SOCIO-TECHNICAL SYSTEMS: USING ACTOR-NETWORK THEORY TO MAKE THE SOCIAL MORE TANGIBLE IN A TECHNICAL SPACE

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ABSTRACT

In technical spaces, the social can be seen as incidental (a distant factor to be monitored for avoidable negative impact), inaccessible (something to be assigned to someone with specialised skills), and implausible (involving wicked problems and improbable resolution). As a result, the social aspects of technical effort can be managed separately, haphazardly, without a common language, and outside of recognisable processes and transferable skills. This paper positions the social and technical as interconnected. It applies a systematic literature review to extend actor-network theory. The study offers language and a method to make the social aspects of technical work more describable, accessible, and systematic. It provides a framework for engineering practitioners to describe, analyse, and design socio-technical systems.

OPSOMMING

In tegniese ruimtes kan die sosiale gesien word as toevallig ('n veraf faktor wat gemonitor moet word vir vermybare negatiewe impak), ontoeganklik (iets wat aan iemand met gespesialiseerde vaardighede toegeken moet word) en onwaarskynlik (wat moeilike probleme en onwaarskynlike oplossing behels). Gevolglik kan die sosiale aspekte van tegniese inspanning afsonderlik, lukraak, sonder 'n gemeenskaplike taal, en buite herkenbare prosesse en oordraagbare vaardighede bestuur word. Hierdie artikel posisioneer die sosiale en tegniese as onderling verbind. Dit pas 'n sistematiese literatuuroorsig toe om akteur-netwerkteorie uit te brei. Die studie bied die taal en 'n metode om die sosiale aspekte van tegniese werk meer beskryfbaar, toeganklik en sistematies te maak, en bied 'n raamwerk vir ingenieurspraktisyns om sosio-tegniese stelsels te beskryf, te analiseer en te ontwerp.

1. INTRODUCTION

1.1. Background and problem statement

According to the Engineering Council of South Africa [1], engineering is the practice of science that is concerned with the resolution of engineering problems. An engineering problem is a problematic situation that is responsive to analysis using engineering principles [1, 2]. The council states that engineers identify complex engineering problems and develop solutions while demonstrating pre-defined outcomes that include both technical and social aspects [3]. The council does not explicitly outline whether the social and technical aspects ought to be treated equally or unequally, but says that engineers are required to manage them in an integrated manner [3]. The South African Department of Higher Education and Training's definition of industrial engineers [4] indicates that these engineers solve problems that involve both social and technical aspects. Although this discipline integrates social and technical elements, few tools in this discipline allow for the systematic and elemental integration of social and technical aspects throughout the problem life cycle.

Industrial engineers are associated with methodologies such as total quality management, lean management, business process re-engineering, business process modelling, and value engineering. Researchers assert that the application of these methodologies involves a blending of social and technical elements within complex systems [5–8]. Lean management has been described as a socio-technical intervention [6], and is understood to involve socially and technically embedded relations [7]. The implementation of business process modelling is tied to socio-technical entanglement [8]. South African value engineering practitioners state that social elements are as important as the technical in the application of this methodology [9]. Although all these methods are associated with a socio-technical blend, there are few tools that industrial engineers can apply to describe, analyse, and visualise the relationship between social and technical aspects at an elemental level in a complex socio-technical system (CSTS).

Actor-network theory (ANT) is a method for studying the work of scientists and engineers in society [10] in a context where the separation of the social and technical is difficult [11]. ANT is used to study the socio-technical relationship between human and non-human objects at an elemental level within a heterogeneous network [5, 8]. In ANT, the social and technical aspects hold equal importance, and emphasis is placed on the relations of human and non-human objects [10] while considering their functionality and mechanisms in the defined context [12]. This paper offers an ANT-based framework to assist industrial engineers with analysing CSTSs throughout the problem life cycle.

The application of ANT in engineering is not novel; however, it is emerging. Researchers and engineering educators have found ANT-based tools to be a useful addition to the engineer's toolbox [13, 14]. They assert that ANT offers engineers a way to examine abstract and open-ended socio-technical conditions, explore the interaction of engineering and society, review the power and ethical factors associated with engineering work, and understand the impact of engineering. They propose that ANT suits engineers because it aligns with systems thinking and facilitates a way to model socio-technical systems (STSs). However, these researchers and educators have also encountered difficulties that are associated with the ANT vocabulary, transferring the method from sociology to engineering, and understanding the method. This paper aims to offer a way to overcome some of these difficulties by contributing to the translation of ANT concepts and by developing a visual framework to guide ANT application.

1.2. Research objectives

The research question for this study is: "How can industrial engineers apply actor-network theory to study the relation of socio-technical elements in complex systems?" The following research objectives (RO) are used to answer this question:

- RO1: Introduce STSs and actor-network theory.
- RO2: Identify and analyse how actor-network theory has been applied in problem identification and solution implementation in CSTSs.
- RO3: Develop a framework that can enable the examination of CSTSs in the field of industrial engineering.

