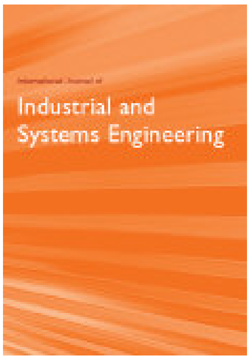


International Journal of Industrial and Systems Engineering

ISSN online: 1748-5045 - ISSN print: 1748-5037
https://www.inderscience.com/ijise

Application of cognitive work analysis in support of systems engineering of a socio-technical system

Henk van den Heever, Rudolph Oosthuizen

DOI: 10.1504/IJISE.2023.10048719

Article History:

Received:	18 January 2022
Accepted:	29 May 2022
Published online:	08 January 2024

Application of cognitive work analysis in support of systems engineering of a socio-technical system

Henk van den Heever and
Rudolph Oosthuizen*

Department of Engineering and Technology Management,
University of Pretoria,
140 Lunnon Rd., Hillcrest, Pretoria, 0002, South Africa
Email: henk.vandenheever@gmail.com
Email: rudolph.oosthuizen@up.ac.za
*Corresponding author

Abstract: This paper presents a validation workflow to support system requirements analysis. Systems engineering supports the development of socio-technical systems. However, the traditional systems engineering approach of reducing the system to component level to perform detailed designs and integrate them into a solution system may miss unexpected emergent behaviour when introducing a new technology into a socio-technical system. It may require changes in the socio-technical system's information flows, processes and procedures. Ignoring these emerging requirements may result in undesirable results or failures in the system. Cognitive work analysis, with work domain analysis in particular, provides a framework for analysing, modelling and designing socio-technical systems. The output abstraction hierarchy models were evaluated using a focus group approach for perceived utility in uncovering potential design emergence. The focus groups supported both the models and the proposed method. This structured approach will support requirements capturing and analysis for developing and engineering socio-technical systems.

Keywords: cognitive work analysis; CWA; systems engineering; requirements analysis; work domain analysis; WDA; emergence; socio-technical.

Reference to this paper should be made as follows: van den Heever, H. and Oosthuizen, R. (2024) 'Application of cognitive work analysis in support of systems engineering of a socio-technical system', *Int. J. Industrial and Systems Engineering*, Vol. 46, No. 1, pp.90–106.

Biographical notes: Henk van den Heever obtained his BEng in Comp. and Elect. from the North West University in 2008. In 2009, he joined SASOL Ltd., where he has been involved in the maintenance, engineering and governance of automation, process control and functional safety systems as part of the C&I fraternity. In 2015, he took up specialisation in functional safety. He completed a MEM at the University of Pretoria in 2022.

Rudolph Oosthuizen joined the South African Air Force in 1990, where he performed systems engineering roles in electronic warfare and command and control (C2). At the University of Pretoria, he obtained his BEng in Elec. in 1994, BEng (Honours) in Indus. in 1998, MEM in 2002 and PhD in Engineering Management in 2015. In 2008, he joined the CSIR as a Systems Engineer on multiple C2 projects. Since May 2020, he has been appointed as a Senior Lecturer at the Graduate School of Technology Management at

University of Pretoria, where he teaches Systems Engineering and Systems Thinking. Lately, his focus has been on data science and artificial intelligence for decision support and situation awareness. He is registered as a Professional Engineer with the ECSA and Certified Systems Engineering Professional (CSEP) with INCOSE.

This paper is a revised and expanded version of a paper entitled 'Application of cognitive work analysis in early phases of a complex system development project' presented at the 15th Systems Engineering Conference of INCOSE, South Africa, Pretoria, 15–16 September 2021.

1 Introduction

Systems engineering (SE) supports the successful development of complicated and complex systems that address user requirements and development objectives over a desired operating life (Kossiakoff et al., 2011). Therefore, systems are implemented to solve a problem or achieve goals. Stakeholder mental models, needs and requirements form the golden thread from beginning to end in a socio-technical system (STS) development project. Project success depends on capturing, transforming and refining these visions and needs (Ambrogio et al., 2022; Pretorius et al., 2019). The relationships between the originating requirements, the subsystems and the individual components need to be captured early, communicated thoroughly and revisited periodically (Madni, 2015). Also, developing a complex system requires a multidisciplinary team with a common understanding of the design and user requirements (Chen et al., 2021; Kossiakoff et al., 2011).

Incomplete requirements are a leading contributor to project failure. The causes include unrealistic expectations, changing requirements, poor user involvement and unclear objectives (Gupta et al., 2019; van Lamsweerde, 2000; Rosato, 2018). However, during the early stages of a project, design freedom is highest and diminishes with design decisions. Modern systems tend to be socio-technical in nature. In a STS, humans apply technology to perform work associated with processes within a social structure to realise system objectives. The STS has linear relationships as designed and nonlinear relationships due to the complex consequence of unforeseen interactions. Introducing a new technology typically results in additional task possibilities, the evolution of user requirements and emergent behaviour within STSs that result in unexpected, complex and counterintuitive consequences. Useful properties such as robustness, adaptability and flexibility may emerge (Amadi-Echendu and Thopil, 2020; Carroll and Rosson, 1992; Fromm, 2006). Therefore, capturing a comprehensive set of requirements early on is vital to achieving an STS that fully address stakeholder needs (Madni, 2015).

The traditional SE approach of decomposition and localised optimisation may hinder the successful development of STSs. SE is often applied to manage the inherent risk associated with technology introduction. However, STS theory aims to jointly optimise the social and technical elements. The ability to anticipate challenges to technology adoption is invaluable. Analysis and modelling of the problem and solution spaces lead to an improved understanding of system requirements (Read et al., 2018, 2015a; Shadrick et al., 2005). Cognitive work analysis (CWA) provides a formative framework to analyse cognitive work. Instead of being normative, CWA enables the analysis, modelling and design of STSs by exploring how these systems might reasonably function (Jenkins et al., 2008). The output model constructs aid in understanding STSs and informing requirements analysis and design (Naikar, 2011). This study aims to evaluate the benefits of supporting the SE process by applying CWA to requirement analysis in the early phases of system design for a human-machine interface (HMI).

