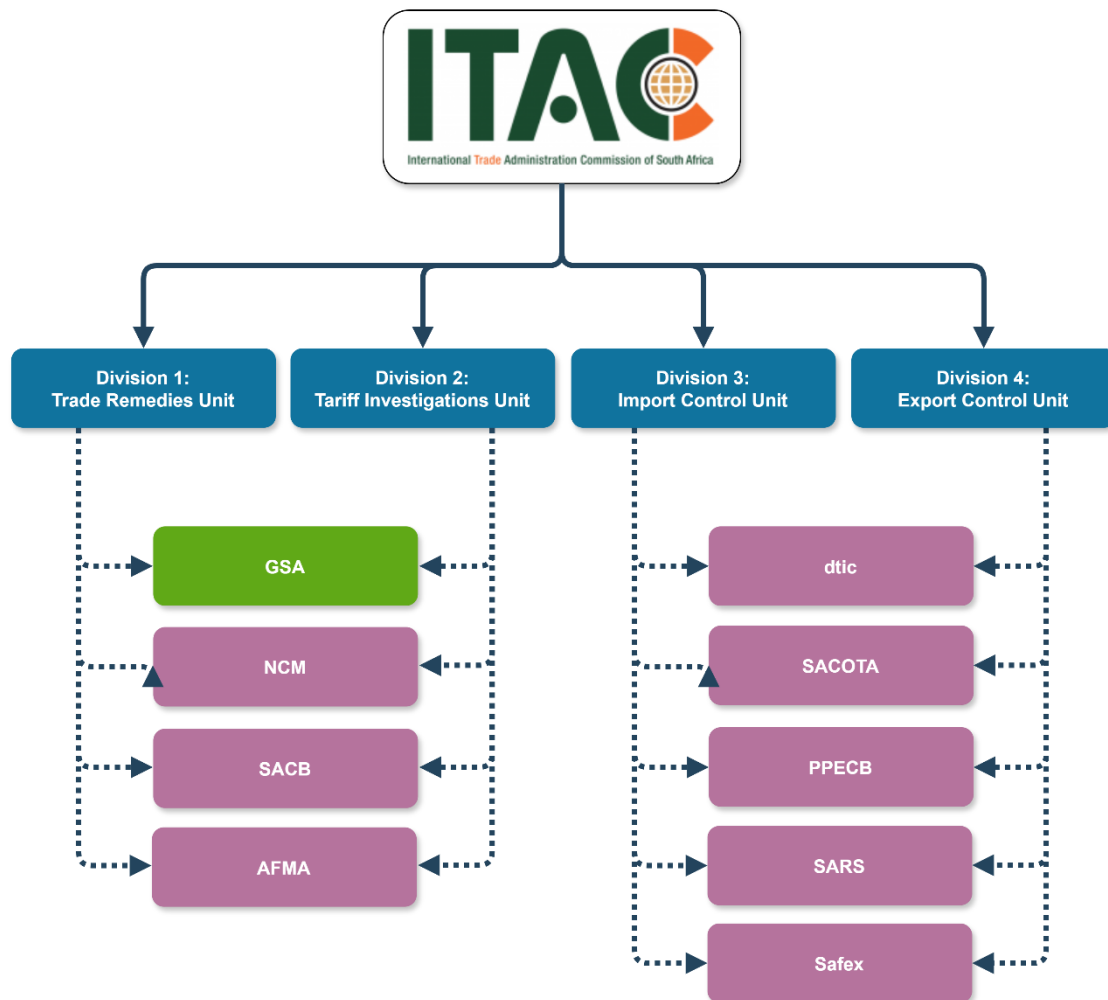


Figure 32. ITAC systems architecture.

#### 4.1.4 Economy or Market Information Entities

The economy and market information entities focus on supplying grain-related economic and market statistics and estimates, as well as information on amended grain regulations and other grain media. Therefore, the system entities discussed in this section are BFAP, SAGIS, NAMC, CEC, AWSA, SARS and JSE Safex.

##### 4.1.4.1 Bureau for Food and Agricultural Policy

BFAP was established in 2003 as a non-profit organisation that provides unbiased, well-tested, research-based market and policy information to stakeholders of the agro-food, fibre and beverage sectors [77]. The agro-seed (grain) industry is one of the stakeholders. The analysis and insights provided by BFAP are used to inform decision-making regarding investments, policies and sustainable agriculture. The organisation comprises eight divisions, in line with BFAP’s multi-disciplinary approach. These divisions are Water, Energy, Food and Land (Division 1), Integrated Systems (Division 2), Data Science (Division 3), Value Chain Analytics (Division 4), Commodity, Markets, Trade and Foresights (Division 5), Consumer and Food Economics (Division 6), Agri-socio Economics (Division 7) and Farm and Production Analytics (Division 8) [77]. All these divisions speak to the grain industry to a certain extent — some more than others. Figure 33 represents the systems architecture of BFAP in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

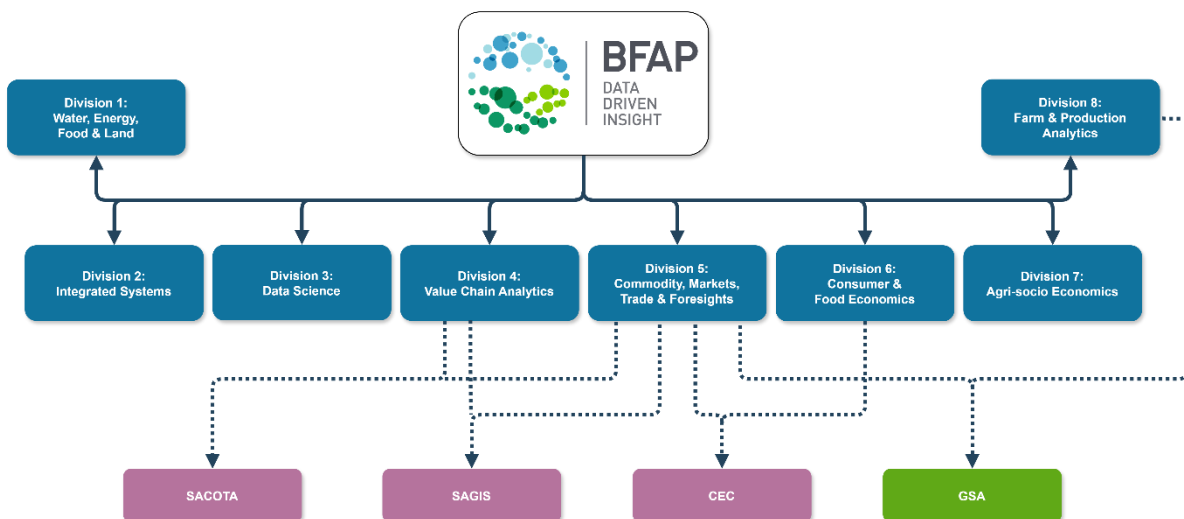


Figure 33. BFAP systems architecture.

#### 4.1.4.2 South African Grain Information Service

SAGIS is a non-profit company that was founded in 1997 after the rise of the free market system in South Africa [97]. During this time, the marketing and control boards, once operated by the individual grain commodity industries, were deregulated according to the Marketing of Agricultural Products Act, No. 47 of 1996 [97]. Therefore, SAGIS was established to gather, process, analyse and distribute reliable market information to the grain industry, as was previously done by these individual industries. Market participants, which include all individual supply chain entity members (input providers, processors, storers, import traders and export traders), are compelled under the above-mentioned act to submit information to SAGIS. The submitted information is processed by the three divisions of the company, namely [97]:

- **Division 1:** The Information Department gathers, analyses and disseminates the submitted information.
- **Division 2:** The Inspection Department verifies the submitted information for accuracy, completeness, consistency and reliability using stocktaking or audits. Internal control measures include cross-referencing submitted information with the information supplied by harbour authorities, dtic and PPECB (which are not statutory compelled to submit information). External control measures include SAGIS inspectors auditing the stock documents and negotiating with the associations that represent the individual members of all the supply chain entities, such as NCM, SACB, AFMA, Agbiz Grain and GSA.
- **Division 3:** The Corporate Department handles SAGIS's personal matters, finances and administration.

To provide reliable data to the grain industry, SAGIS works in close liaison with government entities (such as DALRRD and dtic) and interest representative entities (such as the grain trusts). The market and economic statistics provided include, amongst others, the audited versions of crop estimates (from CEC), supply and demand estimates (from CEC), import and export tariff lines (from SARS) and grain analytics (from BFAP) [97].

Figure 34 represents the systems architecture of SAGIS in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

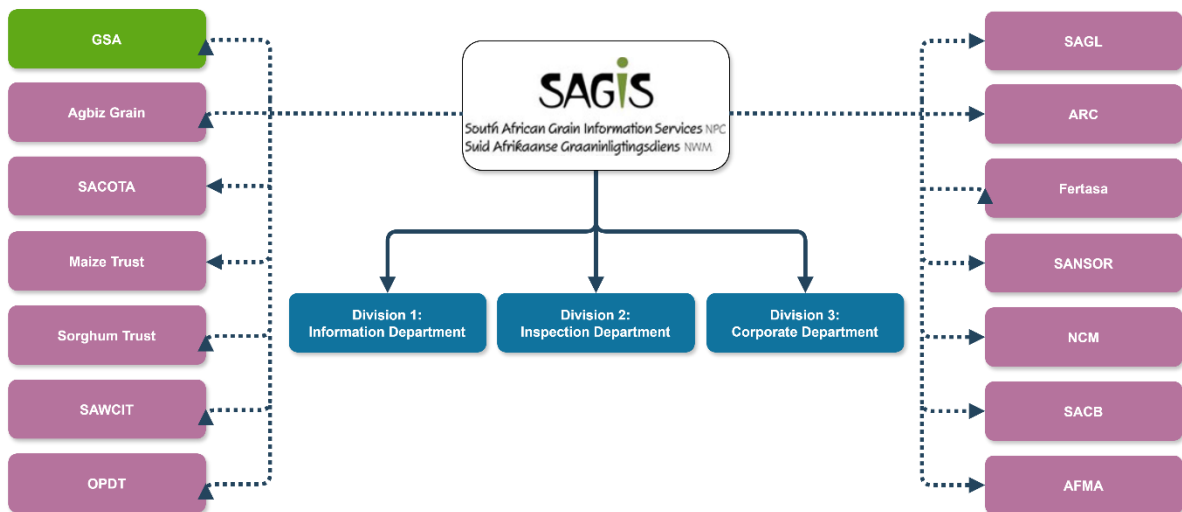


Figure 34. SAGIS systems architecture.

#### 4.1.4.3 National Agricultural Marketing Council

NAMC was established by the Marketing of Agricultural Products Act, No. 47 of 1996 and acts as a statutory body that reports to DALRRD [150]. The council is responsible for supplying advisory services to key stakeholders of the grain industry. It performs its duty using its four divisions, which are [98]:

- **Division 1:** The Agribusiness Development Division (ADD) was established in 2006. The division collaborates with various institutions to provide technical assistance, training programmes and partnerships to smallholder agricultural farmers. It also aims to develop historically disadvantaged enterprises and promote transformation.
- **Division 2:** The Agricultural Trusts Division facilitates communication between the Minister of DALRRD and the twelve agricultural industry trusts, of which four are linked to the grain industry, *i.e.* the Maize Trust, Sorghum Trust, OPDT and SAWCIT. Ministerial trustees serve on the board of trustees of each industry trust, to ensure that the trusts' objectives and activities are aligned with the government's transformation mandate and to report thereon to the Minister.
- **Division 3:** The Statutory Measures Division facilitates the implementation of statutory measures as mandated by the Marketing of Agricultural Products Act.
- **Division 4:** The Markets and Economic Research Centre (MERC) was established in 2007. It is a portal for tracking and sharing recent economic trends, market information and marketing policy research with farmers. It has three business units, namely the agro-food chains unit, the smallholder market access unit and the trade unit.

Figure 36 represents the systems architecture of NAMC in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple. Since CEC is an official committee of NAMC, it is therefore included in the systems architecture of NAMC [99]. Additionally, the grain industry trusts, linked to Division 2 of NAMC, are also included in the systems architecture of NAMC.

#### 4.1.4.4 Crop Estimates (Liaison) Committee

CEC (or CELC) was established in 1998 upon the request of the Minister of DALRRD as an official committee of NAMC, as was previously mentioned [99]. The committee constitutes stakeholders of the grain industry (such as GSA, Agbiz Grain, NCM, AFMA, Safex *etc.*) and is chaired by a council member of NAMC. See Figure 36 for the systems architecture of NAMC, which includes CEC, even though the committee operates autonomously.