2. LITERATURE REVIEW

2.1. Complex socio-technical systems

A socio-technical system (STS) is defined as a system that involves both human and non-human elements and in which the interaction of these two classes results in certain outcomes. STSs are often assumed to be complex [15]. There is no universally accepted definition of 'complexity' [15, 16]. Some authors describe complex systems based on shared attributes [16], while others propose that complexity be defined using categories [15]. This study adopts the principle that assumes that all STSs are complex [15], and offers the following definition:

> A complex socio-technical system (CSTS) involves both human and non-human elements, such that the interaction of these elements results in an outcome, and complexity is an inherent characteristic of the system because of the presence and relation of both human and non-human elements.

2.2. Socio-technical approaches in engineering

Socio-technical systems theory (STST) originated in the 1950s [17–20]. It shifted the way engineers approached design. This concept describes STSs as involving interdependencies between two subsystems, a social subsystem and a technical subsystem [19]. It views organisations as STSs, in which both the social and the technical factors are examined when introducing change [18, 22], and assumes that optimal performance can only be achieved if both factors are optimised [22].

Various methods can be applied to achieve optimal performance. The STST toolbox consists of methods such as soft systems methodology, socio-technical systems engineering, systems thinking, contextual design, cognitive engineering, cognitive work analysis, and human-centred design [21]. The implementation of these methodologies has achieved notable success [22]. However, the application of these methodologies experienced a decline in the 1990s, with organisations opting for operations management techniques [23]. The lean management method has gained more interest because it enables the elimination of unnecessary complexity in STSs [15].

The application of STST has not only been impacted by the choice to opt for operations management methodologies. ANT has been found to address some limitations associated with STST [24]. The origins of ANT have a relationship with engineering and society [25–27], and are linked to research by Michel Callon, Bruno Latour, and John Law in the late 1970s [28], who solidified the method in the 1980s [29]. ANT is not a theory but a method that can be used to study STSs [13]. When comparing STST and ANT, the following can be determined:

- STST principles are associated with functionality and rely on hierarchy, where the dynamics of an organisation are a result of the rules set by top management. STST assumes that management-driven change is beneficial to the organisation and society. Conversely, ANT principles are associated with practicality, and do not rely on hierarchy; there is no dominant force, and outcomes are achieved through ongoing mediation, resulting in a negotiated order [24].
- STST views an STS as two subsystems [21, 30]: the social and the technical interact at the subsystem level; whereas ANT views an STS as an actor-network that is made of human and non-human elements, and the social and technical aspects interact at the elemental level [13].
- In STST, the social and the technical are defined as separate [31] and independent [30]. In contrast, ANT does not treat the social and the technical as separate [13].
- STST views humans as the key aspect and assumes that the social subsystem directs the entire system [21]. Conversely, ANT rejects the existence of a single direction of influence between the social and the technical in which society is the cause and the technical is the effect [13]. ANT assumes that there is a bi-directional relationship between the human and non-human elements [13].

The differences between STST and ANT are presented not to indicate that one method is better than the other, but to reflect the distinctions and to put forward that there may be socio-technical contexts that are more responsive to STST, and others that are more responsive to ANT. STST thinking aligns with contexts that require the separation of the social and the technical into two independent subsystems in which the emphasis needs to be placed on functionality, order is achieved through hierarchy, the social and technical interact at the subsystem level, and humans are assumed to direct the entire system. Conversely, ANT thinking fits a context that does not separate the social and the technical into two subsystems, but views the human and non-human elements as fundamental components that make up a heterogeneous socio-technical network; the emphasis is placed on practicality; the social and technical elements are given equal importance; any part of the system can drive change; order is achieved through negotiation; the social and the technical interact at an elemental level; and the relation of social and the technical directs the entire system.

The characteristics of ANT have resulted in the use of this method in diverse disciplines. ANT has been applied in the engineering discipline because it facilitates the examination of systems [13]. ANT's enabling of the scrutiny of change dynamics has resulted in its application in lean management [6, 32], lean six sigma [33], business process re-engineering [34, 35], and lean management in the public sector [7, 36]. ANT has enabled the exploration of the relationship between technology and society in m-learning [11], e-health [37], and e-government [5]. This method has also supported the investigation of the impact of STSs on financial inclusion [38], information security awareness [39], and management accountability [40].

ANT does not only provide an alternative method to simultaneously study the social and the technical; it also offers an alternative terminology to describe the studied context [41].

2.3. ANT methodology and terminology

ANT is a set of terms and a method used to describe and study the actions and relations of human and non-human elements in an STS [29]. In ANT, human and non-human elements are called actors, and the STS is called an actor-network. The actor-network is assumed to undergo a formation and development process called translation until it reaches a negotiated order. Actors, actor-network, and the translation process are three key concepts in ANT, and they are outlined in Table 1.