2 Theory

2.1 Complex systems

A system can be loosely defined as any set of integrated components or elements that work together to accomplish a common objective (Walden et al., 2015). A system exhibits behaviour patterns and characteristics not observed exclusively in terms of its constituents' inherent abilities and behaviours. These emergent properties primarily drive systems development through the execution of projects (Kossiakoff et al., 2011). Complex systems are characterised by emergence, which occurs due to interactions between their constituent components and the environment resulting in behaviours at the system level that are difficult to predict, deduce and design (Fromm, 2006). System complexity may be described as the unexpected behaviour and nonlinear interactions of intricately intertwined system elements that exhibit even in simple systems due to dynamic context-dependent interactions (Oosthuizen and Pretorius, 2015; Ottino, 2004).

The term 'socio-technical' refers to people interacting with technology to perform work in the context of a 'social' organisational structure. Not considering potential changes to work practices caused by new technology may limit the possible efficiency and productivity improvements. Successful introduction of new technology requires joint optimisation of the social and technical systems to fulfil the purpose of the shared system (Baxter and Sommerville, 2011; Trist, 1981).

A 'cognitive system' can plan and modify its action based on knowledge about itself and the environment through self-organisation. Often an STS performing cognitive work is viewed as a cognitive system. Nonlinear interaction within a cognitive system cause emergence of new cognitive states due to the functional layout of human-to-human and human-to-artefact interactions within the environment. However, introducing new technology results in an emergence of affordances and constraints to the work domain, some of which are unexpected and unpredictable. Therefore, designs for human work should focus on the functional work structure (Carroll and Rosson, 1992; Read et al., 2015b).

2.2 Systems engineering

As the technocentric development of STSs often involves the piecewise introduction of new technology, the impact on the total STS should not be neglected. However, modelling and analysis of the elements of the problem and solution spaces as part of the SE approach should support the development of STSs (Oosthuizen and Pretorius, 2016). SE is a systematic and iterative process to design and utilise a system to address user requirements. The typical SE process reduces the problem as a whole through analysis to achieve the lowest level of decomposition, at which design and localised optimisation are performed (Walden et al., 2015). According to Walden et al. (2015), the traditional SE process establishes a full set of clear user requirements at the start of the project. For a successful project, the requirements have to encapsulate the combined mental image of the stakeholders (Pretorius et al., 2019).

Human systems integration (HSI) includes the interdisciplinary technical and management process for integrating humans into a system (Shamsuzzoha et al., 2020; Walden et al., 2015). HSI supports introducing new automation technology into existing STSs. Studies have shown that early HSI-related design commitments may account for as much as 60% of systems' lifecycle costs, most of which are irreversible beyond the early phases of development. Therefore, object analysis early during the requirements development process informs better user interface designs (Bennett et al., 2018; Hardman and Colombi, 2012).

However, traditional SE processes often struggle with the design and integration of STSs due to unpredictable and dynamic behaviour and the unintended consequences of new technology introduction. Not considering the cognitive style and behavioural constraints affecting operators and failing to develop and apply appropriate methods to support SE negatively affects projects (Sage and Rouse, 1999). Salmon et al. (2016) suggest that systems thinking approaches such as CWA provide suitable methods for developing safe and efficient systems.

The CWA framework develops constructs or models of the work demand and constraints on actors (Naikar, 2011). The constraints shape operator behaviour. Therefore, as a systems-based approach, CWA analyses how social humans perform under constraints within the greater environment (Read et al., 2015b). STSs tend to be open and exposed to unforeseeable events that threaten their effectiveness; therefore, designs also need to support operator adaptation. However, design should not prescribe the work but provide decision support that promotes problem-solving. While traditional engineering approaches seek complete design descriptions, CWA draws on the utility of emergence in cognitive systems and specifically refrains from such complete descriptions (Naikar, 2011, 2017). CWA models help evolve user requirements and complement the iterative approaches of SE (Jenkins et al., 2008).

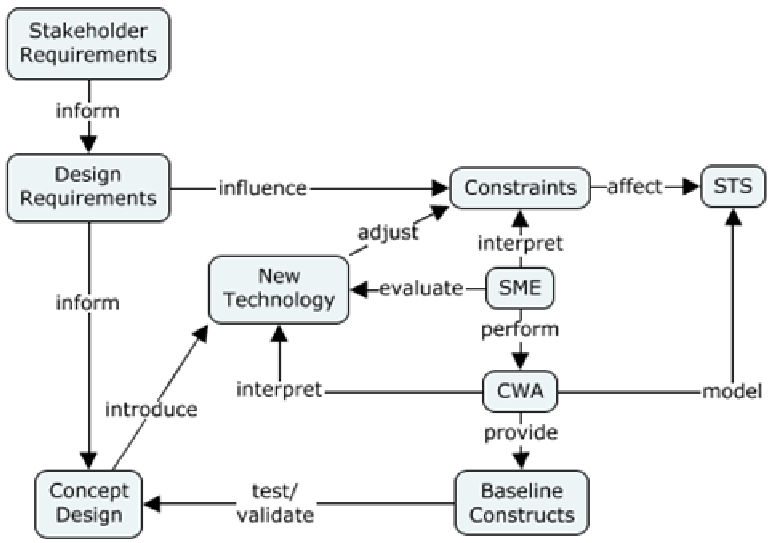
3 Conceptual method

Naikar (2017) posits that CWA is ideal for improving and validating HMI designs. This includes introducing new technology into existing STSs. Birrell et al. (2012) also demonstrated how CWA identifies relationships between casual domain functions and objects, predicts their mutual influences, and makes explicit connections and influences. As such, the resultant models provide a suitable gauge as to whether a particular design will fulfil the intended functional purposes.

The conceptual framework for this research study is presented in Figure 1. The successful introduction of systems and new technology into STSs is generally managed through SE processes. Therein, stakeholder requirements inform the development of design requirements and design concepts.

Introducing new technology into STSs results in changes to the constraints of the work domain and ultimately leads to new and sometimes unexpected affordances (Carroll and Rosson, 1992) due to self-organisational linked emergence. Therefore, design needs to focus on providing goal-oriented constraints that will emerge robust and effective workways (Read et al., 2018, 2015a). For this research, CWA was identified as an appropriate method for modelling STSs since it focuses on analysing constraints that shape behaviour. Assessing the influences of design requirements on the STS constraints benefits from the involvement of expert practitioners (Jamieson, 2003; Lundberg and Johansson, 2021).