#### 4.1.4.5 Agricultural Writers South Africa

AWSA was established in 1977 when seven agricultural journalists founded an agricultural journalist association. It was founded as a non-profit, voluntary, professional association run by journalists for journalists that advocates for the image and standards of journalism in the agricultural sector in South Africa [108]. AWSA has different divisions, focusing on different media outlets, namely magazines, newspapers, radio and television. Its member base consists predominantly of agricultural media centrums. However, Agbiz Grain and GSA also serve as corporate members. Figure 35 represents the systems architecture of AWSA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

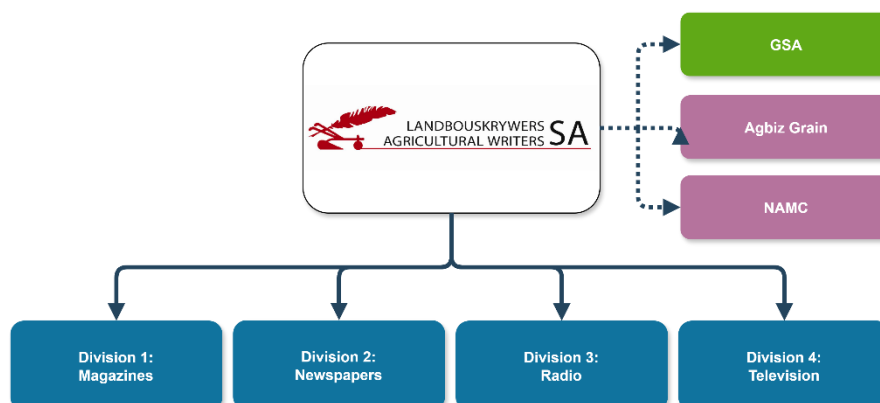


Figure 35. AWSA systems architecture.

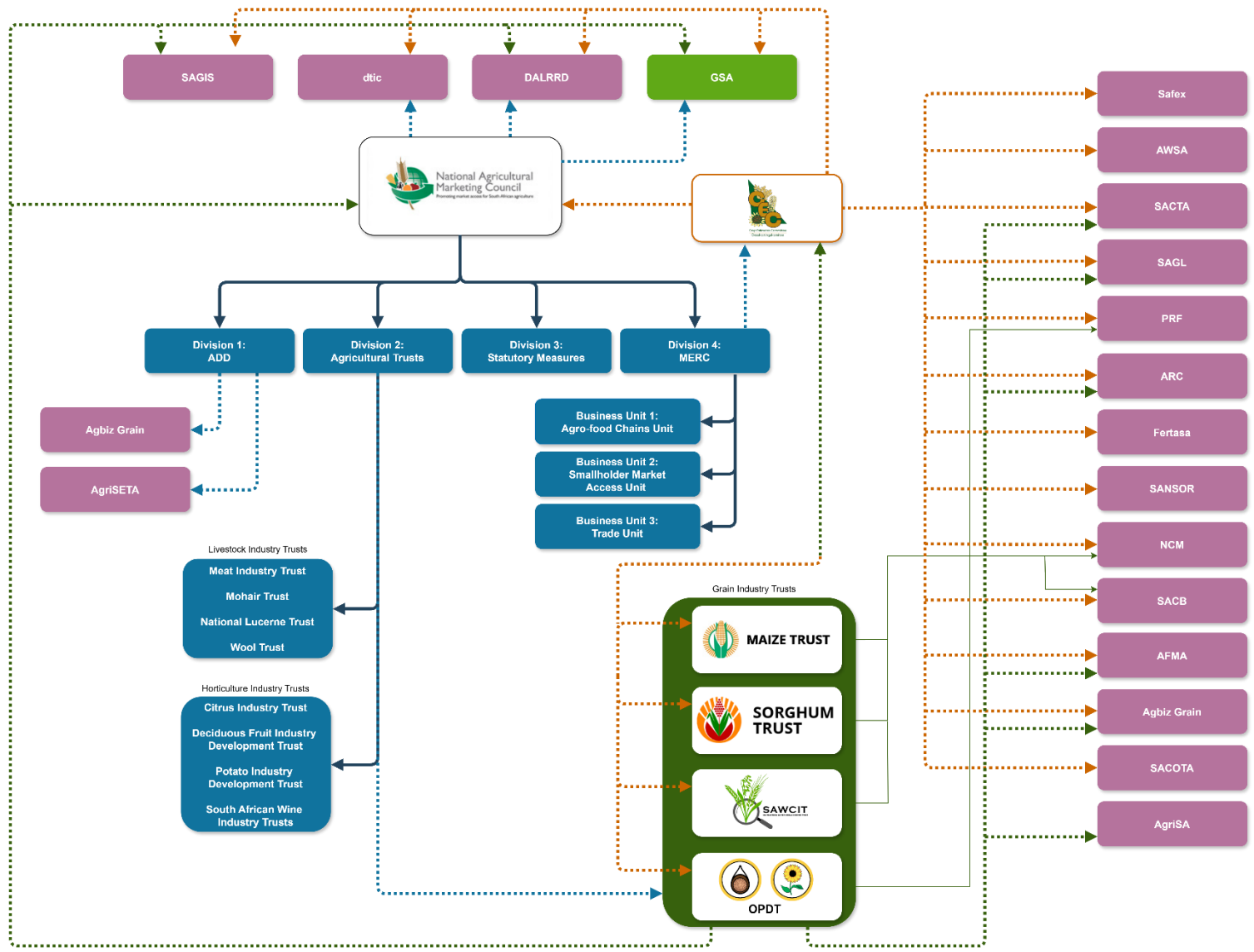


Figure 36. NAMC (including CEC and the trusts) systems architecture.

#### 4.1.4.6 South African Revenue Services

SARS was established by the South African Revenue Service Act, No. 34 of 1997 as an autonomous agency which reports to the National Treasury (NT) [151]. The agency is South Africa's official tax collecting authority, which is responsible for ensuring the collection of all revenues due, the compliance with all tax and customs regulations and the facilitation of legitimate trade. One of the functions of SARS is to provide quality and responsive service, therefore engaging with industry representative bodies in advocacy and lobbying activities. An example is the dispensation that allows a vendor that manages a farming enterprise to acquire certain goods (used in conducting a farming enterprise) at a zero rate or import certain goods (like animal feed, fertiliser and pesticides) exempt from value-added tax (VAT) [114]. SARS forms part of the systems architecture of the NT, as depicted in Figure 40.

#### 4.1.4.7 South African Futures Exchange

Safex is a futures exchange subsidiary of JSE Limited but functions as a self-regulatory authority by the Financial Markets Control Act, No. 55 of 1989 [115]. It comprises two divisions, namely [115]:

- **Division 1:** The Financial Markets Division was established in 1990 for the trading of equity derivatives.
- **Division 2:** The Agricultural Markets Division (AMD) was established in 1995 for the trading of agricultural derivatives. This division provides a platform for transparent price discovery by buyers and sellers, as well as price risk management (as assured through the derivatives clearing structure) for the grains market in Southern Africa.

Figure 37 represents the systems architecture of Safex in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

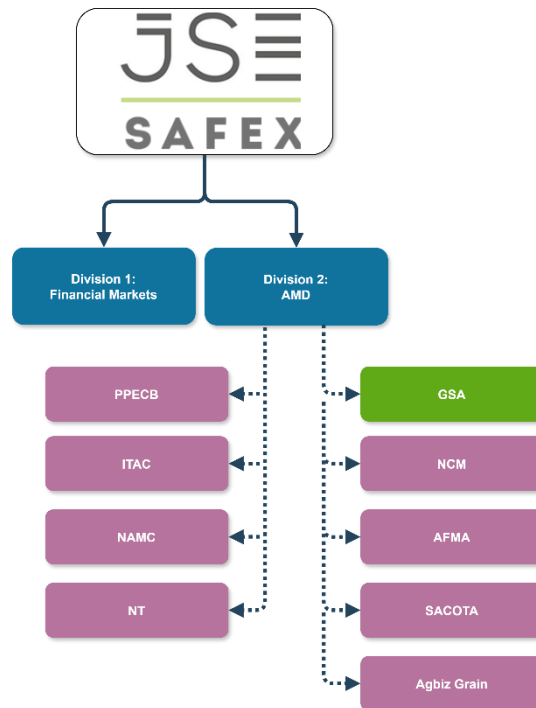


Figure 37. JSE Safex systems architecture.

#### 4.1.5 Government Entities

The cabinet of South Africa is made up of the president, deputy president and 32 ministers [152]. Each of these ministers is appointed as the head of a national department. The three national departments predominantly linked to the grain industry are discussed in this section. These government entities include DALRRD, dtic and the NT.

##### 4.1.5.1 Department of Agriculture, Land Reform and Rural Development

DALRRD is a South African national department and was created in June 2019 by merging the agricultural functions of two former national departments, namely the Department of Rural Development and Land Reform and the Department of Agriculture, Forestry and Fisheries [100]. The department is responsible for ensuring equitable access to land, integrated rural development, sustainable agriculture and food security. DALRRD has nine reporting entities, which include ARC, NAMC and PPECB [100]. Figure 38 represents the systems architecture of DALRRD in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

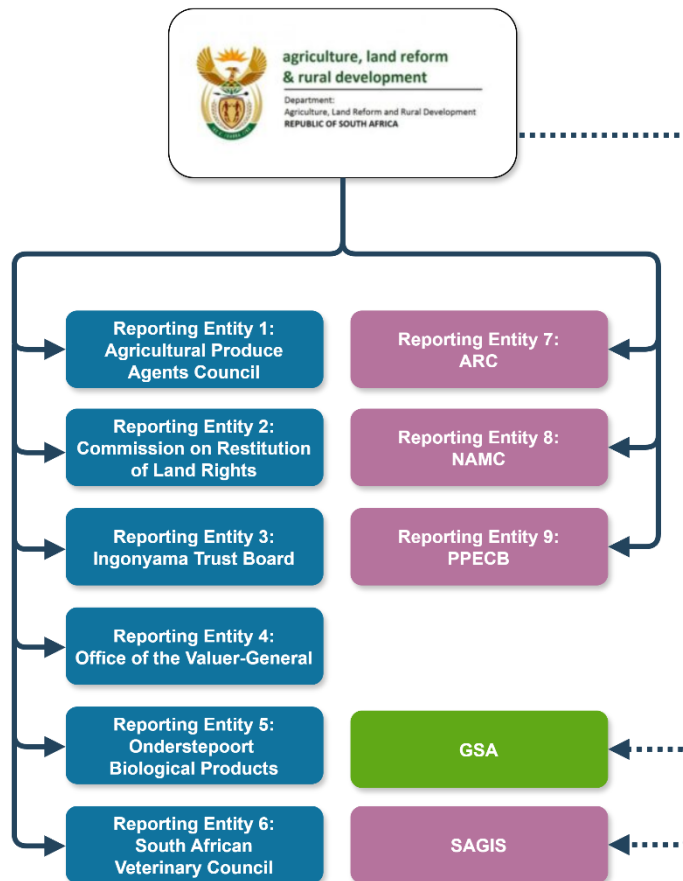


Figure 38. DALRRD systems architecture.

#### 4.1.5.2 Department of Trade, Industry and Competition

dtic is a South African national department and was created in June 2019 by merging the two former national departments, namely the Department of Trade and Industry and the Economic Development Department [101]. The department is responsible for creating and maintaining an environment conducive to investment, trade and enterprise participation and growth, as well as promoting structural transformation to achieve industrial and global economic competitiveness. dtic has nineteen reporting entities, which include ITAC and the Competition Commission which is part of NAMC [101]. Figure 39 represents the systems architecture of dtic in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

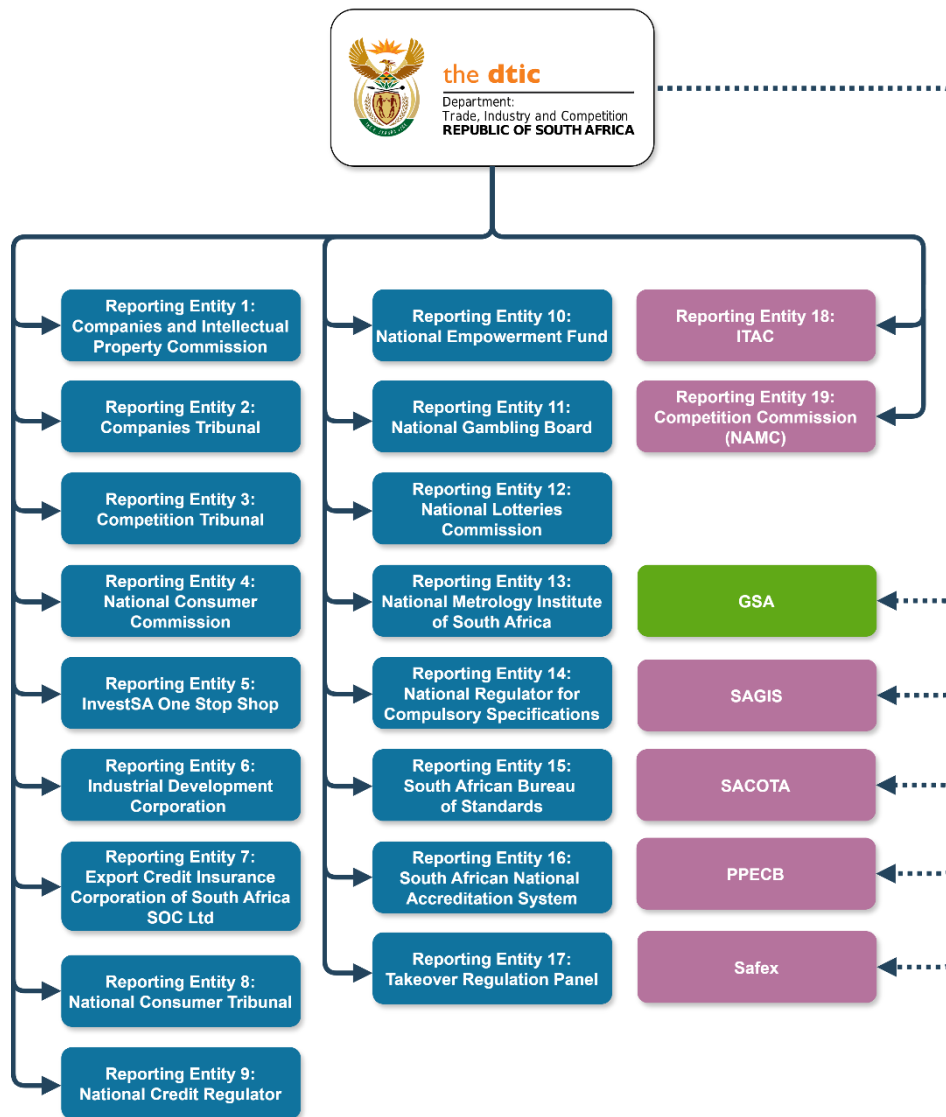


Figure 39. dtic systems architecture.