Table 1: Three key ANT concepts

Core Concepts	Principles	Processes
Actor (also called actant or object)	An actor is defined as something that acts or to which activity is granted by others. An actor can be anything (either human or non-human) if it is allowed to be the source of action [42]. The actor is defined by the network [43]. Through the concept of generalised symmetry, human and non-human elements are assumed to be equal; both elements are given even weighting during the analysis; both have influence; humans action their influence through agency; non-humans action their influence through performativity; and all of the elements and their associated relationships are studied in the analysis [13, 36].	An actor can bend space around itself, making other actors dependent upon it [44]. Actors have properties and interests that enable them to request, demand, allow, modify, deflect, betray, appropriate, or refuse an action or interests presented by other actors in the STS [13, 45].
Actor-network	An actor-network is a heterogeneous system made up of human and non-human actors in a particular socio-technical context of relation [42]. Latour [42, 46] cautions users of this method not to limit the definition of an actor-network to that which is associated with technical networks in the fields of mathematics of engineering. Latour states that actor-networks can be local or global; they may not have compulsory paths; they have no strategically positioned nodes; and they do the tracing.	The movements or journey of the actor-network are traced, mapped, and followed through a process called translation [42, 46].
Translation	Translation is the complex journey undertaken by actors in an actor-network, such that the outcomes are unpredictable and are a function of the actor-network dynamic [36, 47].	The four moments of translation are problematisation, interessement, enrolment, and mobilisation [6, 29, 34, 36].

Table 2 outlines the four moments of translation.

Table 2: Four moments of translation [6, 29, 34, 36]

Moment of translation	Principle
Problematisation	During this moment, initiating/focal actors define a problem, a solution, and the interests/identities/roles of other actors that are consistent with the solution. The problem and solution are defined so that they are recognisable to others and to create an obligatory passage point (OPP) for entering the network. An OPP is a situation that must occur for all actors to achieve their interests in the actor-network. The OPP exists in the direct pathway of the focal actors; other actors need to overcome obstacles to pass through the OPP.

Interessement	This moment occurs after actors have passed through the OPP. The focal actors negotiate with and convince other actors to engage in an actor-network and to contribute to a solution. Not all of the actors participate in the negotiation: they can send representatives.
Enrolment	The actors accept the roles/interests defined for them by the initiating actors. Inscription (the process in which the agreement between the actors is committed to the shared memory of the STS) can occur if agreement is reached [44]. The actors are locked into roles and contribute to the solution. There is an emerging actor-network in which actors' actions become coordinated.
Mobilisation	The network exists as a coherent whole; there is wide acceptance of the solution; and inscription takes place. The actor-network can be formed into a black box or a single actor through a process called punctualisation – that is, the consolidation of a set of actors into a single actor – and a punctualised actor-network can become a black box when it reaches stability [13]. Stability is the temporary order that is reached when there is sufficiently wide acceptance of a solution [44]; actor-network stability and durability are often used as indicators of the viability of a solution for the studied context [12]. The stability achieved by actor-networks is said to be temporary; it can be strengthened by changes in actors, actors' interests/actions/roles, or relations resulting in durability over time [39]; similarly, it can be weakened by changes in actors, actors' interests/actions/roles, or relations disintegrating over time [48].

ANT principles can be used to define a problem and to study the impact of a solution across space, over time, and through a socio-technical lens. In addition, ANT offers terminology. Other terms found in the ANT lexicon are irreversibility [44]; betrayal [44]; mediators and intermediaries [26, 45]; and patterning [13].

It has been argued that ANT contains complex jargon and lacks defined models for application [12, 41, 48]. Research has been published to clarify the terms [26, 42, 43, 46]. There have also been advances in ANT research that have resulted in the development of graphical syntax and visualisation frameworks.

2.4. ANT visualisation frameworks

Researchers have developed ANT analysis diagrams [48] and established an ANT graphical syntax [12] and visual representations [38, 40, 49]. Tsohou *et al.* [39] acknowledge that actor-networks transform over time, and have added to the visualisation syntax of ANT by mapping using freeze frames. Graphical advances achieved in ANT research have resulted in the depiction of source actors, target actors, translators, the four translation moments, black boxes, and freeze frames [12, 38, 39, 49, 50]. These graphical syntax components are shown in Figure 1.

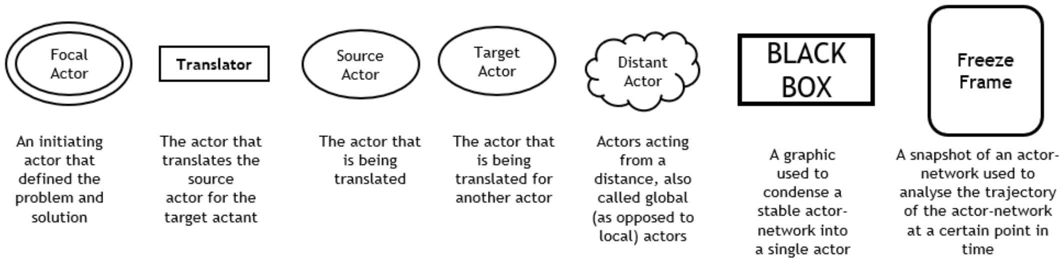

Figure 1: ANT graphical syntax elements

The terms and principles outlined in section 2.3 and the graphical syntax shown in Figure 1 were synthesised and combined by the researchers of this study to establish an ANT conceptual framework (shown in Figure

2). The proposed framework is used to extract data and conduct data synthesis as part of the research methodology.