Figure 1 Conceptual framework (see online version for colours)

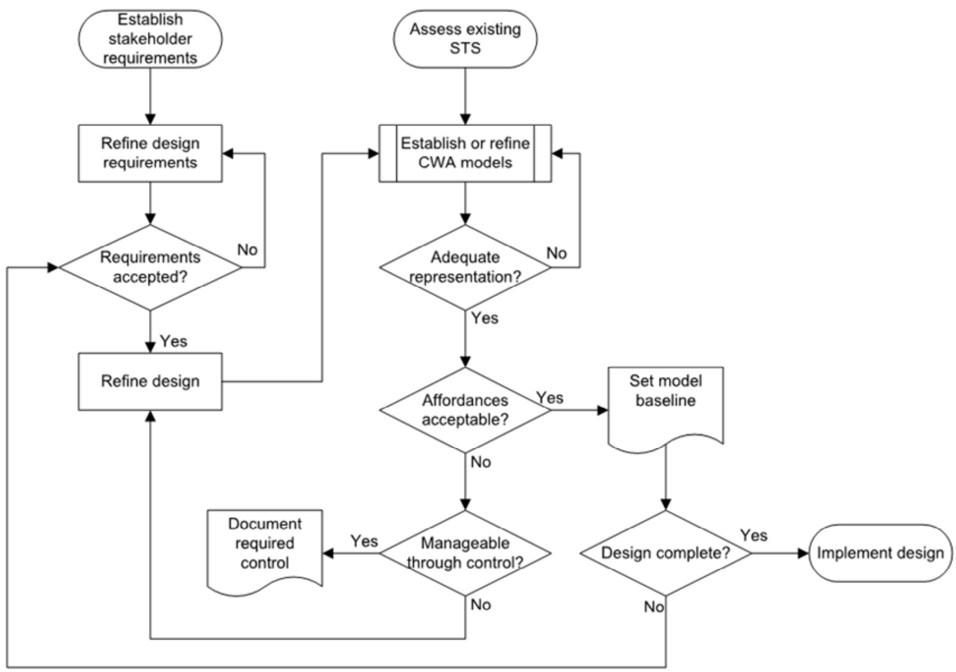


This research proposes the validation workflow in Figure 2 as a means of supplementing the SE process for the introduction of new technology into an existing STS. The workflow proposes concurrent analyses of both the new technology addition and the existing STS. The proposition is that in-process validation using baseline models of the STS will identify changes to constraints brought on by proposed designs. It enables identifying and evaluating potential emergence. The aim is to manage the effects of affordances (risks) and reject design propositions that may lead to unacceptable affordances (hazards). It is an iterative process during which the baseline models are incrementally updated to incorporate approved designs. The workflow is intended to support SE practices and not replace any. As such, and for the simplicity of the diagram, certain implied links are not explicitly shown.

The first step is to capture stakeholder requirements, which at its core intends to introduce new technology into an existing STS or to establish a new STS (which, by its definition, also contains technology). Requirements engineering then decomposes, normalises, and codifies requirements as input to the design process. Requirement acceptance is intended to assess whether all known requirements and/or stakeholder inputs have been refined into the design process. This is part of a generic systems lifecycle where the concept stage may consist of several shorter steps with associated feedback and iteration in a typical stage-gate environment. Refinement of the design transform documented requirements (specification) into deliverables.

In parallel to the stakeholder requirements capture and analysis, information about the STS under design is gathered to establish or update the CWA model. The starting point is to establish the first CWA model(s). Subsequent iterations will assess whether any significant changes in the STS have taken place since the last cycle (e.g., modification brought on by independent projects). Establishing or refining the CWA models signifies the actual modelling process. Here, the work domain analysis (WDA) models the implication of new technology on the STS. Depending on the lifecycle stage and the maturity of the design, it may be beneficial to apply other methodologies from the CWA framework. The proposed design details are modelled onto the baseline CWA models, and the implication is explored. The latter being the process of affordance identification.

Figure 2 Proposed iterative validation workflow



A sanity check determines if the models are an adequate representation. The modelling team must verify facts about the proposed design against the model to ensure that nothing is outstanding before an affordance assessment is undertaken. It was included on recommendation of the focus group. The STS stakeholders need to consider if the affordances highlighted in the CWA models are acceptable. It primarily involves risk management processes. This step should not be undertaken in isolation but form part of established business or project risk management practices. The risk management process informs whether an affordance can be managed through control.

If at this stage, the risk posed by an affordance is perceived as too high for management through control, the affordance is rejected. In this case, the design needs to be revisited. If no new affordances were identified, and all affordances were deemed free of significant risk, the model(s) last modified are confirmed as the current baseline. The final test is intended to signify the stage-gate test for the end of the concept stage by accepting the completeness of the design. However, it may represent any of the project gates as the research has identified possible applications beyond the said stage. The baseline model(s) for physical requirement determination and detailed engineering processes are used to implement the design.

4 Research method

The design science paradigm seeks to devise creative new ideas, practices, and technical capabilities to support analysis, design, implementation, management and use. Design science research (DSR) is a framework for understanding, executing and evaluating research. The research in this paper implemented the three-cycle DSR model as proposed by Hevner (2007) to demonstrate relevance and rigour. Action research, document analysis and case studies are examples of methods that support triangulation in DSR (Easterby-Smith et al., 2021). This study applies triangulation through literature surveys, case studies, and focus group research to support validity.

Literature surveying of extant research was applied to account for collated information from primary and secondary observations of conceptualised models and frameworks. Although predominantly deductive, a literature review may employ inductive reasoning to conceive new theories (Scandura and Williams, 2000), such as the validation workflow proposed in this study. Case study research involves the field implementation and demonstration of methods. It provides a useful method for determining how an artefact performs in a real-life setting where control over events and the behaviour of elements are limited (Oosthuizen and Pretorius, 2016). In this research study, literature and the researcher's experience are applied to construct initial WDA models for introducing new technology into an HMI in an existing STS to enable expert judgement of the validity. The resultant models aided in evaluating the proposed framework through discussion in both individual interviews and the focus group.