#### 4.1.5.3 National Treasury

The NT is a South African national department and was founded in 1910 [112]. The department is responsible for the optimal and transparent management of the national government's finances, to reduce poverty and support the country's most marginalised. This is done in accordance with Chapter 13 of the Constitution of the Republic and Chapter 2 of the Public Finance Management Act [112]. The NT has sixteen reporting entities, which include SARS and LandBank [112]. Figure 40 represents the systems architecture of the NT in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

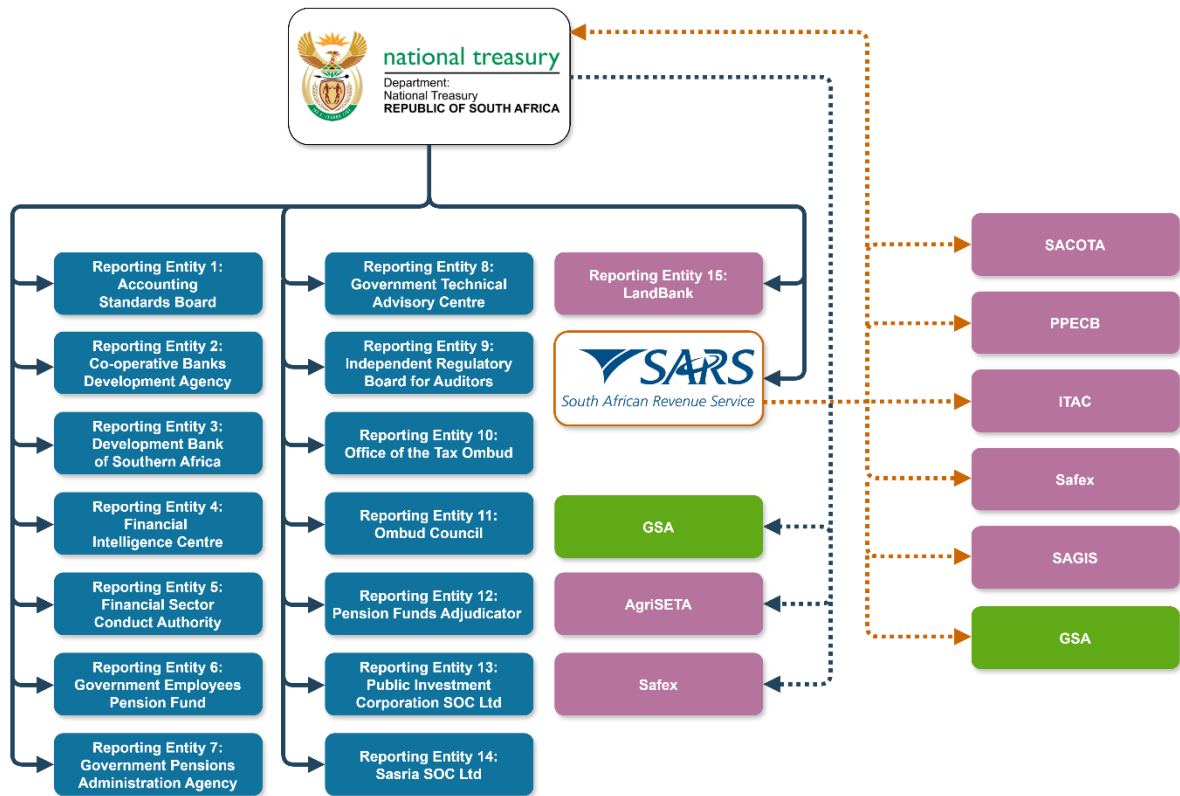


Figure 40. NT systems architecture.

#### 4.1.6 Interest Representative Entities

The interest representative entities focus on representing the interest of the grain producers through the establishment of trusts and unions that advocate for the producers' interests. Therefore, the system entities discussed in this section include agricultural unions (AgriSA, TAU-SA and AFASA) as well as grain industry trusts (Maize Trust, Sorghum Trust, OPDT and SAWCIT).

##### 4.1.6.1 Agriculture Union of South Africa

The South African Agricultural Union (SAAU) was established in 1904. SAAU was a federation of agricultural organisations and unions that were represented in a Provincial Chamber, Commodity Chamber and Corporate (or Agribusiness) Chamber [109]. In 1994, with the increase in the number of provinces under the new government, TAU decided to break away from the SAAU Provincial Chamber, and still exists today, now known as TAU-SA (see section 4.1.6.2). Later, in 1999, SAAU was renamed AgriSA and then in 2002, the Agribusiness Chamber decided to break away from AgriSA and form Agbiz (see section 4.1.3.7). Currently, AgriSA has five divisions [109]:

- **Division 1:** The Provincial Chamber facilitates the communication and co-operation between the provincial affiliates. There are nine provincial affiliates, each comprising numerous farmers' unions as members.
- **Division 2:** The Commodity Chamber assists in uniting the seven largest commodity organisations in South Africa, which can be subdivided into horticulture, animal production and agronomy. Agronomy is the branch of agriculture that deals with crop production, and thus GSA falls under this subdivision of the Commodity Chamber.
- **Division 3:** The Corporate Chamber fosters the synergy of corporates throughout the agricultural value chain. The number of agricultural corporate members is ever-changing and includes, for example, farming equipment manufacturers, law firms, insurance companies, transport providers and retailers. This division links to Agbiz Grain.
- **Division 4:** The Agri Securitas Division aids with rural security. This division links to TAU-SA (Security Division) and AFASA.
- **Division 5:** The Disaster Relief Foundation provides disaster relief to farmers. This division links to TAU-SA (Trauma Fund Division) and AFASA.

Figure 41 represents the systems architecture of AgriSA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

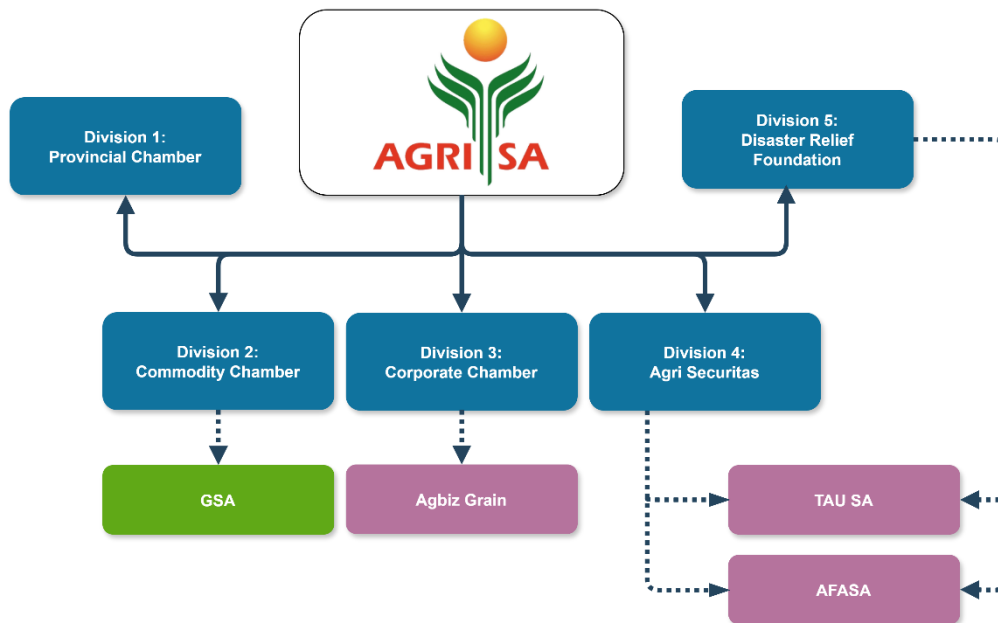


Figure 41. AgriSA systems architecture.

#### 4.1.6.2 Transvaal Agricultural Union South Africa

TAU was initially established in 1897 as a union exclusively for farmers from the ‘Transvaal’ region [102]. In 1994, when it decided to function independently from AgriSA, it was renamed as TAU-SA (or TLU-SA in Afrikaans) and restructured to function as a farmers’ union for predominantly Afrikaans farmers. This union organisation comprises seven divisions, which include the Labour Affairs Committee (Division 1), Property Rights Committee (Division 2), Economic Sustainability Committee (Division 3), Environmental Management Committee (Division 4), Local Government Committee (Division 5), Security Committee (Division 6) and Trauma Fund Committee (Division 7) [102]. Division 3 of TAU-SA links to Division 5 of AFASA in terms of its function. Figure 42 represents the systems architecture of TAU-SA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

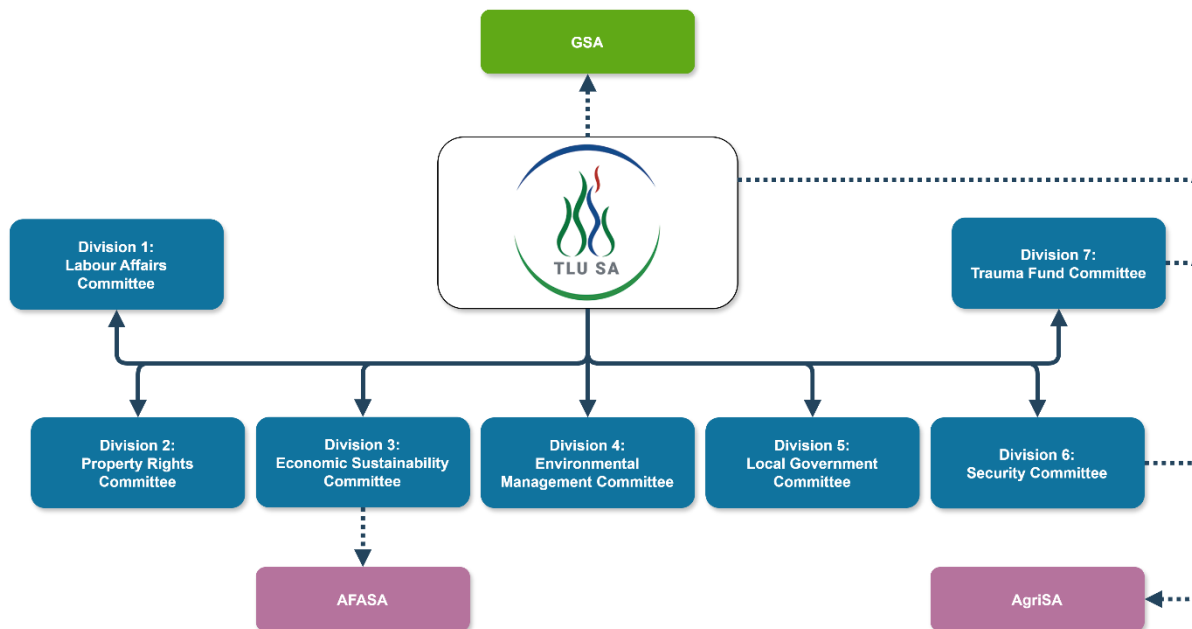


Figure 42. TAU-SA systems architecture.

#### 4.1.6.3 African Farmers Association of South Africa

AFASA was founded in 2011 as a farmers' union predominantly for African farmers [103]. Its founding members were part of the former National African Farmers' Union (NAFU SA) which was established in 1991. This union organisation comprises five divisions, which include the Youth Desk (Division 1), Women Desk (Division 2), Commodity Committee (Division 3), Membership Committee (Division 4) and Economic Sustainability Committee (Division 5) [103]. Figure 43 represents the systems architecture of AFASA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

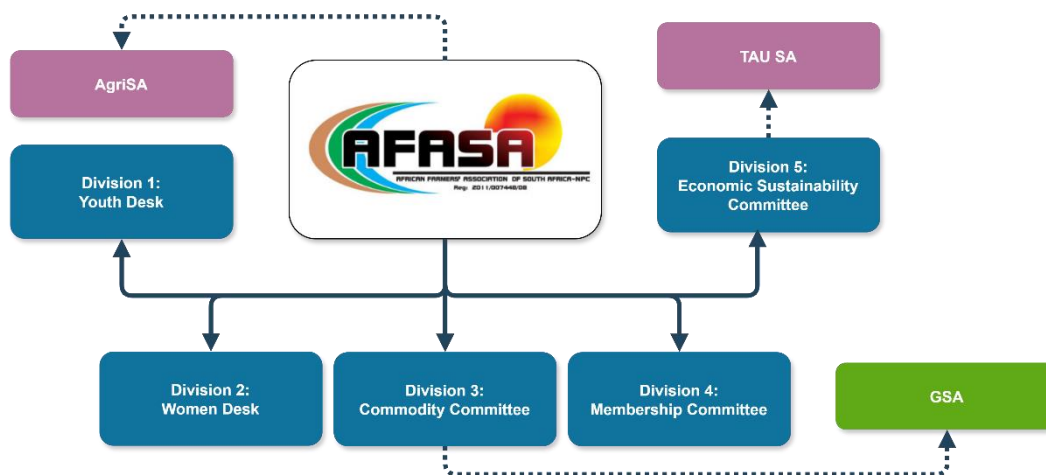


Figure 43. AFASA systems architecture.