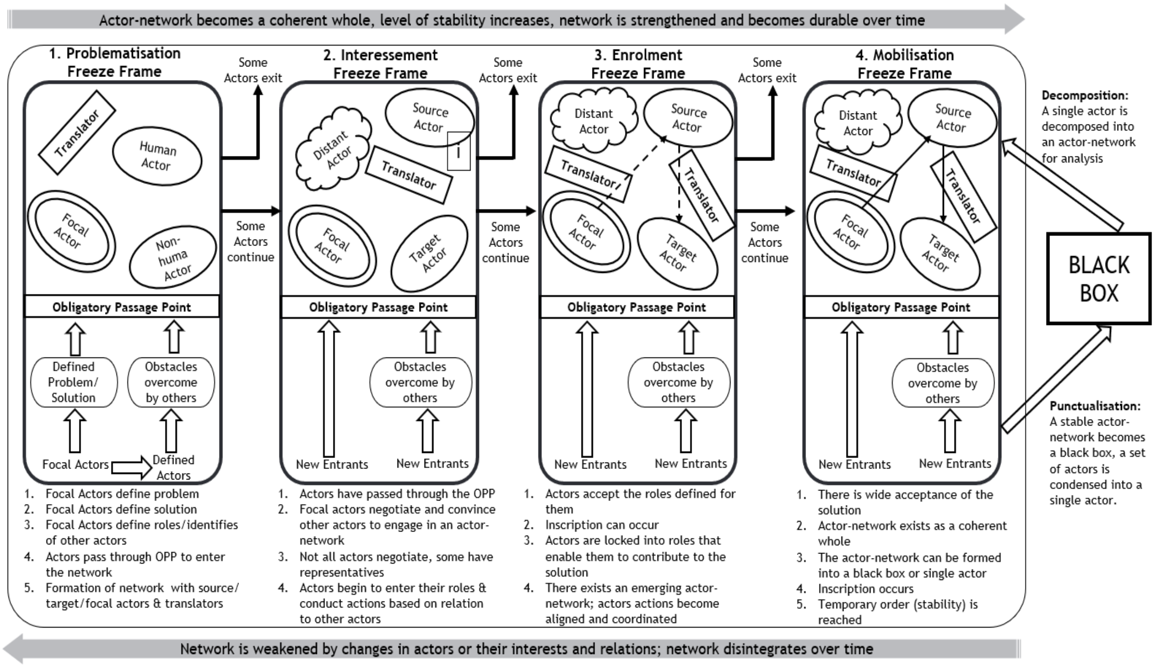

Figure 2: Proposed ANT conceptual framework

Advances in visualisation frameworks have helped to overcome the limitations associated with ANT; however, this method has been subject to other criticisms.

2.5. Criticisms of ANT

ANT has been subject to some criticism because of the power it gives to non-human elements, its concept of symmetry, and its unstructured approach. Non-human objects having 'interests' has been criticised because it is a characteristic that cannot be exhibited by non-living objects [48, 51]. ANT researchers acknowledge the criticisms, and assert that the definitions contained in ANT are not intended to define humans and non-humans as similar [51]: the aim is to offer a metaphor for studying CSTSs without the complication of differentiating between the social and the technical facets [44]. Similarly, its generalised symmetry has created difficulties [48]. ANT researchers [26, 48, 51] state that treating human and non-human elements equally is meant to offer a way to place the social and the technical on an even relational field to ensure that the study is free from prior assumptions of privilege.

The unstructured nature of ANT [12, 41, 48] has resulted in varied interpretations. The variations have been accepted, resulting in the formation of the term 'post-ANT' [48]. The unstructured approach is viewed as necessary, as it enables ANT to be translatable; but fixing ANT would eliminate this intrinsic characteristic [52]. Researchers caution against over-simplification during adaptation, and advise ANT users to maintain the integrity of key concepts such as actor, actor-network, and translation [42, 52].

Researchers have acknowledged the criticisms of ANT, provided clarification, and improved the method. They also acknowledge the need for interpretive flexibility [5], and encourage the spread of ANT while preserving the key concepts. This paper aims to translate ANT for engineers while preserving the integrity of its key concepts.

3. RESEARCH METHODOLOGY

3.1. Introduction to the methodology

To achieve the first two objectives of this study, a systematic literature review (SLR) approach was selected to enable an expansive and exhaustive identification and analysis of the literature. This study aimed to use the identified literature to develop a framework, and thus an extending SLR was selected, as this type of review is used for theory-building purposes [53]. The review protocol (Table 3) was guided by Fink [54], Xiao and Watson [53], and the Preferred Reporting Items for Systematic Reviews (PRISMA) checklist [55, 56].

Table 3: SLR protocol

Item	***Study protocol selection***
Review question	To answer the overall research question, the first steps require the systematic identification of the literature that shows how ANT has been applied to solve problems; thus the review question is as follows: How has ANT been applied to identify problems and to implement solutions in CSTSs?
Inclusion criteria	White literature [57], excluding books: published journal papers and conference proceedings. Theory-building reviews employ peer-reviewed studies to ensure data integrity [53]. Research that applies actor-network theory to examine problems, solutions/interventions in STSs. Research written in the English language.
Exclusion criteria	Research that applies ANT on social aspects only or technical aspects only. Research that is non-application-based (conceptual or opinion-based).
Search strategy	Search methods: Free text searching (Google Scholar), manual and bibliographic searching (scoping review bibliography). Search engine: Google Scholar and eight publishers applied as filters: SpringerLink, Emerald Insight, ProQuest, SAGE Publications, Elsevier, Taylor & Francis, Wiley, and IEEE Xplore Library. Google Scholar was selected for its advanced search capabilities.
Search terms and Boolean operators	Terms: Actor-network theory AND: Application, Implementation, Execution, Utilisation, Use, Practice, or Employment
Search timeframe	Start date: 1980; end date: 2022
Search approach	Two reviewers searched independently and in parallel to ensure rigour [53]. The reviewers ordered the search results by relevance, and examined the first 200 data retrievals. The protocol was tested before the search was started.