A qualitative interview can be described as a directed conversation soliciting answers about a given topic through predetermined questions (Easterby-Smith et al., 2021). Qualitative interviews were employed as part of case study research to elicit expert opinions about the make-up of the work domain within an existing STS and in the form of a focus group discussion. Focus group discussions aimed to evaluate the effectiveness and efficiency of the proposed validation framework. Tremblay et al. (2010) presented the use of exploratory focus group (EFG) and confirmatory focus group (CFG) concepts in support of design science. Since DSR seeks to improve an artefact's design and verify its utility incrementally, both exploration and confirmation are required.

During this case study, models were incrementally revised to reflect the state of the constraints on the STS and the potential influence of new technology thereon. This accounts for exploration. Evaluation of the framework's utility provides for the required confirmation. Since the artefact is predominantly a decision support tool, Tremblay et al. (2010) suggest that experts with mixed skills be intentionally selected. A group of five subject matter experts (SMEs) with diverse knowledge (operations, project execution, HMI design) and experience (range 6 to 18 years) were approached.

This research study used template analysis to organise and interpret data (Easterby-Smith et al., 2021). Codes for the preliminary template may be determined through a review of literature, informal and anecdotal evidence, exploratory research, or experience. The template is refined by revision between exploration sessions, with the final template used to code confirmation sessions. Transcripts from qualitative interviews were analysed to verify elements of the work domain and their relationships. Elements of exploration and confirmation were applied to evaluate the utility of CWA as a validation tool in aid of SE. The utility of the artefacts was demonstrated as the impact of new technology on successive models of the STS was detected.

5 Results

5.1 Pre-technology assessment

WDA is employed to represent both the work domain's inherent and implied constraints. Work domain analyses were conducted to produce an abstraction hierarchy (AH) of a test case HMI based on the five levels of abstraction (i.e., domain purpose, domain values, general functions, physical functions and objects). In this way, the WDA allow analysts to consider a system at different levels of abstraction. Means-end links between the constituents allow for consideration of how the levels are connected and interact (Birrell et al., 2012). The initial AH of a typical HMI was drafted from literature and operational experience.

This AH was presented to the five engineers independently for discussion, verification and enhancement. However, none of the engineers had prior knowledge of CWA or the STS concept. A short introduction was provided at the onset of the interviews. Statements recorded during the individual interviews that were perceived to either directly or indirectly question the content of the AH model was coded as 'challenge model'. Twenty-four such statements were coded, mostly based on inexperience in CWA, misconception and opinion. Only nine valid challenges were isolated and applied to refine the AH. All subsequent challenges recorded during the focus group were refuted. Figure 3 provides a visual breakdown of the nature of the challenges the model received.

Figure 3 Distribution of challenges to the existing STS models (see online version for colours)

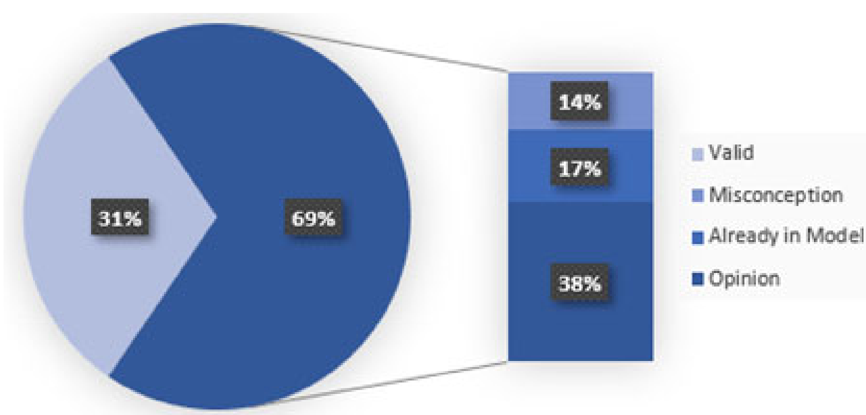


Figure 4 AH for STS before new technology introduction (see online version for colours)