#### **4.1.6.4 Maize Trust**

The Maize Trust was established in August 1998. It is a field crop commodity trust that provides funding for the benefit of the maize industry — in particular for maize research and development projects and the dissemination of market information required by the industry [104]. The Maize Trust, like the other grain industry trusts, comprises a board of directors and reports to NAMC. See Figure 36 for the systems architecture of NAMC, which includes the grain industry trusts, even though the trusts operate autonomously.

#### **4.1.6.5 Sorghum Trust**

The Sorghum Trust was established in May 1998. It is a field crop commodity trust that provides funding for the benefit of the sorghum industry — in particular for sorghum research and development projects and the dissemination of market information required by the industry [105]. See Figure 36 for the systems architecture of the Sorghum Trust.

#### **4.1.6.6 South African Winter Cereal Industry Trust**

SAWCIT was established in 2020, replacing the Winter Cereal Trust. Winter cereals include wheat, barley and oats. SAWCIT is a field crop commodity trust that provides funding for the benefit of the winter cereal industry — in particular for winter cereal research and development projects and the dissemination of market information required by the industry [106]. See Figure 36 for the systems architecture of SAWCIT.

#### **4.1.6.7 Oil and Protein Seed Development Trust**

OPDT was established in 1997. Oilseeds include sunflowers, groundnuts, soybeans and canola. OPDT is a field crop commodity trust that provides funding for the benefit of the oilseeds industry — in particular for protein and oilseed research and development projects and the dissemination of market information required by the industry [107]. See Figure 36 for the systems architecture of OPDT.

## 4.1.7 Grain Producer Development Entities

The grain producer development entities focus on the development of South African producers, in this case specifically grain producers. The development comes in the form of providing education (CropLife and AgriSETA) or financial assistance (LandBank), as discussed in this section.

### 4.1.7.1 CropLife South Africa

CropLife is an international non-profit industry association founded in 2001. CropLife South Africa focuses on the educational development of its members (grain producers). The association provides its members with an abundance of resources and agri-intel on crop protection and plant biotechnology solutions, as well as with training through their continuing professional development (CPD) programmes and basic crop protection courses [110]. CropLife has two divisions, namely [110]:

- **Division 1:** The Research Division researches crop protection and plant biotechnology.
- **Division 2:** The Education Division presents CPD programmes and training courses where the research findings are shared.

The aim of this association is to promote sustainable agriculture. Figure 44 represents the systems architecture of CropLife in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

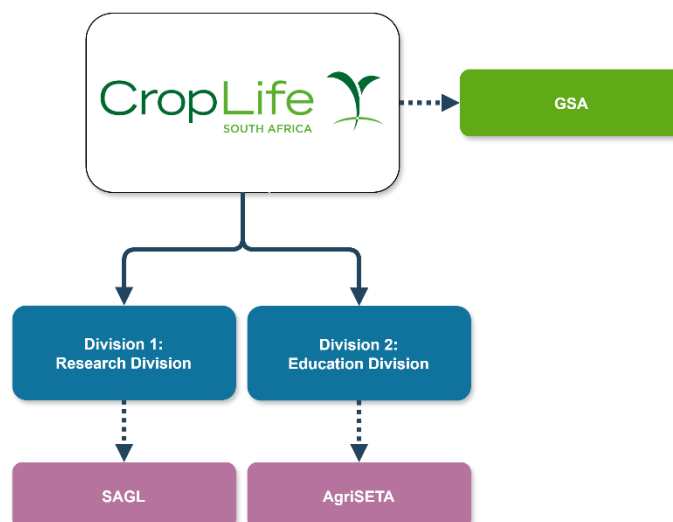


Figure 44. CropLife systems architecture.

#### 4.1.7.2 Agriculture Sector Education and Training Authority

AgriSETA provides quality, accessible education in primary and secondary agriculture to the agricultural workforce, by the Skills Development Act, No. 97 of 1998 [111]. The goal of the education programmes is to develop the skills of the agricultural workforce and to promote opportunities for social, economic and employment growth for farming enterprises. AgriSETA facilitates learning using its four divisions, which are Learning Programmes and Projects (Division 1), Skills Planning and Research (Division 2), Education Training and Quality Assurance (Division 3) and Corporate Services (Division 4) [111]. In addition, AgriSETA collaborates with other industry stakeholders and tertiary education institutions for funding educational programmes, bursaries for tertiary studies, apprenticeships, in-service training and internships. To ensure all agricultural education programmes are up to standard, AgriSETA is also responsible for the accreditation of sector-specific training providers. For example, CropLife’s Basic Crop Protection Course is accredited by AgriSETA. Figure 45 represents the systems architecture of AgriSETA in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

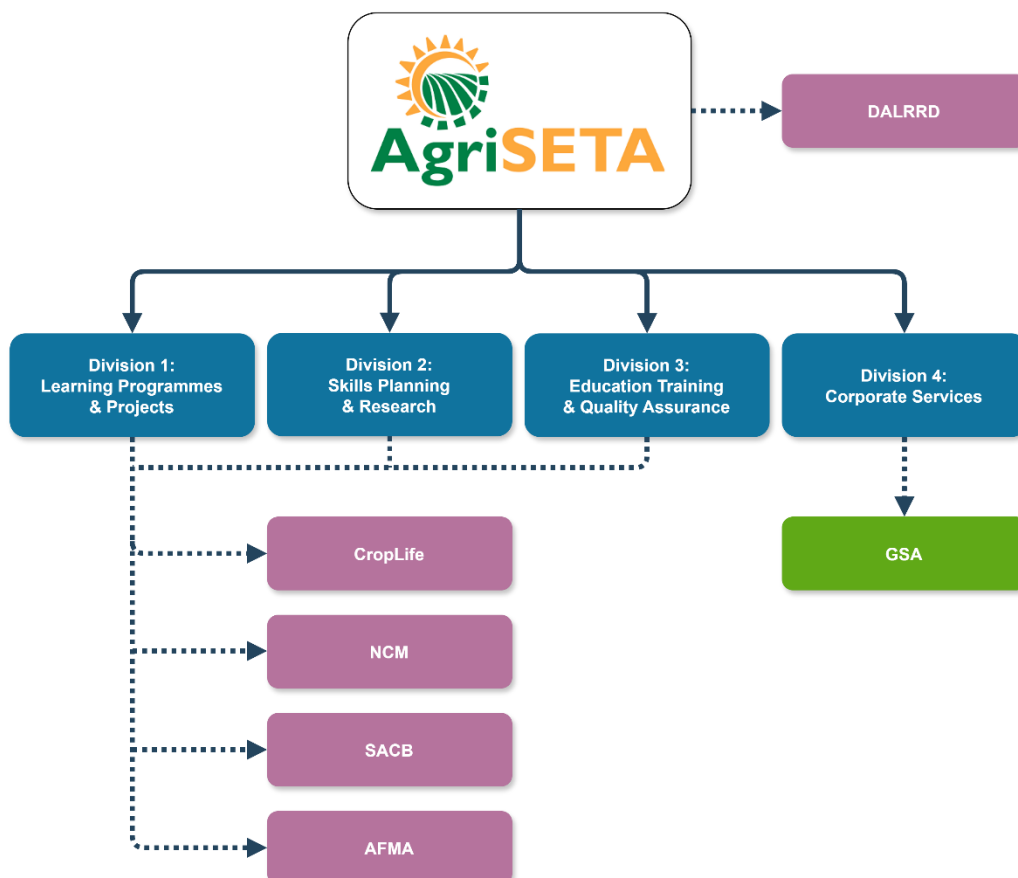


Figure 45. AgriSETA systems architecture.

#### 4.1.7.3 Land and Agricultural Development Bank of South Africa

LandBank was established in 1912 as a specialist agricultural bank that provides commercial and new-entrant farmers and agribusinesses with financial services which enable them to acquire land, equipment, assets and production credit [113]. The Blended Finance Scheme (BFS) is a finance programme that was established through a collaboration between LandBank and DALRRD [153]. The BFS aims to facilitate the participation of marginalised farmers in the agricultural value chain. LandBank has four divisions [113]:

- **Division 1:** The Sector Growth Support Unit focuses on the prioritisation of investment and participation in high-potential regions and crops.
- **Division 2:** The Supply Chain Development Unit focuses on aligning production processing supply and demand.
- **Division 3:** The Production Expansion and Intensification Unit focuses on increasing the economic contribution and productivity of a farming enterprise.
- **Division 4:** The Agricultural Innovation Unit focuses on promoting innovation by investing in young farmers, entrepreneurs and new ventures.

Figure 46 represents the systems architecture of LandBank in blue, as well as its link with the centric system (GSA) in green and the other constituent systems in purple.

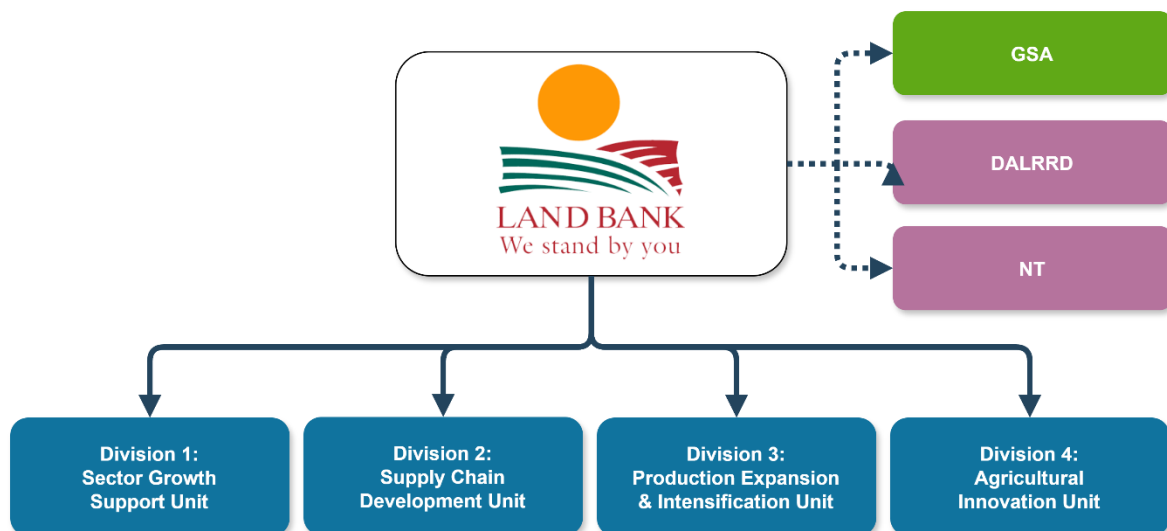


Figure 46. LandBank systems architecture.

## 4.2 Development of the SoS Network Architecture

Figure 47 depicts how the external entities connect to GSA (in red), as well as to each other (in black).