3.2. SLR search results

The search yielded 3 145 records for screening. The application of the SLR criteria by two reviewers resulted in the selection of 23 review articles, as shown in Figure 3.

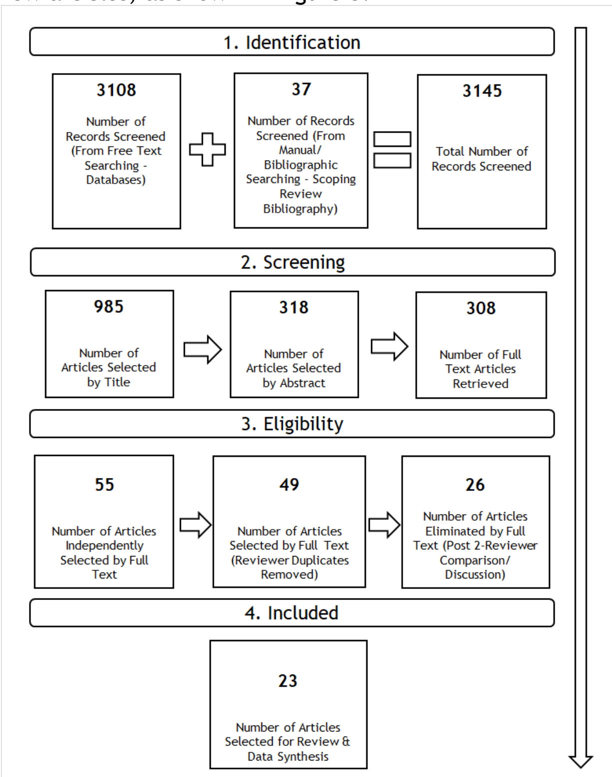

Figure 3: SLR search process results

3.3. Critical appraisal

A critical appraisal was conducted according to the qualitative characteristics (credibility, transferability, dependability, and confirmability) [58, 59]. The articles were assessed, assigned a critical appraisal score, and ranked. A low score does not indicate low quality; rather, it indicates that the article did not include sufficient evidence of the examined characteristics. It is acknowledged that academic communities adopt varying formats, which can impact the authors' ability to include such evidence. Therefore, this study did not exclude any studies based on low scores; and the results shown in Table 4 are presented to indicate the data limitations.

Table 4: Critical appraisal results

Critical appraisal results: Rank 1-12	**Rank**	1	2	3	4	5	6	7	8	9	10	11	12
	Reference	[45]	[5]	[60]	[61]	[62]	[63]	[44]	[6]	[64]	[65]	[66]	[67]
	Score	100 %	91%	91%	91%	91%	82%	82%	82%	82%	73%	73%	73%
Critical appraisal results: Rank 13-23	**Rank**	13	14	15	16	17	18	19	20	21	22	23	-
	Reference	[68]	[69]	[70]	[71]	[11]	[72]	[73]	[74]	[75]	[76]	[77]	-
	Score	73%	64%	64%	64%	64%	55%	55%	45%	36%	36%	27%	-

3.4. Data extraction and synthesis

The 23 articles were selected because they involved problem identification and solution implementation using the four moments of translation. Microsoft Excel and Zotero were used to manage and extract the data. Thematic synthesis [53] was used to group the extracted data. The selection of the articles and the data extraction and synthesis were used to achieve the first two objectives of this study. The conceptual framework outlined in Figure 2 and the framework synthesis [53] were employed to develop an ANT framework that could be applied by industrial engineers to manage complex STSs; this achieved the third objective of this study, and answered the overall research question.

4. RESULTS AND DISCUSSION

4.1. Overview of articles

The selected articles were published over 19 years, with the first published in 2004 and the last published in 2022 (Figure 4, View 1). Nineteen journal papers and four conference papers were selected (Figure 4, View 2), with most of the articles published by Emerald Publishing and Taylor & Francis (Figure 4, View 3). All of the articles involved the application of ANT in a socio-technical context using a case study research methodology. Of the case studies, 74% were in the public sector and 26% were in the private sector (Figure 4, View 4). The studied contexts were located in 14 countries on six continents, although most of the cases were in Australia, China, and Sweden (Figure 4, View 5). The case studies covered various fields, with most of the studied STSs being in the higher education and information technology fields (Figure 4, View 6).