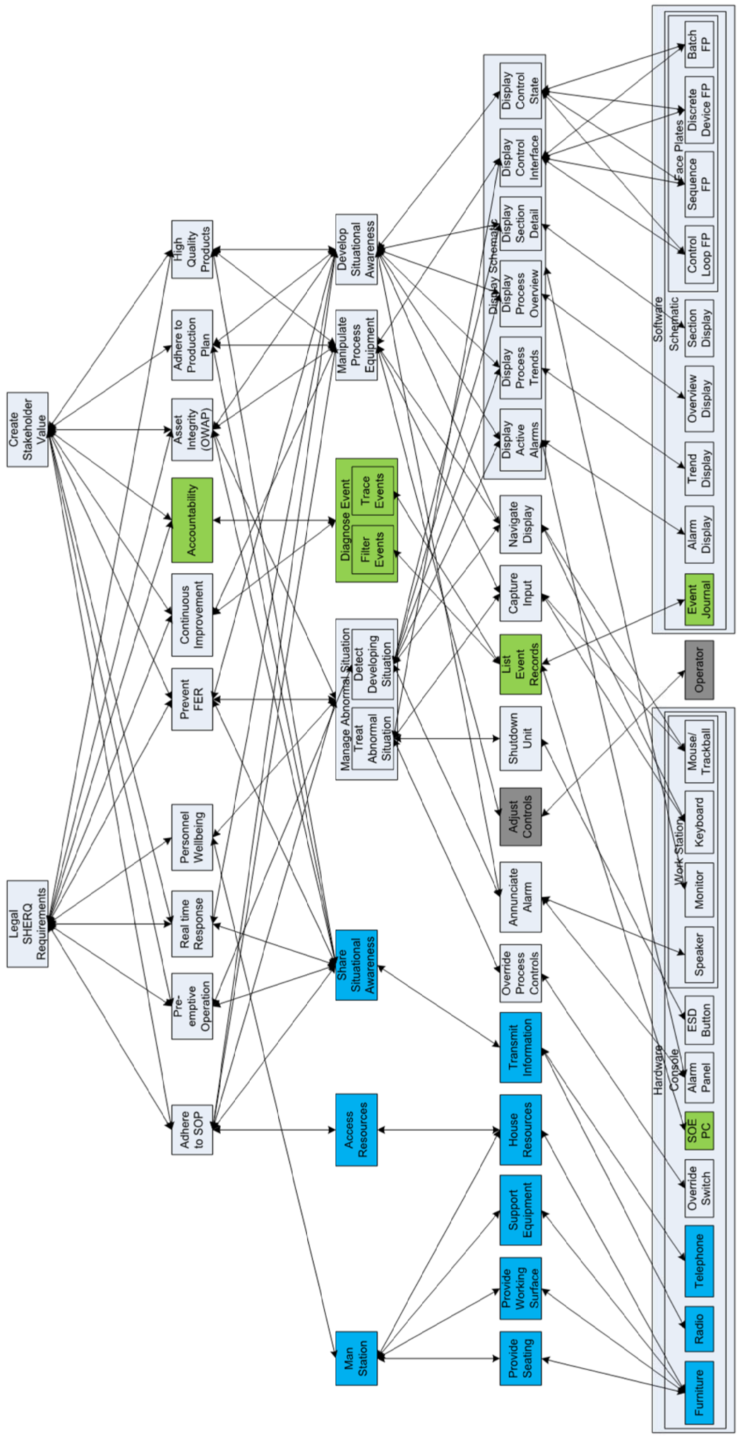
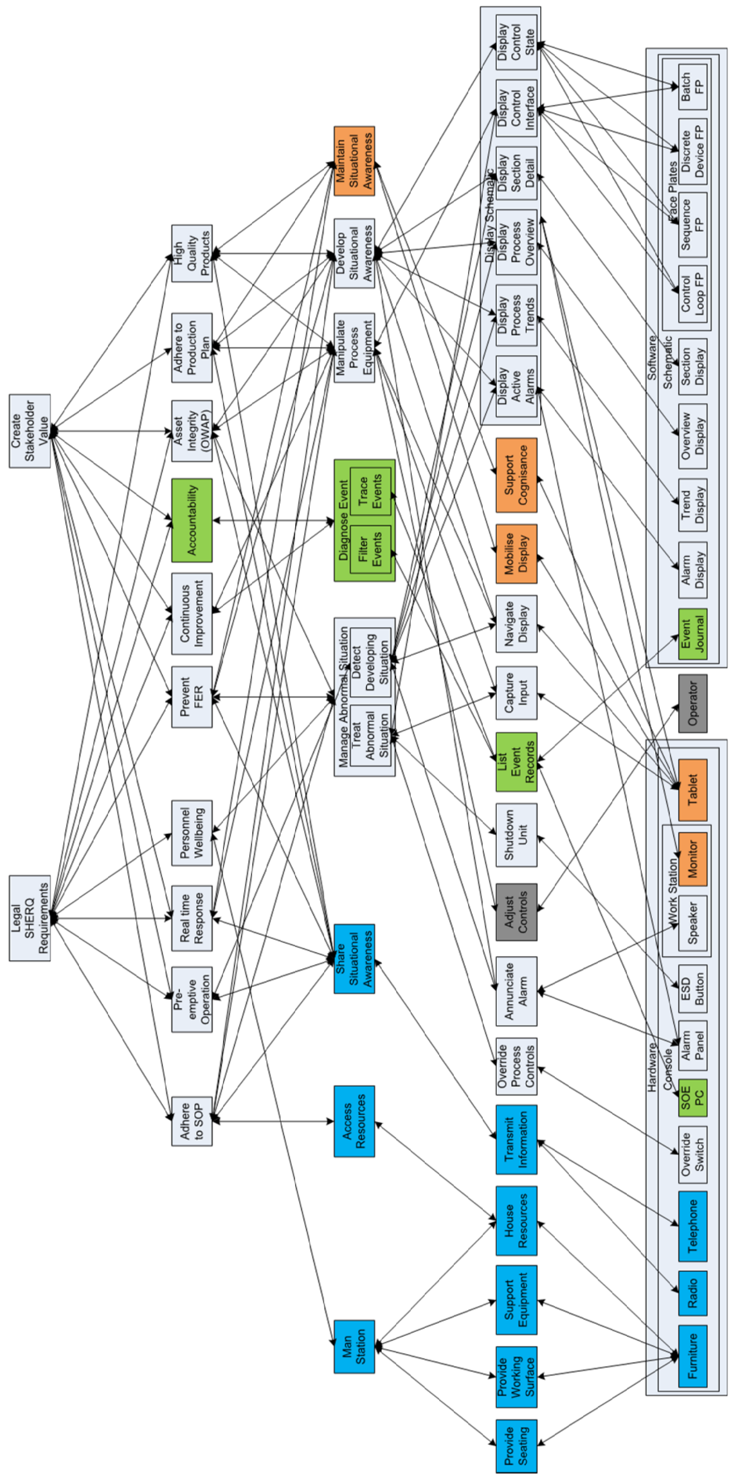


Figure 5 AH with identified affordances (see online version for colours)



During data analysis, codes emerged for the confirmation of proposed objects ('confirm object') and links ('confirm link') in the model and for the model in general ('support model'). A total of 63 such statements were coded. The ratio of confirmation statements to valid challenges was 7:1 or 87.5%. Given that the initial AH was refined with SME inputs and that no subsequent challenges held merit, it can be argued that the resultant baseline models, e.g., Figure 4, are reasonable representations of the STS. This claim is further supported by the following quote from the focus group discussions:

> "We can argue that it is complete because of the interviews you've had with experts in this field…all of them have provided comments and suggestions as to what they think could be improved, and as comments have been incorporated into the model presented to us now, from my point of view, it is a sufficient model."

The claim extends beyond the initial baseline since the proposed technology introduction does not impact the AH structure. The steps described above represent the assessment of the existing STS, the establishment of the relevant CWA model(s), the initial affordance assessment, and the initial baselining per the proposed workflow in Figure 2.

5.2 Proposed technology introduction

At this point, the AH model was altered to reflect the proposed new technology introduction, which includes the replacement of the traditional keyboard and mouse interface with a tablet computer, unto which graphic displays may also be ported. The altered model was presented to the focus group to achieve consensus on the content, identify and assess affordances brought on by the proposed change, and explore the viability of the proposed workflow. The baseline model underwent six cycles of scrutinisation, none of which identified any physical objects or technical functions supporting a general functional requirement to 'maintain situational awareness'. Using the altered model, the focus group identified two opportunities afforded by the tablet hardware. The two technical functions 'mobilise display' and 'support cognisance' result from the presence of the physical object 'tablet'. Display mobility stems from graphics portability, while new granular analogue adjustments support operator cognisance (Figure 5).