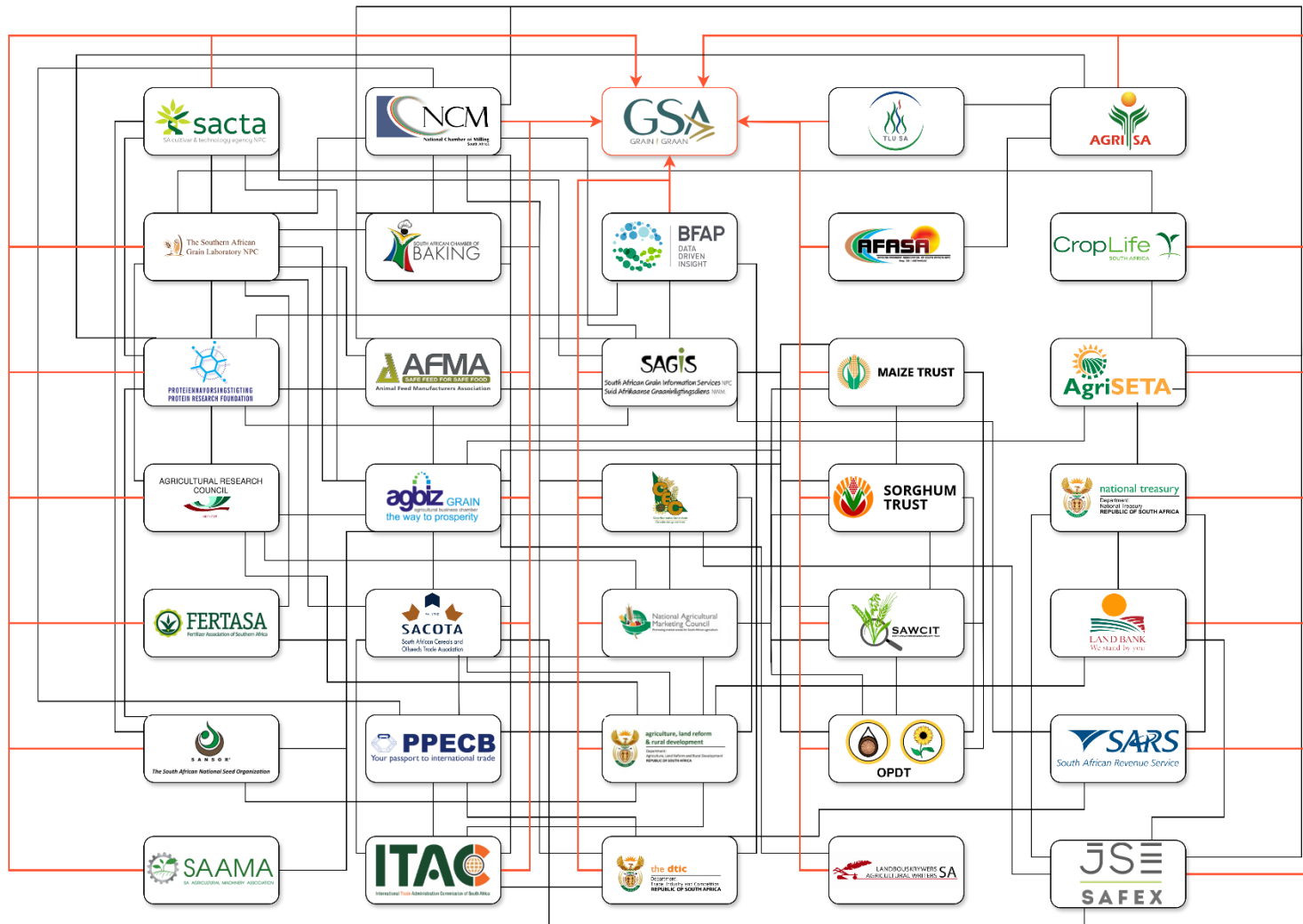
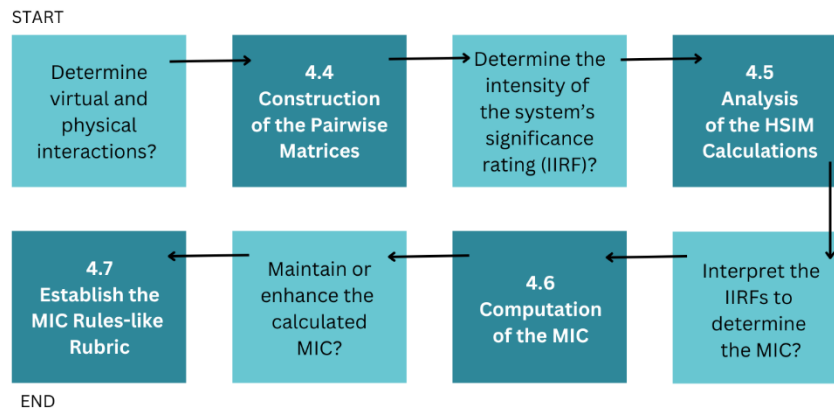


Figure 47. SoS Network for GSA and external entities.

### 4.3 Addressing the Gap Identified in the Literature Review

A comprehensive literature study, presented in Chapter 2, was conducted on the phenomenon of systems engineering. The main lacuna identified from this literature study was in the field of systems engineering management, specifically the quantification of management effort. The next sections of this chapter focus on addressing the pinpointed research gap. This is visually depicted in Figure 48.



**Figure 48.** Steps to address the research lacuna.

### 4.4 Construction of the Metric System Pairwise Matrices

From Figure 47 it is evident that the agro-seed nurturing (grain) industry is a complex system. The constituent system entities interact on a virtual and physical level. To quantify the virtual and physical interactions between the systems (GSA and the external entities), the HSIM method was applied. In other words, the HSIM method was applied to derive quantitative data from the qualitative data presented. Virtual interactions include the propagation of information and the criticality of the propagation of information. Alternatively, physical interactions include the effort required to manage the hardware, software and people of constituent systems. For each interaction mentioned, a contextual question (CQ) was developed from which the inter-systems pairwise matrix was determined. This was done by allocating either the number 0 or 1 to the interaction between system  $i$  and system  $j$ , as described in section 3.4.





Both CQ1 and CQ2 speak to the virtual interactions between the constituent systems. The third CQ is: “Does system  $i$  have in its custody, more hardware to manage in terms of their numbers, complexity and critical nature in comparison to system  $j$ ?”. To answer this question, **the hardware matrix** as depicted in **Matrix H**, was drawn as shown in Figure 51. The allocation of the numbers 0 and 1, was done through investigating the number and nature of the hardware of the constituent systems, based on the knowledge supplied by GSA and the relevant constituent systems. For example,  $S_{ij} \neq S_{ji}$  where  $S_{12} = 0$  and  $S_{21} = 1$ , because S1, SACTA, has in its custody hardware of a lesser number and level of complexity and criticality than S2, SAGL.

$i \backslash j$	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32	S33	S34	S35		
S1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	7
S2	1	0	1	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	0	1	0	0	0	0	0	20
S3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	5
S4	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	28
S5	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	17
S6	1	1	1	1	1	0	1	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	17
S7	1	0	1	1	1	1	0	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	16
S8	1	0	1	0	1	1	1	0	1	1	1	0	0	0	1	0	1	0	1	0	1	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	16
S9	1	0	1	0	1	1	1	1	0	1	1	0	0	0	1	0	1	0	1	0	1	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	16
S10	1	0	1	0	1	1	1	1	1	0	1	0	0	0	1	0	1	0	1	0	1	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	16
S11	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	0	1	0	0	24
S12	1	0	1	0	1	1	1	1	1	1	1	0	0	0	1	0	1	1	1	1	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	19
S13	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	1	0	0	25
S14	1	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	0	27
S15	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	0	0	23
S16	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	0	1	0	1	0	1	0	0	24
S17	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0	0	0	0	8
S18	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	27
S19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	4
S20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34
S21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34
S22	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	0	1	1	0	1	0	0	27
S23	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1	0	1	1	0	1	0	0	27
S24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	4
S25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	4
S26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	4
S27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	4
S28	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	0	0	1	1	1	1	1	1	1	0	0	1	1	0	0	0	0	24
S29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	0	1	0	0	29
S30	1	0	1	0	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	1	0	0	13	
S31	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	0	0	29	
S32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	34
S33	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	29
S34	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	0	30
S35	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	0	31

Figure 51. Pairwise Matrix H (focused on hardware management).

The fourth CQ is: “Does system  $i$  have in its custody, more software to manage in terms of their numbers, complexity and critical nature in comparison to system  $j$ ?”. To answer this question, **the software matrix** as depicted in **Matrix S**, was drawn as shown in Figure 52. The allocation of the numbers 0 and 1, was done through investigating the number and nature of the software of the constituent systems, based on the knowledge supplied by GSA and the relevant constituent systems. For example,  $S_{ij} = S_{ji} = 1$  where  $S_{12} = S_{21}$ , because S1 and S2, SACTA and SAGL, respectively, have in their custody software of the same number and level of complexity and criticality.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32	S33	S34	S35			
S1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34	
S2	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34
S3	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34
S4	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34
S5	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29
S6	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29
S7	0	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29
S8	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
S9	0	0	0	0	0	0	0	1	0	1	1	0	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
S10	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
S11	0	0	0	0	0	0	0	1	1	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
S12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
S13	0	0	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29
S14	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
S15	0	0	0	0	0	0	0	1	1	1	1	0	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
S16	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29
S17	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29
S18	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
S19	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
S20	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
S21	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
S22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	6
S23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	6
S24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	6
S25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	6
S26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	6
S27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	6
S28	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	14
S29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6
S30	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29	
S31	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
S32	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
S33	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
S34	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	29
S35	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34

Figure 52. Pairwise Matrix S (focused on software management).

The fifth CQ is: “Does system  $i$  have more human resources in its custody to manage in comparison with system  $j$ ?”. To answer this question, **the people matrix** as depicted in **Matrix P**, was drawn as shown in Figure 53. The allocation of the numbers 0 and 1, was done through investigating the number of people (human resources) of the constituent systems, based on the knowledge supplied by GSA and the respective constituent systems. For example,  $S_{ij} \neq S_{ji}$  where  $S_{12} = 0$  and  $S_{21} = 1$ , because S1, SACTA, has fewer human resources than S2, SAGL.

CQ3, CQ4 and CQ5 speak to the physical interactions between the constituent systems.

i \ j	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32	S33	S34	S35			
S1	0	0	1	0	0	1	0	0	1	0	1	1	1	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	0	0	0	1	0	0	0	15		
S2	1	0	1	0	0	1	1	1	1	0	1	1	1	0	0	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	0	22	
S3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	3	
S4	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	29	
S5	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	27	
S6	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	1	0	0	0	13	
S7	1	0	1	0	0	1	0	0	1	0	1	1	1	0	0	1	0	0	1	1	1	0	0	1	1	1	1	1	1	0	1	0	1	0	0	0	18	
S8	1	1	1	0	0	1	1	0	1	0	1	1	1	0	0	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0	1	0	0	22	
S9	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	8	
S10	1	1	1	0	0	1	1	1	1	0	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	0	0	25
S11	1	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	1	0	0	0	15	
S12	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	
S13	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	
S14	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	31	
S15	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	31	
S16	1	0	1	0	0	1	1	0	1	0	1	1	1	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	
S17	1	0	1	0	0	1	1	0	1	0	1	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	
S18	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	26	
S19	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	
S20	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	
S21	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	
S22	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	
S23	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	25	
S24	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	
S25	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	
S26	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	
S27	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	
S28	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	
S29	1	0	1	0	0	1	1	0	1	0	1	1	1	0	0	1	0	0	1	1	1	0	0	1	1	1	1	1	1	1	0	1	0	1	0	0	19	
S30	1	0	1	0	0	1	0	0	1	0	1	1	1	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	16	
S31	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	29	
S32	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	
S33	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	33	
S34	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	34
S35	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	33

Figure 53. Pairwise Matrix P (focused on human resource management).

## 4.5 Analysis of the HSIM Calculations Per Identified Matrix

From each matrix, the intensity of system  $i$ 's significance rating, also known as the intensity of importance rating for factor  $i$  ( $IIRF_i$ ), was calculated using the following formula:

$$IIRF_i = \left( \frac{N_{SF_i}}{T_{NF}} \cdot M_{SR} \right) + \left( \frac{B}{T_{NF}} \right) (M_{SR} - C)$$

$$\text{where } C = \frac{M_{PSF} \cdot M_{SR}}{T_{NF}} \quad \text{and} \quad B = N_{SF_i} + 1$$

Table 5 shows the calculated  $IIRF_i$  for Matrix I, Table 6 for Matrix C, Table 7 for Matrix H, Table 8 for Matrix S and Table 9 for Matrix P. In each table, the columns mean the following:

- The **first column** represents the constituent system's number, from S1 to S35.
- The **second column** represents the number of subordinate systems ( $N_{SF_i}$  in the formula above) of an individual constituent system.
- The **third column** represents the total number of systems ( $T_{NF}$  in the formula above), which is 35 for all the individual constituent systems.
- The **fourth column** represents the maximum possible scale rating ( $M_{SR}$  in the formula above), where 9 was assigned for all the individual constituent systems.
- The **fifth column** represents the maximum number of subordinate systems that can be considered ( $M_{PSF}$  in the formula above), which is 34 for all the individual constituent systems. This is because the maximum number of subordinate systems that can be considered is always the total number of systems minus 1.
- The **sixth column** represents  $C$  in the formula above.
- The **seventh column** represents  $B$  in the formula above.