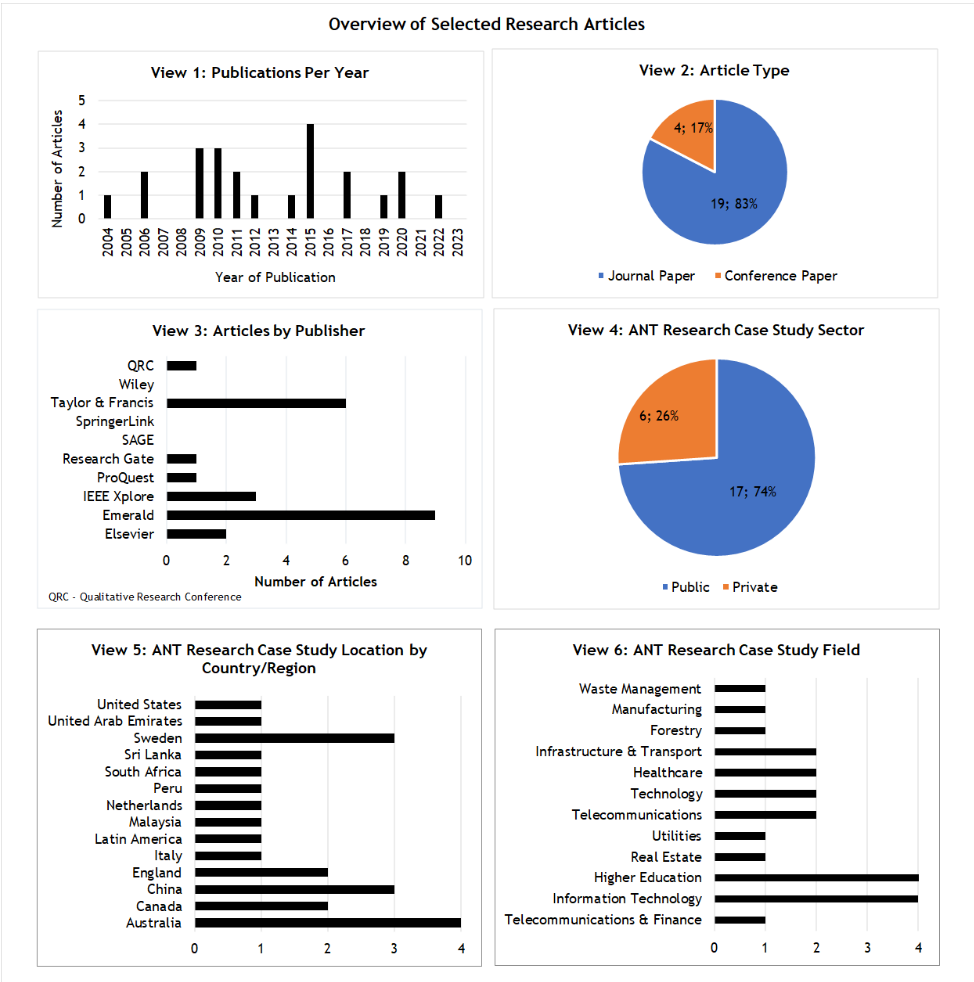

Figure 4: Overview of selected research articles

The distribution of the data over 19 years enabled the development of a framework based on perspectives that do not change over time. A sample consisting of 19 out of 23 journal articles was suitable for the requirements of this study, as 'extending reviews' are required to use trustworthy data to build theory [53, 57]. Over 70% of the case studies found in the selected articles occurred in the public sector. This was suitable for this study, as theory-building reviews need to include data that is sufficiently similar to build theory [53]. The explored studies might be similar in article type and sector; however, a notable variation existed in the case study locations and fields. Also, the ANT method enables interpretive flexibility [5], which causes variation. The variation was managed by applying the inclusion/exclusion criteria and by using a structured and consistent data extraction process. The variation was as beneficial as the similarities because principles that prevail in different circumstances facilitate reproducibility and applicability. The overview of the articles is presented to show the expansiveness of the case studies (field, location, time) and the limitations of the data (sector, number of articles, literature type). The data was extracted to identify the problems and the solutions that were amenable to ANT (section 4.2) and to establish an ANT application framework (section 4.3).

4.2. Application of ANT in problem identification and solution implementation

The selected articles contained 26 case studies; Hellman *et al*. [65] explored three case studies, Aubry [69] examined two case studies, and the other 21 articles contained one case study each. The studies exposed problems and solutions that were amenable to ANT. The problems and solutions were identified using the problematisation principle, and the translation (implementation) of the solutions was outlined using the other moments of translation (interessement, enrolment, and mobilisation). Table 5 contains a summary of the identified problems and translated (implemented) solutions in a particular STS. Forty-six per cent of the case studies involved problems and solutions related to lean [6, 45], efficiency [5], re-engineering [44, 61], process improvement [63, 65], cost reduction [6], project management [69], and engineering education [76]. These concepts are directly relevant to the approaches applied by industrial engineers to manage CSTSs in their work (see section 1.1).

Nineteen per cent of the case studies involved problems and solutions that are specific to information technology [60, 62, 71, 73, 76]. Other case studies were related to privatisation [64], technology infrastructure [67, 77], higher education management [11, 74], forestry [68], online user authenticity [72], intellectual capital [70], and technology usage [66]. These concepts might not be immediately relevant to the tools and techniques associated with industrial engineers; however, the processes in these fields could be suitable for engineering science.