In part, the focus group sought to understand, refine and approve the initial stakeholder requirements, establish a conceptual design, and assess the impact thereof on the STS through concurrent modelling of the existing and the proposed components. Beyond the benefit presented above, affordances such as the unwanted ability to misuse the reception capabilities of the television monitors and the connective nature of the tablets were identified. These were not modelled on the resultant AH as appropriate controls could be defined. Given that the project's onset was analysed and the controls still required engineering, the design cannot be complete. As such, one full iteration of the proposed validation workflow was simulated.

6 Discussion

6.1 Proposition 1 – modelling techniques aid the design of STSs

The initial literature review established that requirements analysis is key to successfully establishing STSs. Data from the focus group contained fifty statements supporting the utility of the proposed workflow, of which 58% relate to the method's ability to support requirements analysis; this category overshadowed all others. Statements supporting WDA as an appropriate STS modelling technique were also recorded during the individual interview process. The distribution of code analysis is presented in Figure 6. It can thus be argued that SMEs perceive modelling and, in particular CWA, as beneficial to the design of STSs.

Figure 6 Distribution of individual support for WDA utility (see online version for colours)

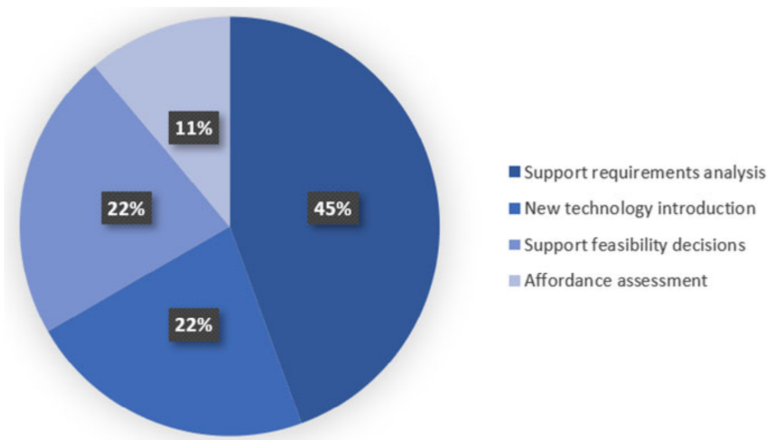
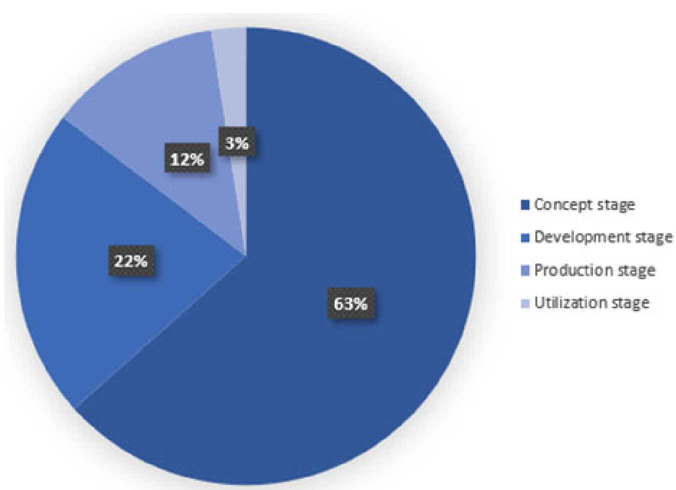


Figure 7 Distribution across the SE lifecycle (see online version for colours)

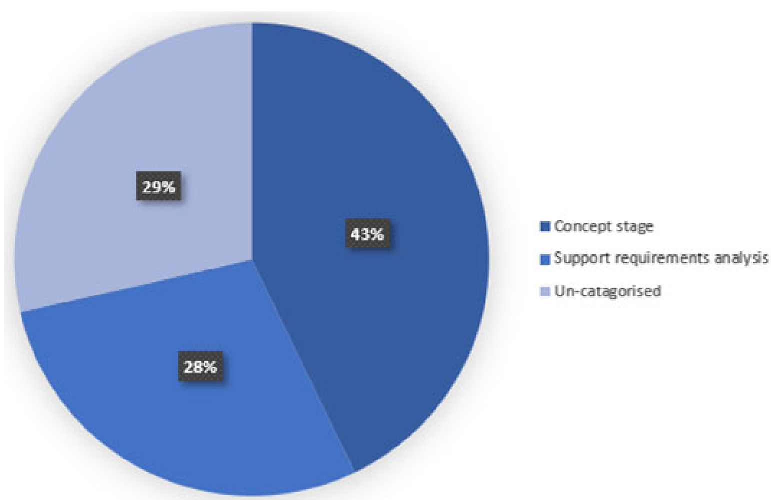


The situated cognition and self-organising nature of STSs result in the development of cognitive processes and procedures, which become effective and robust over time. These get challenged when new technologies are introduced and may lead to disruptions or even the inability of functional performance (Read et al., 2015a; Shadrick et al., 2005). As such, a comprehensive set of requirements must be established as early in a project as possible since it is at the onset that design freedom is at its highest and then diminishes as design decisions are made (Madni, 2015). From the above literature, it can be seen that early impact upon design requirements is most beneficial. Thirty-five responses related to applying the proposed workflow were coded from the focus group, as seen in Figure 7. Of these, 63% supported using the workflow during the concept stage and a further 22% toward support of the development stage. It can be argued that SME opinion supports the proposed modelling methodology.

6.2 Proposition 2 – application of CWA promotes the success of HMI projects

The ability of a system to attain the utility sought is a measure of the quality of the products and the success of the project that acquired it (McManus and Wood-Harper, 2007). Thus, requirement elicitation and analysis are vital to project success (Rosato, 2018). CWA is used to analyse cognitive work, as performed by an operator on an HMI, to inform the design of such systems. By its nature, CWA is formative and seeks to understand how an STS might reasonably function (Jenkins et al., 2008). CWA provides a framework for the analysis, modelling, and design of STSs. The resultant models capture the structure of the problem space and how the technology present functionally achieves system requirements. The CWA constructs aid in understanding STSs and inform design and requirements analysis (Naikar, 2011). The focus group discussion coded for improved project success contains 43% statements related to the application in the concept stage and 28% to applications supporting requirements analysis, as seen in Figure 8. Therefore, applying CWA for the design of HMIs is likely to promote success.