In other words,

$$C = \frac{\text{column 5 value} \times \text{column 4 value}}{\text{column 3 value}} \quad \text{and} \quad B = \text{column 2 value} + 1 \quad \text{and}$$

$$IIRF_i = \left( \frac{\text{column 2 value}}{\text{column 3 value}} \times \text{column 4 value} \right) + \frac{\text{column 7 value}}{\text{column 3 value}} \times (\text{column 4 value} - \text{column 6 value})$$

Thus, row S1 in the information propagation matrix (Matrix I) is used as an example of how the  $IIRF_i$  is calculated, as indicated in red in Table 5:

$$IIRF_1 = \left( \frac{N_{SF1}}{T_{NF}} \cdot M_{SR} \right) + \left( \frac{B}{T_{NF}} \right) (M_{SR} - C) = \left( \frac{8}{35} \cdot 9 \right) + \left( \frac{9}{35} \right) (9 - 8,743) = \mathbf{2,123265}$$

$$\text{where } C = \frac{M_{PSF} \cdot M_{SR}}{T_{NF}} = \frac{34 \times 9}{35} = 8,743 \quad \text{and} \quad B = N_{SF_i} + 1 = 8 + 1 = 9$$

**Table 5.** Intensity of system *i*'s significance rating (*IIRFi*) for Matrix I.

System no.	No. of subordinate systems	Total no. of systems	Max. scale rating	Max. no. of subordinate systems	C	B	<b>IIRF(i) for Matrix I</b>
S1	8	35	9	34	8,743	9	<b>2,123265</b>
S2	11	35	9	34	8,743	12	2,916735
S3	7	35	9	34	8,743	8	1,858776
S4	12	35	9	34	8,743	13	3,181224
S5	3	35	9	34	8,743	4	0,800816
S6	5	35	9	34	8,743	6	1,329796
S7	2	35	9	34	8,743	3	0,536327
S8	8	35	9	34	8,743	9	2,123265
S9	5	35	9	34	8,743	6	1,329796
S10	10	35	9	34	8,743	11	2,652245
S11	18	35	9	34	8,743	19	4,768163
S12	15	35	9	34	8,743	16	3,974694
S13	12	35	9	34	8,743	13	3,181224
S14	9	35	9	34	8,743	10	2,387755
S15	6	35	9	34	8,743	7	1,594286
S16	4	35	9	34	8,743	5	1,065306
S17	14	35	9	34	8,743	15	3,710204
S18	10	35	9	34	8,743	11	2,652245
S19	22	35	9	34	8,743	23	5,826122
S20	5	35	9	34	8,743	6	1,329796
S21	7	35	9	34	8,743	8	1,858776
S22	3	35	9	34	8,743	4	0,800816
S23	3	35	9	34	8,743	4	0,800816
S24	12	35	9	34	8,743	13	3,181224
S25	12	35	9	34	8,743	13	3,181224
S26	12	35	9	34	8,743	13	3,181224
S27	11	35	9	34	8,743	12	2,916735
S28	3	35	9	34	8,743	4	0,800816
S29	4	35	9	34	8,743	5	1,065306
S30	3	35	9	34	8,743	4	0,800816
S31	6	35	9	34	8,743	7	1,594286
S32	5	35	9	34	8,743	6	1,329796
S33	3	35	9	34	8,743	4	0,800816
S34	7	35	9	34	8,743	8	1,858776
S35	9	35	9	34	8,743	10	2,387755

**Table 6.** Intensity of system *i*'s significance rating (*IIRFi*) for Matrix C.

System no.	No. of subordinate systems	Total no. of systems	Max. scale rating	Max. no. of subordinate systems	C	B	<b>IIRF(i) for Matrix C</b>
S1	6	35	9	34	8,743	7	1,594286
S2	11	35	9	34	8,743	12	2,916735
S3	7	35	9	34	8,743	8	1,858776
S4	8	35	9	34	8,743	9	2,123265
S5	3	35	9	34	8,743	4	0,800816
S6	5	35	9	34	8,743	6	1,329796
S7	2	35	9	34	8,743	3	0,536327
S8	7	35	9	34	8,743	8	1,858776
S9	4	35	9	34	8,743	5	1,065306
S10	8	35	9	34	8,743	9	2,123265
S11	11	35	9	34	8,743	12	2,916735
S12	14	35	9	34	8,743	15	3,710204
S13	12	35	9	34	8,743	13	3,181224
S14	9	35	9	34	8,743	10	2,387755
S15	2	35	9	34	8,743	3	0,536327
S16	4	35	9	34	8,743	5	1,065306
S17	11	35	9	34	8,743	12	2,916735
S18	10	35	9	34	8,743	11	2,652245
S19	22	35	9	34	8,743	23	5,826122
S20	1	35	9	34	8,743	2	0,271837
S21	3	35	9	34	8,743	4	0,800816
S22	3	35	9	34	8,743	4	0,800816
S23	3	35	9	34	8,743	4	0,800816
S24	10	35	9	34	8,743	11	2,652245
S25	10	35	9	34	8,743	11	2,652245
S26	10	35	9	34	8,743	11	2,652245
S27	9	35	9	34	8,743	10	2,387755
S28	1	35	9	34	8,743	2	0,271837
S29	2	35	9	34	8,743	3	0,536327
S30	1	35	9	34	8,743	2	0,271837
S31	6	35	9	34	8,743	7	1,594286
S32	5	35	9	34	8,743	6	1,329796
S33	2	35	9	34	8,743	3	0,536327
S34	6	35	9	34	8,743	7	1,594286
S35	8	35	9	34	8,743	9	2,123265

**Table 7.** Intensity of system *i*'s significance rating (*IIRFi*) for Matrix H.

System no.	No. of subordinate systems	Total no. of systems	Max. scale rating	Max. no. of subordinate systems	C	B	<b>IIRF(i) for Matrix H</b>
S1	7	35	9	34	8,743	8	1,858776
S2	20	35	9	34	8,743	21	5,297143
S3	5	35	9	34	8,743	6	1,329796
S4	28	35	9	34	8,743	29	7,413061
S5	17	35	9	34	8,743	18	4,503673
S6	17	35	9	34	8,743	18	4,503673
S7	16	35	9	34	8,743	17	4,239184
S8	16	35	9	34	8,743	17	4,239184
S9	16	35	9	34	8,743	17	4,239184
S10	16	35	9	34	8,743	17	4,239184
S11	24	35	9	34	8,743	25	6,355102
S12	19	35	9	34	8,743	20	5,032653
S13	25	35	9	34	8,743	26	6,619592
S14	27	35	9	34	8,743	28	7,148571
S15	23	35	9	34	8,743	24	6,090612
S16	24	35	9	34	8,743	25	6,355102
S17	8	35	9	34	8,743	9	2,123265
S18	27	35	9	34	8,743	28	7,148571
S19	4	35	9	34	8,743	5	1,065306
S20	34	35	9	34	8,743	35	9,000000
S21	34	35	9	34	8,743	35	9,000000
S22	27	35	9	34	8,743	28	7,148571
S23	27	35	9	34	8,743	28	7,148571
S24	4	35	9	34	8,743	5	1,065306
S25	4	35	9	34	8,743	5	1,065306
S26	4	35	9	34	8,743	5	1,065306
S27	4	35	9	34	8,743	5	1,065306
S28	24	35	9	34	8,743	25	6,355102
S29	29	35	9	34	8,743	30	7,677551
S30	13	35	9	34	8,743	14	3,445714
S31	29	35	9	34	8,743	30	7,677551
S32	34	35	9	34	8,743	35	9,000000
S33	29	35	9	34	8,743	30	7,677551
S34	30	35	9	34	8,743	31	7,942041
S35	31	35	9	34	8,743	32	8,206531

**Table 8.** Intensity of system *i*'s significance rating (*IIRFi*) for Matrix S.

System no.	No. of subordinate systems	Total no. of systems	Max. scale rating	Max. no. of subordinate systems	C	B	<b>IIRF(i) for Matrix S</b>
S1	34	35	9	34	8,743	35	9,000000
S2	34	35	9	34	8,743	35	9,000000
S3	34	35	9	34	8,743	35	9,000000
S4	34	35	9	34	8,743	35	9,000000
S5	29	35	9	34	8,743	30	7,677551
S6	29	35	9	34	8,743	30	7,677551
S7	29	35	9	34	8,743	30	7,677551
S8	21	35	9	34	8,743	22	5,561633
S9	21	35	9	34	8,743	22	5,561633
S10	21	35	9	34	8,743	22	5,561633
S11	21	35	9	34	8,743	22	5,561633
S12	14	35	9	34	8,743	15	3,710204
S13	29	35	9	34	8,743	30	7,677551
S14	14	35	9	34	8,743	15	3,710204
S15	21	35	9	34	8,743	22	5,561633
S16	29	35	9	34	8,743	30	7,677551
S17	29	35	9	34	8,743	30	7,677551
S18	14	35	9	34	8,743	15	3,710204
S19	14	35	9	34	8,743	15	3,710204
S20	14	35	9	34	8,743	15	3,710204
S21	14	35	9	34	8,743	15	3,710204
S22	6	35	9	34	8,743	7	1,594286
S23	6	35	9	34	8,743	7	1,594286
S24	6	35	9	34	8,743	7	1,594286
S25	6	35	9	34	8,743	7	1,594286
S26	6	35	9	34	8,743	7	1,594286
S27	6	35	9	34	8,743	7	1,594286
S28	14	35	9	34	8,743	15	3,710204
S29	6	35	9	34	8,743	7	1,594286
S30	29	35	9	34	8,743	30	7,677551
S31	21	35	9	34	8,743	22	5,561633
S32	14	35	9	34	8,743	15	3,710204
S33	21	35	9	34	8,743	22	5,561633
S34	29	35	9	34	8,743	30	7,677551
S35	34	35	9	34	8,743	35	9,000000

**Table 9.** Intensity of system *i*'s significance rating (*IIRFi*) for Matrix P.

System no.	No. of subordinate systems	Total no. of systems	Max. scale rating	Max. no. of subordinate systems	C	B	<b>IIRF(i) for Matrix P</b>
S1	15	35	9	34	8,743	16	3,974694
S2	22	35	9	34	8,743	23	5,826122
S3	3	35	9	34	8,743	4	0,800816
S4	29	35	9	34	8,743	30	7,677551
S5	27	35	9	34	8,743	28	7,148571
S6	13	35	9	34	8,743	14	3,445714
S7	18	35	9	34	8,743	19	4,768163
S8	22	35	9	34	8,743	23	5,826122
S9	8	35	9	34	8,743	9	2,123265
S10	25	35	9	34	8,743	26	6,619592
S11	15	35	9	34	8,743	16	3,974694
S12	6	35	9	34	8,743	7	1,594286
S13	13	35	9	34	8,743	14	3,445714
S14	31	35	9	34	8,743	32	8,206531
S15	31	35	9	34	8,743	32	8,206531
S16	18	35	9	34	8,743	19	4,768163
S17	20	35	9	34	8,743	21	5,297143
S18	26	35	9	34	8,743	27	6,884082
S19	6	35	9	34	8,743	7	1,594286
S20	11	35	9	34	8,743	12	2,916735
S21	11	35	9	34	8,743	12	2,916735
S22	25	35	9	34	8,743	26	6,619592
S23	25	35	9	34	8,743	26	6,619592
S24	6	35	9	34	8,743	7	1,594286
S25	3	35	9	34	8,743	4	0,800816
S26	3	35	9	34	8,743	4	0,800816
S27	8	35	9	34	8,743	9	2,123265
S28	3	35	9	34	8,743	4	0,800816
S29	19	35	9	34	8,743	20	5,032653
S30	16	35	9	34	8,743	17	4,239184
S31	29	35	9	34	8,743	30	7,677551
S32	12	35	9	34	8,743	13	3,181224
S33	33	35	9	34	8,743	34	8,735510
S34	34	35	9	34	8,743	35	9,000000
S35	33	35	9	34	8,743	34	8,735510

## 4.6 Solving the Management Index for Competitiveness

The  $IIRF_{i-overall}$  was calculated by averaging the ratings of the virtual and physical interaction matrices. For the virtual interaction,  $IIRF_{i-virtual}$  is equivalent to the average of the  $IIRF_{i-Matrix I}$  and the  $IIRF_{i-Matrix C}$ . For the physical interaction,  $IIRF_{i-physical}$  is equivalent to the average of the  $IIRF_{i-Matrix H}$ , the  $IIRF_{i-Matrix S}$  and the  $IIRF_{i-Matrix P}$ .

Therefore, the overall rating of S1, as an example, is calculated, as indicated in blue in Table 10:

$$\begin{aligned}
 IIRF_{1-overall} &= \frac{\frac{IIRF_{1-Matrix I} + IIRF_{1-Matrix C}}{2} + \frac{IIRF_{1-Matrix H} + IIRF_{1-Matrix S} + IIRF_{1-Matrix P}}{3}}{2} \\
 &= \frac{\frac{2,123265 + 1,594286}{2} + \frac{1,858776 + 9,000000 + 3,974694}{3}}{2} \\
 &= \mathbf{3,401633}
 \end{aligned}$$

From the  $IIRF_{i-overall}$  as depicted in Table 10, the significance rating was normalised as shown in Column 2 of Table 11. The normalised overall significance rating of S1, as an example, is calculated, as indicated in green in Table 11:

$$\begin{aligned}
 N_{Wi} &= \frac{(x_i)^{1/35}}{\sum_{i=1}^{35} (x_i)^{1/35}} \\
 N_{W1} &= \frac{(3,401633)^{1/35}}{\sum_{i=1}^{35} (3,401633)^{1/35} \dots (5,451429)^{1/35}} \\
 N_{W1} &= \frac{(3,401633)^{1/35}}{36,249370} = \mathbf{0.028569}
 \end{aligned}$$

After the normalised values were obtained, the MIC was computed, using the generalised model developed and described in Chapter 3. The MIC was calculated to be **0,50** as displayed in Table 11. Thus, to determine the MIC, the average of the  $N_{Wi}$  value per individual constituent system was calculated as 0,028571 by using the following mathematical formula:

$$N_{Wavg} = \frac{\sum_{i=1}^{35} N_{Wi}}{35} = \frac{(0,028569 + 0,028853 \dots + 0,028956)}{35} = 0,028571$$

The  $N_{Wi}$  values are displayed in Column 3 of Table 11 and these values were rearranged in ascending order (as displayed in Column 4 of Table 11).

This calculated average was used to divide the normalised values into two clusters. Cluster 1 ( $C_1$ ) for all values equal to or more than the average, and Cluster 2 ( $C_2$ ) for all values below the average. For each cluster, the count (the number of scores per cluster) was determined by using the following Heaviside-function:

$$H(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases}$$

$$\text{where } C_1 = \frac{\sum_{i=1}^n H(N_{Wi} - N_{Wavg})}{n}$$

$$\text{and } C_2 = 1 - C_1$$

As an example, for S1,  $x = N_{W1} - N_{Wavg} = 0,028569 - 0,028571 = -0,000002$ . Therefore,  $x < 0$ , which means  $H(x) = 0$  and S1 will not count towards  $C_1$ . In contrast, for S35,  $x = N_{W35} - N_{Wavg} = 0,028956 - 0,028571 = 0,000385$ . Therefore,  $x > 0$ , which means  $H(x) = 1$  and S35 will count towards  $C_1$ . In summary,  $C_1$  determined to be 0.514, meaning 51.4% of the total number of scores, or 18 scores in total.  $C_2 = 1 - C_1 = 0.486$ , meaning 48.6% of the total number of scores, or 17 scores in total.