Table 5: Problems and solutions amenable to ANT concepts

Rank	Case study problem	Case study solution
1	Challenges with employee commitment, customer service, and external pressure [45]	Implementation of lean management
2	A drive to adopt information technologies to increase efficiency and transparency [5]	Implementation of a land administration information system
3	Local people in rural communities require access to information [60]	Implementation of an information system to deliver information and improve living conditions
4	Weaknesses identified in the expenditure technology informational base resulted in delays and inaccuracies [61]	Re-engineering and upgrading of expenditure technology
5	The utilisation of paper-based records [62]	Introduction of a new point-of-care technology system for nurses
6	A need for improvement in transport operations [63]	Implementation of an improvement project to ensure sustainable operations and improved functions
7	A threat to organisation objectives from changes in the business environment [44]	Implementation of a re-engineering process
8	The firm identified cost reduction as a major issue [6]	Implementation of Lean project to reduce costs and improve process performance

Rank	Case study problem	Case study solution
9	A need to privatise solid waste management to improve environmental management [64]	Privatisation of solid waste management
10	Hospital A: develop patient-centeredness and improve quality and performance [65]	Implementation of process orientation initiative
10	Hospital B: pressure to reduce waiting times and comply with service time targets [65]	Implementation of an emergency care process
10	Hospital C: constrained resources limiting the ability to improve quality [65]	Implementation of process orientation initiative
11	A need to facilitate internationalisation by promoting interaction between university stakeholders [66]	Implementation of a Facebook page to facilitate online interaction
12	Identification of security gaps in the Wi-Fi standards [67]	Rollout of WAPI (wireless LAN authentication and privacy infrastructure)
13	Land licensees were concerned about the increasing pressures imposed by government goals [68]	Rollout of licensee-endorsed production-orientated vision for forest management
14	Conflicts at the interface between organisation hierarchy and project management (PM) structures (two case studies) [69]	Achieve PM deliverables while managing the interface between PM structures and an organisation's hierarchy
15	A need to measure intellectual capital (IC) [70]	Implementation of a model that enables IC measurement and reporting
16	Opportunities presented by new business information modelling (BIM) technology and a low increase in productivity [71]	Implementation of BIM to increase productivity
17	A need to determine the suitable balance between face-to-face and online teaching [11]	Rollout of an e-learning package
18	Authenticity concerns in digital dating [72]	Establish user authenticity to drive Tinder's success
19	Dissatisfaction with computer laboratory because of low speed and memory limitations [73]	Rollout of new information technology infrastructure
20	A need to establish knowledge exchange [74]	Rollout of a knowledge exchange process
21	Financial and strategic problems in an undergraduate engineering programme [75]	The implementation of a single undergraduate engineering programme
22	The need to understand information-sharing networking during disaster management [76]	To model information-sharing networking during disaster management
23	An aim to promote 4G mobile technologies to avoid failures experienced with 3G in China [77]	The rollout of long-term evolution time division duplex (LTE TDD) technology in China

A notable number (46%) of the examples in Table 5 was directly relevant to the work of industrial engineers. Although the majority were not directly relevant to industrial engineering, most were suitable for engineering science. Therefore, the ANT concepts employed to explore the above problems and solutions were compared with the conceptual framework outlined in Figure 2 to develop an ANT application framework.

4.3. Proposed ANT framework

The review articles introduced concepts such as unknown actors [66] and isolated actors [62]. In addition, the studies placed a notable emphasis on an actor's interest [5, 6, 11, 44, 45, 60, 61, 63–65, 74, 75, 77]. As a result, unknown actors, isolated actors, and actors' interests were used to extend the graphical syntax found in Figure 2 to produce the updated graphical syntax shown in Figure 5.

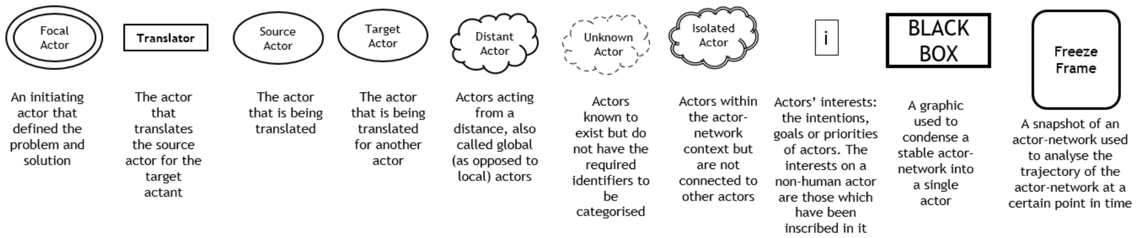

Figure 5: Updated ANT graphical syntax elements

After updating the graphical syntax, the new syntax elements (Figure 5), the conceptual framework (Figure 2), and the ANT concepts used to explore the problems/solutions summarised in Table 5 were synthesised to produce an ANT application framework (Figure 6). The framework is colour-coded to reflect the variation in the application of ANT components in the review articles. Green indicates the ANT concepts applied in more than 66% of the case studies; amber indicates the ANT concepts applied in more than 33% but less than 66% of the case studies; and red indicates the ANT concepts applied in less than 33% of the case studies. ANT is a method used to follow science in action [25, 46]; this suggests that CSTSs are dynamic. Therefore, the presence of amber and red elements in the framework does not necessarily mean that the framework is empirically irrelevant; the dynamics of the STSs might not have reached certain development levels when the contexts were examined by the researchers.