Figure 8 Distribution of perceived areas of project improvements (see online version for colours)



The need to consider technological, organisational and human factors throughout the stages of the SE lifecycle is a burden on SE professionals. A key component toward improving the outcome of SE projects is a proper understanding of the problem to be solved. An improved understanding of system requirements may be achieved through analysis and modelling of both the problem and solution spaces (Oosthuizen and Pretorius, 2016). The application of the proposed workflow during the research design implementation saw the creation of CWA models for both the problem (existing STS) and solution (new technology introduction) spaces. This led to an improved understanding of system requirements. Not only at the micro-level but also at the macro level, as is evident from the flowing revelations by participants:

> "Without having implemented a system like that before, the user can very quickly see what changes that system will bring to a traditional HMI project. And also helping prepare for those changes."

> "It will be easier to establish what or how the physical hardware gives the goals set out in the function, the top layer, and in doing so ensure that the projects executed successfully."

SE may be aided by modelling that assists in exploring the operational, functional and structural elements of the problem and solution. The quality and relevance of the toolset consist in part of its ability to identify hazards to both systems and projects alike. It is also a function of expertise and rigour during application. Systems thinking approaches such as CWA provide methods for developing safe and efficient systems (Hardman and Colombi, 2012; Salmon et al., 2016).

The reduced number of challenges recorded between the interview process and the focus group discussions shows how the proposed method's iterative nature leads to higher quality models as more discrepancies are detected and addressed. Furthermore, the affordance identification and assessment actions resulted in identifying previously unforeseen advantages and hazards that may otherwise have gone undetected and could subsequently be managed or exploited. This further supports the proposition that CWA is likely to improve the outcome of HMI projects.

7 Conclusions

Introducing new technology into an STS brings about additional task possibilities and may result in emergent behaviour. The classical SE approach of reduction, localised optimisation and synthesis seem inept at efficient and effective engineering of such systems. Dire consequences may result if due consideration is not given to this emergence a priori (Read et al., 2018, 2015b). Correcting HSI problems after the fact tends to be very expensive. Walden et al. (2015) show that roughly 70% of total project costs are committed by the end of the concept stage for modern STS projects. Also, HSI-related design costs account for as much as 60% of total project costs, which are mostly irreversible beyond the initial stages. User and systems requirements identified early in the SE process have a limited disruptive impact on project performance and success. These expenses can be avoided if HSI is considered earlier in the SE process (Read et al., 2015a). Requirement elicitation and analysis, as part of the SE process, thus play a vital role in project success (Rosato, 2018).

This research study evaluated the benefit of applying CWA modelling to support SE in developing complex STSs. An artefact was conceived to support SE professionals using CWA modelling in the early lifecycle phases. Rigour was achieved in the research process by demonstrating and evaluating the proposed artefact. The impact of new technology introduction on an existing STS was modelled and served to simulate the application of the artefact. A focus group was employed as part of the methodology to demonstrate the case through simulation. The group further acted to interpret input documents and resultant models and judge the utility of the proposed artefact.

The initial AH models were improved and verified by SMEs who supported both the models and the proposed method. This shows that the artefact may find real-world applications. The method's success may be influenced by the level of expertise and the number of minds involved. This supports the notion that quality models are only achievable through an iterative process involving both modelling and domain expertise (Jamieson, 2003).

In this research study, the application of the CWA framework was limited to WDA. Other modelling techniques from the CWA framework may be explored to aid requirements analysis. Although the single iteration simulated by this research study was limited to the concept phase, the focus group identified several additional application possibilities for AH models in support of the SE lifecycle. It is recommended that future research test the benefits of applying other CWA techniques as the focus of the research artefact so that parallels may be drawn. Furthermore, it is proposed that future research explore the benefits of applying the proposed method beyond just the concept phase of the SE lifecycle.

References

Amadi-Echendu, J. and Thopil, G.A. (2020) 'Resilience is paramount for managing socio-technological systems during and post-Covid-19', *IEEE Engineering Management Review*, IEEE, Vol. 48, No. 3, pp.118–128.

Ambrogio, G., Filice, L., Longo, F. and Padovano, A. (2022) 'Workforce and supply chain disruption as a digital and technological innovation opportunity for resilient manufacturing systems in the COVID-19 pandemic', *Computers & Industrial Engineering*, Vol. 169, p.108158, Elsevier.

Baxter, G. and Sommerville, I. (2011) 'Socio-technical systems: from design methods to systems engineering', *Interacting with Computers*, Vol. 23, No. 1, pp.4–17, OUP.

Bennett, K.B., Bryant, A. and Sushereba, C. (2018) 'Ecological interface design for computer network defense', *Human Factors*, Vol. 60, No. 5, pp.610–625, SAGE Publications Sage CA, Los Angeles, CA.

Birrell, S.A., Young, M.S., Jenkins, D.P. and Stanton, N.A. (2012) 'Cognitive work analysis for safe and efficient driving', *Theoretical Issues in Ergonomics Science*, Vol. 13, No. 4, pp.430–449, Taylor & Francis.

Carroll, J.M. and Rosson, M.B. (1992) 'Getting around the task-artifact cycle: how to make claims and design by scenario', *ACM Transactions on Information Systems (TOIS)*, Vol. 10, No. 2, pp.181–212, ACM, New York, NY, USA.

Chen, C., Ma, N. and Song, Y. (2021) 'Single commercial aircraft system value evaluation method based on requirements engineering and value driven design in a commercial aircraft preliminary design stage', *International Journal of Industrial and Systems Engineering*, Vol. 38, No. 1, pp.84–106, Inderscience Publishers (IEL).

Easterby-Smith, M., Jaspersen, L.J., Thorpe, R. and Valizade, D. (2021) *Management and Business Research*, Sage, Los Angeles, CA.

Fromm, J. (2006) *On Engineering and Emergence*, ArXiv preprint Nlin/0601002.

Gupta, V., Kapur, P.K., Kumar, D. and Singh, S.P. (2019) 'Analytical evaluation of agile success factors influencing quality in banking sector', *International Journal of Industrial and Systems Engineering*, Vol. 33, No. 3, pp.346–373, Inderscience Publishers (IEL).