Furthermore, for each cluster, the sum (the summation of the normalised values) was determined, by using the following Heaviside-function:

$$T_1 = \frac{\sum_{i=1}^n (H(N_{Wi} - N_{Wavg}) \times N_{Wi})}{n}$$

$$\text{and } T_2 = \sum_{i=1}^n N_{Wi} - T_1$$

As an example, for S1, where  $H(x) = 0$  and  $T_1 = \frac{0 \times N_{Wi}}{n} = 0$ . Thus, S1 will not count towards  $T_1$ . In contrast, for S35, where  $H(x) = 1$ , S35 will count towards  $T_1$ . In summary,  $T_1$  was calculated as 0,517513. Subsequently,  $T_2 = 1 - T_1 = 0,482487$ .

The MIC was determined, by multiplying the percentage per cluster with the sum per cluster and then adding these two values together. In other words:

$$MIC = \sum_{j=1}^2 C_j T_j = C_1 T_1 + C_2 T_2 = (0,514)(0,517513) + (0,486)(0,482487) = \mathbf{0,50}$$

**Table 10.** Overall intensity of system *i*'s significance rating (*IIRFi*).

System no.	Virtual Interactions		Physical Interactions			<b>IIRF(i) Overall</b>
	IIRF(i) for Matrix I	IIRF(i) for Matrix C	IIRF(i) for Matrix H	IIRF(i) for Matrix S	IIRF(i) for Matrix P	
S1	2,123265	1,594286	1,858776	9,000000	3,974694	<b>3,401633</b>
S2	2,916735	2,916735	5,297143	9,000000	5,826122	4,812245
S3	1,858776	1,858776	1,329796	9,000000	0,800816	2,784490
S4	3,181224	2,123265	7,413061	9,000000	7,677551	5,341224
S5	0,800816	0,800816	4,503673	7,677551	7,148571	3,622041
S6	1,329796	1,329796	4,503673	7,677551	3,445714	3,269388
S7	0,536327	0,536327	4,239184	7,677551	4,768163	3,048980
S8	2,123265	1,858776	4,239184	5,561633	5,826122	3,600000
S9	1,329796	1,065306	4,239184	5,561633	2,123265	2,586122
S10	2,652245	2,123265	4,239184	5,561633	6,619592	3,930612
S11	4,768163	2,916735	6,355102	5,561633	3,974694	4,569796
S12	3,974694	3,710204	5,032653	3,710204	1,594286	3,644082
S13	3,181224	3,181224	6,619592	7,677551	3,445714	4,547755
S14	2,387755	2,387755	7,148571	3,710204	8,206531	4,371429
S15	1,594286	0,536327	6,090612	5,561633	8,206531	3,842449
S16	1,065306	1,065306	6,355102	7,677551	4,768163	3,666122
S17	3,710204	2,916735	2,123265	7,677551	5,297143	4,173061
S18	2,652245	2,652245	7,148571	3,710204	6,884082	4,283265
S19	5,826122	5,826122	1,065306	3,710204	1,594286	3,974694
S20	1,329796	0,271837	9,000000	3,710204	2,916735	3,004898
S21	1,858776	0,800816	9,000000	3,710204	2,916735	3,269388
S22	0,800816	0,800816	7,148571	1,594286	6,619592	2,960816
S23	0,800816	0,800816	7,148571	1,594286	6,619592	2,960816
S24	3,181224	2,652245	1,065306	1,594286	1,594286	2,167347
S25	3,181224	2,652245	1,065306	1,594286	0,800816	2,035102
S26	3,181224	2,652245	1,065306	1,594286	0,800816	2,035102
S27	2,916735	2,387755	1,065306	1,594286	2,123265	2,123265
S28	0,800816	0,271837	6,355102	3,710204	0,800816	2,079184
S29	1,065306	0,536327	7,677551	1,594286	5,032653	2,784490
S30	0,800816	0,271837	3,445714	7,677551	4,239184	2,828571
S31	1,594286	1,594286	7,677551	5,561633	7,677551	4,283265
S32	1,329796	1,329796	9,000000	3,710204	3,181224	3,313469
S33	0,800816	0,536327	7,677551	5,561633	8,735510	3,996735
S34	1,858776	1,594286	7,942041	7,677551	9,000000	4,966531
S35	2,387755	2,123265	8,206531	9,000000	8,735510	5,451429

**Table 11.** Management Index of Competitiveness.

System no.	IIRF(i) Overall	Normalised IIRF(i) Overall	Rearranged Normalised IIRF(i)	Cluster 1 (Above or Equal)	Cluster 2 (Below)
S1	3,401633	0,028569	0,028152		1
S2	4,812245	0,028853	0,028152		1
S3	2,784490	0,028406	0,028170		1
S4	5,341224	0,028939	0,028187		1
S5	3,622041	0,028620	0,028203		1
S6	3,269388	0,028536	0,028346		1
S7	3,048980	0,028480	0,028406		1
S8	3,600000	0,028615	0,028406		1
S9	2,586122	0,028346	0,028419		1
S10	3,930612	0,028687	0,028456		1
S11	4,569796	0,028811	0,028456		1
S12	3,644082	0,028625	0,028468		1
S13	4,547755	0,028807	0,028480		1
S14	4,371429	0,028774	0,028536		1
S15	3,842449	0,028668	0,028536		1
S16	3,666122	0,028630	0,028547		1
S17	4,173061	0,028736	0,028569		1
S18	4,283265	0,028757	0,028615	1	
S19	3,974694	0,028696	0,028620	1	
S20	3,004898	0,028468	0,028625	1	
S21	3,269388	0,028536	0,028630	1	
S22	2,960816	0,028456	0,028668	1	
S23	2,960816	0,028456	0,028687	1	
S24	2,167347	0,028203	0,028696	1	
S25	2,035102	0,028152	0,028701	1	
S26	2,035102	0,028152	0,028736	1	
S27	2,123265	0,028187	0,028757	1	
S28	2,079184	0,028170	0,028757	1	
S29	2,784490	0,028406	0,028774	1	
S30	2,828571	0,028419	0,028807	1	
S31	4,283265	0,028757	0,028811	1	
S32	3,313469	0,028547	0,028853	1	
S33	3,996735	0,028701	0,028879	1	
S34	4,966531	0,028879	0,028939	1	
S35	5,451429	0,028956	0,028956	1	
SUM			COUNT	18	17
AVG		0,028571	SUM	0,517513	0,482487
Management Index of Competitiveness				<b>0,500500359</b>	

#### 4.7 Establishment of the MIC Rules-like Rubric

The top five most-rated systems are S35, S4, S34, S2 and S11 (highest to lowest), as indicated in yellow in Table 11. These systems are Safex, ARC, SARS, SAGL and Agbiz Grain, respectively. Therefore, more managerial effort must be directed to these most weighted constituent systems to improve the overall MIC of the grain SoSs. To make the required improvements more practical and incremental, specific rules that govern each level of competitiveness were created. These rules reflect the necessary actions to be carried out and adhered to in order to maintain or enhance the competitiveness level.

The rules are presented in a rules-like rubric format. In the first column, the intervals of the MIC are presented. The first interval,  $0 < MIC \leq 0.1$  refers to non-existent management towards competitiveness. Thereafter,  $0.1 < MIC \leq 0.3$ , for low;  $0.3 < MIC \leq 0.45$ , for moderately low;  $0.45 < MIC \leq 0.6$ , for standard;  $0.6 < MIC \leq 0.75$ , for moderately high;  $0.75 < MIC \leq 0.9$ , for high and lastly,  $0.9 < MIC \leq 1.0$ , for world-class competitive management. Furthermore, the MIC rules-like rubric is divided into five main sections, each with five sub-sections. The main sections include research, industry role players, market and economy, interest representation and development. At each interval level, under each sub-section of the rubric, a governing rule is specified. The rules-like rubric format is shown in Figure 54. Thereafter, the specific governing rules, per main section, are depicted in Tables 12 to 16.

	Research					Industry Role Players					Market & Economy					Interest Representation					Development				
$0 < x \leq 0.1$																									
$0.1 < x \leq 0.3$																									
$0.3 < x \leq 0.45$																									
$0.45 < x \leq 0.6$																									
$0.6 < x \leq 0.75$																									
$0.75 < x \leq 0.9$																									
$0.9 < x \leq 1.0$																									

Figure 54. Rules-like rubric layout.

**Table 12.** The research section of the rules-like rubric.

	Research				
	Availability of Research	Nature of Research	Global Collaboration	Equipment & Software	Publication of Research
$0 < x \leq 0.1$	No research available	No research available	Entities have no outside connections	No technology used to conduct research	No research publication
$0.1 < x \leq 0.3$	Research is scarce and not real problem-focused	Research is mostly inaccurate and scarce	Entities have only local connections	Basic technology and software used	Research is shared with local outside connections
$0.3 < x \leq 0.45$	Research readily available and more problem-focused	Research is usually accurate and readily conducted	Entities have provincial connections	Some use of outdated smart technology and software	Research is published by centralised provincial centres
$0.45 < x \leq 0.6$	Research available upon request of industry entities	Research is accurate with specific focus groups	Entities have national connections	Smart technology and software regularly used, but somewhat outdated	Research is published by centralised national centre
$0.6 < x \leq 0.75$	Research available reacting on real problems	Research is accurate and verified through multiple studies	Entities have some international connections	Regularly updated smart technology and software used	Research is integrated on national level and shared with centralised international centre
$0.75 < x \leq 0.9$	Pro-active research available upon request of industry entities	Data is accurate and new gaps (lacunae) are studied	Entities have global connections	Market leading technology and software used	Research is published by centralised international centre
$0.9 < x \leq 1.0$	Pro-active research on trend mapping of possible real problems	Research is accurate and pro-active	Entities have close-communicating global connections	Market leading technology and software customised for use	Research is integrated on international level and published

**Table 13.** The industry role players section of the rules-like rubric.

	Industry Role Players				
	Registration	Data Sharing	Global Collaboration	Global Competitiveness	Advocacy
$0 < x \leq 0.1$	No registration bodies for supply chain role players	No data sharing	Entities have no outside connections	No collaboration for supply chain competitiveness	No advocacy
$0.1 < x \leq 0.3$	Local registration, but no verification	Data shared only as necessary	Entities have only local connections	Data outcomes linked to smaller goals	Supply chain role players represented on local level
$0.3 < x \leq 0.45$	Verified national registration, but no management	Individual data sharing between connecting supply chain role players	Entities have provincial connections	Data outcomes linked to provincial goals	Supply chain role players represented on provincial level
$0.45 < x \leq 0.6$	Verified and managed national registration	Data sharing after cycle-end with forecasts for the next cycle	Entities have national connections	Data outcomes linked to national goals	Supply chain role players represented on national level
$0.6 < x \leq 0.75$	Verified, managed national and verified international registration	Data and forecasts shared and updated within intervals in the cycle	Entities have some international connections	SDGs known with no direct link to data outcomes	Supply chain role players represented on national level with delegated forums
$0.75 < x \leq 0.9$	Verified and managed international registration from national registration	Data and forecasts shared and updated on a daily basis	Entities have global connections	SDGs known with direct link to data outcomes	Supply chain role players represented on international level
$0.9 < x \leq 1.0$	Collaboration from local to global registration levels	Data and forecasts shared and updated in real-time	Entities have close-communicating global connections	Market & economic data outcomes fulfil SDGs	Active advocacy on for supply chain role players on international level

**Table 14.** The market and economy section of the rules-like rubric.

	<b>Market &amp; Economy</b>				
	<b>Availability of Data</b>	<b>Nature of Data</b>	<b>Global Collaboration</b>	<b>Goal Connection</b>	<b>Publication of Data</b>
$0 < x \leq 0.1$	No data available	No data available	Entities have no outside connections	No data available	No data publication
$0.1 < x \leq 0.3$	Historic data available after cycle-end, usually year-end	Data is mostly inaccurate estimates	Entities have only local connections	Data outcomes linked to smaller goals	Data is shared with local outside connections
$0.3 < x \leq 0.45$	Data available after cycle-end with forecasts made during the next cycle	Data is usually accurate integrating all provincial data	Entities have provincial connections	Data outcomes linked to provincial goals	Data is published by centralised provincial information centres
$0.45 < x \leq 0.6$	Data available after cycle-end with forecasts for the next cycle	Data is accurate integrating all national data	Entities have national connections	Data outcomes linked to national goals	Data is published by centralised national information centre
$0.6 < x \leq 0.75$	Data and forecasts available and updated within intervals in the cycle	Data is accurate verifying national data and linking to global data	Entities have some international connections	SDGs known with no direct link to data outcomes	Data is integrated on national level and shared with centralised international centre
$0.75 < x \leq 0.9$	Data and forecasts available and updated on a daily basis	Data is accurate verifying and integrating global data	Entities have global connections	SDGs known with direct link to data outcomes	Data is published by centralised international centre
$0.9 < x \leq 1.0$	Data and forecasts available and updated in real-time	Data is accurate verifying and integrating global data in real-time	Entities have close-communicating global connections	Market & economic data outcomes fulfil SDGs	Data is integrated on international level and published

\* SDGs refer to Sustainable Development Goals.