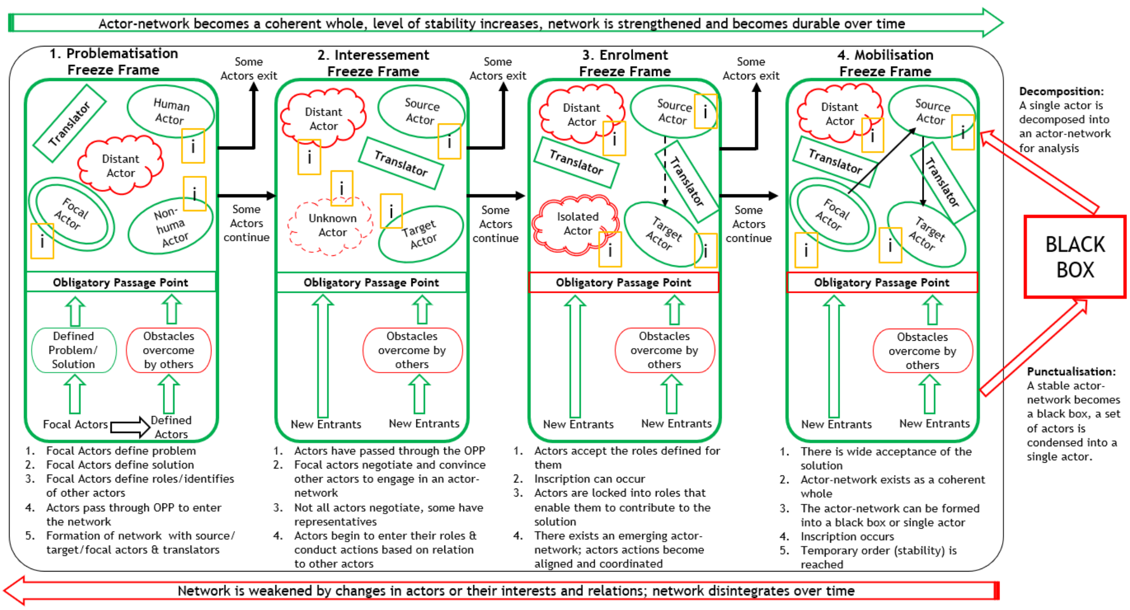

Figure 6: Proposed ANT application framework

The ANT components contained in the framework and their sequence were compared with the ANT components and sequencing applied in the review articles' case studies. It was found that all of the case studies generally followed the sequence outlined in the framework (1. Problematisation, 2. Interessement, 3. Enrolment, 4. Mobilisation). This was expected because this order reflects the sequencing of the four moments of translation in actor-network theory [78].

Conversely, not all of the ANT components that are represented in the framework were present in the case studies. This too was expected, because the outcomes of an ANT STS are negotiated over time and are a function of the STS dynamics [36, 47]. Therefore, it is possible for an STS never to pass certain development stages to reach stability and become a black box. For example, 20 case studies reached the mobilisation stage, only five review articles applied the black box concept [6, 11, 44, 60, 62], and only three review articles contained examples of irreversibility [44, 62, 69]. Also, research studies often have a particular focus area, which may have resulted in the exclusion of certain ANT concepts owing to scope.

A red-coloured component worth noting is the OPP at the enrolment and mobilisation stages in the framework (Figure 6). Eighteen out of twenty-six case studies explicitly defined or described a reasonably deducible OPP during the problematisation and interessement stages. However, only one article [75] outlined the existence of an OPP during the enrolment stage. No articles outlined an OPP during the mobilisation stage. According to ANT principles (Table 2), the OPP is defined at the problematisation stage; actors must pass through this point to enter the network, and new actors can enter the network at any stage. Therefore, all stages must have an OPP. The omission of an OPP at certain moments of translation in the examined studies was acceptable because ANT principles emphasise the OPP for problematisation and interessement moments. However, since new actors can enter the network at any stage, further research is required to explore the existence of OPPs during the enrolment and mobilisation stages.

Overall, a majority of the review articles confirmed the existence of the key ANT components found in the proposed framework (green coloured) and were generally aligned with the proposed sequencing of these components. Furthermore, the review revealed the existence of additional socio-technical dynamics such as de-enrolment [61]; re-problematisation [61, 70]; competing problematisations [11, 65, 68]; ongoing problematisations [44]; focal actors as OPPs [70, 77]; and allies [66], all of which were beyond the scope of this study.

5. CONCLUSION

This research aimed to provide an answer to the question: "How can industrial engineers apply actor-network theory to study the relation of socio-technical elements within complex systems?". The study answered this question by defining complex socio-technical systems, contextualising ANT concepts in the world of industrial engineering, providing examples of industrial engineering-relevant problems and solutions that have been explored using ANT principles, and offering a framework for ANT application in the industrial engineering context. This framework could be used by industrial engineers and other technical professionals to analyse the elemental interaction of social and technical aspects throughout the engineering design and complex engineering problem life cycles. The core ANT concepts in the framework align with more than 66% of the examined literature. However, some framework concepts (black box, obstacles, and post-interessement OPPs) did not feature sufficiently in what was examined. This is to be expected, given the interpretive flexibility associated with ANT. In general, the proposed ANT application framework aligns with the examined theoretical and empirical studies. Still, further research is proposed to test this framework empirically and to examine concepts such as de-enrolment, re-problematisation, and ongoing and competing problematisations.

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