Hardman, N. and Colombi, J. (2012) 'An empirical methodology for human integration in the SE technical processes', *Systems Engineering*, Vol. 15, No. 2, pp.172–190, Wiley Online Library.

Hevner, A.R. (2007) 'A three cycle view of design science research', *Scandinavian Journal of Information Systems*, Vol. 19, No. 2, p.4.

Jamieson, G.A. (2003) 'Bridging the gap between cognitive work analysis and ecological interface design', *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, SAGE Publications Sage CA, Los Angeles, CA, Vol. 47, pp.273–277.

Jenkins, D.P., Stanton, N.A., Walker, G.H., Salmon, P.M. and Young, M.S. (2008) 'Applying cognitive work analysis to the design of rapidly reconfigurable interfaces in complex networks', *Theoretical Issues in Ergonomics Science*, Vol. 9, No. 4, pp.273–295, Taylor & Francis.

Kossiakoff, A., Sweet, W.N., Seymour, S.J. and Biemer, S.M. (2011) *Systems Engineering Principles and Practice*, Vol. 83, John Wiley & Sons, Hoboken, New Jersey.

Lundberg, J. and Johansson, B.J.E. (2021) 'A framework for describing interaction between human operators and autonomous, automated, and manual control systems', *Cognition, Technology & Work*, Vol. 23, No. 3, pp.381–401, Springer.

Madni, A.M. (2015) 'Expanding stakeholder participation in upfront system engineering through storytelling in virtual worlds', *Systems Engineering*, Vol. 18, No. 1, pp.16–27, Wiley Online Library.

McManus, J. and Wood-Harper, T. (2007) 'Understanding the sources of information systems project failure', *Management Services*, Vol. 51, No. 3, pp.38–43.

Naikar, N. (2011) *Cognitive Work Analysis: Foundations, Extensions, and Challenges*, Defence Science and Technology Organisation Edinburgh (Australia) Air, Air Operations Division DSTO Defence Science and Technology Organisation, 506 Lorimer St, Fishermans Bend, Victoria 3207 Australia, DSTO-GD-0680, November

Naikar, N. (2017) 'Cognitive work analysis: an influential legacy extending beyond human factors and engineering', *Applied Ergonomics*, Vol. 59, pp.528–540, Elsevier.

Oosthuizen, R. and Pretorius, L. (2015) 'System dynamics modelling of situation awareness', *2015 Military Communications and Information Systems Conference (MilCIS)*, IEEE, pp.1–6.

Oosthuizen, R. and Pretorius, L. (2016) 'Assessing the impact of new technology on complex sociotechnical systems', *South African Journal of Industrial Engineering*, Vol. 27, No. 2, pp.15–29, South African Institute of Industrial Engineers (SAIIE).

Ottino, J.M. (2004) 'Engineering complex systems', *Nature*, Vol. 427, No. 6973, p.399, Nature Publishing Group.

Pretorius, L., Benade, S. and Scribante, N.P. (2019) 'The design of a research tool for conducting research in a complex socio-technical system', *South African Journal of Industrial Engineering*, Vol. 30, No. 4, pp.143–155, South African Institute of Industrial Engineers (SAIIE).

Read, G.J.M., Salmon, P.M. and Lenné, M.G. (2015a) 'Cognitive work analysis and design: current practice and future practitioner requirements', *Theoretical Issues in Ergonomics Science*, Vol. 16, No. 2, pp.154–173, Taylor & Francis.

Read, G.J.M., Salmon, P.M., Lenné, M.G. and Stanton, N.A. (2015b) 'Designing sociotechnical systems with cognitive work analysis: putting theory back into practice', *Ergonomics*, Vol. 58, No. 5, pp.822–851, Taylor & Francis.

Read, G.J.M., Salmon, P.M., Goode, N. and Lenné, M.G. (2018) 'A sociotechnical design toolkit for bridging the gap between systems-based analyses and system design', *Human Factors and Ergonomics in Manufacturing & Service Industries*, Vol. 28, No. 6, pp.327–341, Wiley Online Library.

Rosato, M. (2018) 'Go small for project success', *PMWJ*, Vol. 7, No. 5, pp.1–10.

Sage, A.P. and Rouse, W.B. (1999) 'An introduction to systems engineering and systems management', *Handbook of Systems Engineering and Management*, Vol. 2, John Wiley & Sons, Inc., New York.

Salmon, P.M., Lenné, M.G., Read, G.J.M., Mulvihill, C.M., Cornelissen, M., Walker, G.H., Young, K.L. et al. (2016) 'More than meets the eye: using cognitive work analysis to identify design requirements for future rail level crossing systems', *Applied Ergonomics*, Vol. 53, Part B, pp.312–322, Elsevier.

Scandura, T.A. and Williams, E.A. (2000) 'Research methodology in management: current practices, trends, and implications for future research', *Academy of Management Journal*, Vol. 43, No. 6, pp.1248–1264, Academy of Management, Briarcliff Manor, NY 10510.

Shadrick, S.B., Lussier, J.W. and Hinkle, R. (2005) *Concept Development for Future Domains: A New Method of Knowledge Elicitation*, Army Research Inst. Field Unit, Fort Knoxky.

Shamsuzzoha, A., Helo, P., Piya, S. and Alkahtani, M. (2020) 'Modular product architecture to manage product development complexity', *International Journal of Industrial and Systems Engineering*, Vol. 36, No. 2, pp.225–247, Inderscience Publishers (IEL).

Tremblay, M.C., Hevner, A.R. and Berndt, D.J. (2010) 'Focus groups for artifact refinement and evaluation in design research', *Communications of the Association for Information Systems*, Vol. 26, No. 1, p.27.

Trist, E.L. (1981) *The Evolution of Socio-Technical Systems*, Vol. 2, Ontario Quality of Working Life Centre, Toronto.

van Lamsweerde, A. (2000) 'Requirements engineering in the year 00: a research perspective', *Proceedings of the 22nd International Conference on Software Engineering*, pp.5–19.

Walden, D.D., Roedler, G.J., Forsberg, K., Hamelin, R.D. and Shortell, T.M. (2015) *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, John Wiley & Sons, Hoboken, New Jersey.