**Table 15.** The interest representation section of the rules-like rubric.

	<b>Interest Representation</b>				
	<b>Advocacy</b>	<b>Regulations</b>	<b>Support</b>	<b>Previously Disadvantaged</b>	<b>Global Collaboration</b>
$0 < x \leq 0.1$	No advocacy	No advocacy	Entities receive no support	No development	Entities have no outside connections
$0.1 < x \leq 0.3$	Interest represented on local level	React to unjust regulations	Entities receive support on local level	Development focused on helping previously disadvantaged	Entities have only local connections
$0.3 < x \leq 0.45$	Interest represented on provincial level	Combat unjust regulations	Entities receive support on provincial level	Development schemes focused on helping previously disadvantaged	Entities have provincial connections
$0.45 < x \leq 0.6$	Interest represented on national level	Submission to create just regulations	Entities receive support on national level	Development schemes with delegated desks for previously disadvantaged	Entities have national connections
$0.6 < x \leq 0.75$	Interest represented on national level with delegated forums	Collaborate to create just regulations on national level	Entities receive support on national level with delegated trauma funds	Development schemes with delegated desks for previously disadvantaged	Entities have some international connections
$0.75 < x \leq 0.9$	Interest represented on international level	Collaborate to create just regulations on international level	Entities receive support on international level	Development schemes collaborating on national level	Entities have global connections
$0.9 < x \leq 1.0$	Active advocacy on international level	International committees established to create just and combat unjust regulations	Global state of cohering to support entities	Development schemes collaborating on international level	Entities have close-communicating global connections

**Table 16.** The development section of the rules-like rubric.

	Development				
	Education/CPD	Funding	Technology	Global Collaboration	Previously Disadvantaged
$0 < x \leq 0.1$	No courses available	No funding available	No technology used	Entities have no outside connections	No development
$0.1 < x \leq 0.3$	Basic courses presented in-house	Funding through donations	Basic digitalisation technology used	Entities have only local connections	Development focused on helping previously disadvantaged
$0.3 < x \leq 0.45$	Basic and advanced courses presented in-house	Funding through local development schemes	Some use of outdated smart technology	Entities have provincial connections	Development schemes focused on helping previously disadvantaged
$0.45 < x \leq 0.6$	Basic and advanced courses accredited by national entity	Development funding schemes on national level	Smart technology regularly used, but somewhat outdated	Entities have national connections	Development schemes with delegated desks for previously disadvantaged
$0.6 < x \leq 0.75$	Basic and advanced courses presented by international entity	Development funding schemes on national level with focused assistance	Regularly updated smart technology used	Entities have some international connections	Development schemes with delegated desks for previously disadvantaged
$0.75 < x \leq 0.9$	Basic and advanced courses accredited by international entity	Development funding schemes on international level	Smart technology regularly used and updated from feedback from entities	Entities have global connections	Development schemes collaborating on national level
$0.9 < x \leq 1.0$	Collaborative basic and advanced courses internationally accredited	Development funding schemes on international level with focused assistance	Smart technology regularly used and updated to customised feedback from entities	Entities have close-communicating global connections	Development schemes collaborating on international level

\* CPD refers to Continuing Professional Development.

The MIC for the GSA case study was calculated as 0.50, as shown in Table 11. Therefore, the South African grain industry attains a **standard** level of management towards competitiveness (interval  $0.45 < MIC \leq 0.6$ ). However, to enhance the MIC, the grain industry needs to focus on adhering to all the specified rules within this interval until a MIC value of 0.60 is reached, whereafter enhancement will continue at the hand of the rules specified in the next interval, *i.e.*  $0.6 < MIC \leq 0.75$ . It is essential to direct the focus to the identified top five most-rated constituent systems to reach a MIC of 0.60, *i.e.* the maximum in the current interval. These constituent systems are Safex (S35), ARC (S4), SARS (S34), SAGL (S2) and Agbiz Grain (S11). Figure 55 indicates in which section these identified constituent systems fall.

	Research				Industry Role Players				Market & Economy				Interest Representation				Development			
0 < x ≤ 0.1																				
0.1 < x ≤ 0.3																				
0.3 < x ≤ 0.45																				
0.45 < x ≤ 0.6			S2				S11				S34				S35					
			S4																	
0.6 < x ≤ 0.75																				
0.75 < x ≤ 0.9																				
0.9 < x ≤ 1.0																				

**Figure 55.** Top five constituent systems on the rules-like rubric.

Consequently, all the rules of the market and economy section, as well as the research section need to be adhered to in the first instance (S2, S3, S34 and S35). These rules include data is available after cycle-end with forecasts for the next cycle; accurate data integrating of all national data; entities have national connections; data outcomes link to national goals; data is published by a centralised national information centre; research findings are available upon request of industry entities; research findings are accurate and address specific focus groups; entities have national connections; smart technology and software are regularly used, but somewhat outdated and research findings are published by centralised national centre. Secondly, all the rules of the supply chain role players section, need to be adhered to (S11). These rules include verified and managed national registration; data sharing after cycle-end with forecasts for the next cycle; entities have national connections; data outcomes link to national goals and industry role players are represented on a national level.

## 4.8 Chapter Summary

This chapter presented and discussed the research findings of this study. Individual nested case studies were used to conduct a comparison based on five specified elements. This is presented in section 4.1. From these 35 individual case studies nested under the umbrella case study, namely the grain industry, an SoSs network diagram was drawn. This is portrayed in section 4.2. The quantitative research stemmed from the qualitative data, as explained in section 4.3. The five qualitative elements were then transcribed into five contextual questions, which were used to construct five pairwise matrices, as discussed in section 4.4. These matrices used the HSIM method, as explicated in section 4.5. The normalised HSIM data were interpreted and used to compute the MIC (as presented in section 4.6) and the rule-like rubric was developed (as presented in section 4.7). The next chapter presents the conclusion and recommendations of the study. The conclusions and recommendations are derived from the interpretation of the research findings, as prescribed by Bloomberg and Volpe [145].

## CHAPTER FIVE: CONCLUSION & RECOMMENDATIONS

This chapter evaluates whether the key objectives of the study have been attained. In addition, it also discusses the observed shortcomings of the study, granting a better understanding of the limitations of the study. The chapter also provides the conclusion of the study, proves the significance and appropriateness of the research findings and presents the recommendations for future research.

### 5.1 Conclusion

The value of the MIC tool lies in its ability to quantify the management of SoSs in the field of systems engineering. Today, due to the rapidly changing business environment and globalisation, such a tool is more useful than ever. This holds specifically in the context of the South African agricultural industry which is facing significant challenges related to food security amidst climate change and the related increase in complexities. Quantifying management efforts increases an industry's ability to effectively manage its complex interconnected systems, which in turn is a measure of an industry's competitiveness. Competitive industries for their part, increase a country's global competitiveness.

It is evident from the literature review that the management of SoSs is a relatively unexplored research area. Notably, no existing model establishes a method for quantifying SoSEM – especially not in the agricultural environment from which the GSA case study was taken. This knowledge gap makes it difficult for industries (like the grain industry) to effectively manage a set of multiple, diverse and interrelated constituent systems. This study therefore contributed to filling the identified research gap.

The proposed solution through the chosen research techniques was successful in addressing the research gap. The MIC model addressed this research gap by devising a method to quantify management efforts. Specifically, the study aimed to establish rules (in a rubric format) that govern each level of competitiveness, by reflecting the necessary actions to be carried out and adhered to in order to maintain or enhance the competitiveness level. To validate the application of the MIC model for management SoS competitiveness, a case study approach was adopted, focusing on GSA as centric system and 34 other constituent systems relevant to the grain industry. This verified model allowed for a comprehensive assessment of the management of SoSs and provided guidelines for interpreting the results.

Developing the model to compute the MIC, does not only assist in filling the gap in the literature on SoSEM frameworks, but also establishes a novel research field. Management effort is qualitative and is mostly researched in the field of social studies. Thus, investigating management in the field of engineering, through tasks and activities perception and metrification, explores a new area of research, which is topical in today's interconnected world.

## 5.2 Research Findings

This research has quantified, through algorithmic sensing and metrication, the minimum management effort required by an SoS's overseeing entity, to competitively manage the complex network of systems that forms the heterogeneous SoS network. In a bid to achieve this, a holistic and integrated framework depicting an SoS network of 35 constituent systems in the agricultural grain industry was developed. Furthermore, a quantitative mechanism utilising the HSIM concept was deployed. The verification of the MIC model through the GSA case study yielded valuable insights. The effective minimum management score required for the attainment of competitiveness in holistic management, also known as the MIC, herein, was calculated to be 0.50.

The findings highlight the importance of the interactions, interdependence and interrelationships of variables when formulating a strategy for the management of systems. The SoS traditionally consists of a chain of embedded and interconnected non-metric qualitative tasks and activities. Instead of trying to improve overall management competitiveness through trial-and-error approaches, this study aimed to identify, sense and measure the priority systems that will increase the overall competitiveness the most. The top five most-rated systems are S35, S4, S34, S2 and S11 (highest to lowest), presented in Chapter 4. These systems are Safex, ARC, SARS, SAGL and Agbiz Grain, respectively. Therefore, more managerial effort must be directed to these highest-weighted constituent systems to improve the overall MIC of the grain SoS. To make the required improvements more practical and incremental, specific rules that govern each level of competitiveness were created. These rules reflect the necessary actions to be carried out and adhered to in order to maintain or enhance the competitiveness level.

The results revealed that the four objectives of this study were achieved, which are:

1. Understand, define and describe the historical development of SoSEM and identify possible lacunae in the research of SoSEM: **Detailed in Chapter 2.**

2. Design a holistic network that describes a heterogeneous SoS: **Discussed in section 4.2 and summarised in Figure 47** in Chapter 4.
3. Develop a metric system, by adapting a model for quantifying decision-making through hierarchical prioritisation and pairwise comparisons of the SoS network: **Presented in section 3.5 and summarised in the flowchart in section 3.6** in Chapter 3.
4. Validate the outcomes of objectives 3 and 4, by using the agro-seed nurturing (grain) management industry as a case study, to test the efficacy, effectiveness and overall SoSEM towards industry competitiveness. **Presented in section 4.4 to section 4.7** in Chapter 4.

The findings of this study provide valuable insights that can assist the grain industry in formulating more informed strategies for managing the physical and virtual interactions between constituent systems to enhance the efficient, effective and competitive operation of the chain of tasks and activities in the industry.

### 5.3 Contribution to Knowledge

The HSIM model has traditionally been used to create and assign weights to factors and prioritise these factors usually within any one system. However, in this research, the HSIM concept was extended in its applicative capability by adapting it to an SoSs-centric problem. Hence, several multi-decision variables and scenarios were used to assess the functional and physical compliance of several stand-alone systems in a network of holistic interactions. This was further extended to the computation of competitiveness in the management effort of systems, *i.e.* the MIC. This opened a new dimension to the capabilities and possible adaptability of the HSIM model.

### 5.4 Recommendations for Future Research

To broaden the scope of this study and find effective solutions for the challenges associated with the management of SoSs, several recommendations for further research can be made.

One avenue for further investigation is to expand the study by replicating the case studies across different industries. This will allow researchers to assess whether the management quantification (MIC) model, and its associated governing rules are an effective tool for improving SoS competitiveness. By examining a wider range of case studies, deeper insights into the model's universality, adaptability and robustness across different SoSs contexts can be obtained. Conducting comparative case studies will reduce the industry bias of the findings.

A future study related to this research could also include the addition of more contextual questions deployed towards decision-making for the virtual and physical interactions between constituent systems. Furthermore, the specific rules that govern each level of competitiveness can be refined to provide more comprehensive guidelines to maintain a system's competitiveness. Emerging technologies, like AI and machine learning, could also be explored to future-proof the MIC model.

Another possible area for further study is to shift the focus of the holistic management model for systems to also assess the interactions between sub-systems of the constituent systems. Thus, a focus on the parts and the sum of the parts of the SoSs and the individual constituent systems could be explored. Investigating how management for competitiveness affects the inner relationships within an industry is essential to understanding the broader implications of systems management initiatives.

Additionally, future studies should consider applying similar investigative methods to explore other models for addressing the knowledge gap in the field of systems management. This would ensure the broadening of the literature available on SoSEM. By comparing new research findings with this study, a better understanding of the overall impact and applicability of SoSEM models can be gained. This study, which systematically quantifies the management of SoSs for competitiveness, can serve as the foundation for strategies to express similar concepts that are inherently qualitative, from a metricate point of view. Thus, combining fields like social science and engineering through quantification approaches should be investigated. Technological innovations more focused on the algorithmic perception and measurement of management effort can be investigated. Future research could also concentrate on refining the governing rules for maintaining and enhancing management competitiveness. By increasing the research on management for competitiveness, more informed decision-making and effective planning will be achieved. This will lead to increased global competitiveness.

Incorporating these recommendations into future research will lead to a deeper understanding of systems management and more informed decision-making within the field of SoSEM.

## **5.5 Chapter Summary**

This chapter has provided a conclusion to the dissertation. It summarised the findings of the study and links these findings to the research objectives. The study was successful in achieving its aim and answering the research questions. The chapter also outlined recommendations for future research.

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