AN INVESTIGATION OF THE ROLE OF A WORK ANALYSIS IN THE DESIGN OF AUTOMATION IN RAILWAY SYSTEMS

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ABSTRACT

The past decades has seen automation rapidly increasing in the railway industry, with the "perceived" motivations of faster services, economy, safety, and energy efficiency. However these motivations often obscures the fact that automation also create new burdens and complexities for the operators and maintainers (Bainbridge, 1983; Woods, 1996). Joint Cognitive Systems (JCS) (Woods & Hollnagel, 2006) was derived to address the challenges faced with complex systems.

Several studies have shown the benefits of applying JCS thinking in various industries (Boy & Schmitt, 2013; Effken, Kim, & Shaw, 1997; Hall, Shattuck, & Bennett, 2012; Militello, Dominguez, Lintern, & Klein, 2009), and it is therefore of interested to investigate the practicalities of applying JCS theory in the railway industry.

Underpinning the JCS approach, is the need to study and analyse the work domain (i.e. the field of practice) to provide a functional description of the objectives, goals, and constraints of a work domain that can be used to define the work strategies and associated cognitive and collaborative challenges.

This thesis investigates what the role of a work analysis is within the context of JCS design. Two qualitative case studies were undertaken to investigate the role of a work analysis for the design of automation in railway systems. Although the results highlighted that understanding 'work as done' is critical to the design of a JCS, there were also various deficiencies, challenges and inconsistencies identified with using the outcomes of the work analysis that could hinder the success of a JCS.

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INTRODUCTION

A railway network is a complex socio-technical system that is sensitive to change, particularly to the introduction of automation (Wilson & Norris, 2005). One problem is that railway systems have been around for hundreds of years - wayside signalling dates back as far as 1832 and the first Regulation of Railways Act was introduced in the United Kingdom in 1889. Railway systems are often deeply rooted with long standing legacy infrastructure, multiple stakeholders and deeply embedded working practices (Wilson & Norris, 2005). Introducing change in this environment is a challenge at the best of times. Making wholesale changes to work practices, which are required to introduce automation, is a difficult situation.

The past decades have seen automation rapidly increasing in the railway industry, with the "perceived" motivations of faster services, economy, safety, and energy efficiency. However these motivations often obscures the fact that automation also create new burdens and complexities for the operators and maintainers (Bainbridge, 1983; Woods, 1996).

Joint Cognitive Systems (JCS) (Woods & Hollnagel, 2006) was derived to address the challenges faced with complex systems. The benefits of applying JCS thinking to complex systems has been demonstrated in various industries (Boy & Schmitt, 2013; Effken et al., 1997; Hall et al., 2012; Militello et al., 2009), and it is therefore of interested to investigate the practicalities of applying JCS theory in the railway industry.

In the railway industry, safety-related railway products and applications are developed and certified in accordance with the European CENELEC standards EN50126 (1999); EN50128 (2011); EN50129 (2003). These standards considers human factors using a micro-ergonomic view – a bottom-up view – where goals and objectives are decomposed into functions and then further down to tasks to be allocated to the human and machine agents. This is a by-product of the technology-centred approaches being applied.

For complex systems a macro-ergonomic view – a top-down view – is required (Challenger, Clegg, & Shepherd, 2013; Leveson, 2004) as complex systems cannot be fully decomposed into components. JCS overcomes the deficiency of a technology-centred approaches in that it defines the system relative to its goals and objectives within a larger work or problem space (i.e., ecology; a macro-view), rather than relative to its structures (i.e., human and machine; a micro-view).

Both CENELEC standards and JCS require designs to guard against or tolerate human error. JCS differs slightly by focusing on the ability for the human and technology to coordinate through considering observability and directability rather than tracing failure to human error which is ineffective (Christoffersen & Woods, 2002).

JCS achieves this by requiring the creation of a work environment that makes the boundaries to failure visible and reversible, and that supports the operator when unfamiliar and unanticipated events occur. Unanticipated events are, by definition, situations that were not foreseen by designers. Therefore, systems are not designed to deal with their occurrence and the operator has to engage in solving the problem using knowledge (Rasmussen, 1999; Vicente, 1999). The operator needs to be able to reason about the state and functioning of the process and other agents (be it human or technology). The JCS approach addresses these issues by allowing the operator to acquire relevant information in order to solve the problems faced and decide the best course of action to take to divert or rectify the situation (Amelink, 2010). The laws that govern JCSs at work in essence are summarised as: adaptability, common models, collaboration, responsibility, and balance tradeoffs and dilemmas (i.e. how to create success in a distributed environment) (Woods & Hollnagel, 2006).

Underpinning the JCS approach, is the need to study and analyse the work domain (i.e. the field of practice) to provide a functional synthesis (i.e. an abstraction) of the objectives, goals, and constraints of a work domain that can be used to define the work strategies and associated cognitive and collaborative challenges.

This thesis investigates what the role of a work analysis is within the context of JCS design. Although the study highlights that understanding 'work as done' is critical to the design of JCS, there are also various deficiencies, challenges and inconsistencies associated with using the outcomes of the work analysis that could hinder the success of a JCS.

THEORETICAL FRAMEWORK

Background Theory

Joint Cognitive Systems Theory

Joint Cognitive Systems (JCS) theory emphasises the need to adopt a cognitive systems engineering approach (Underwood & Waterson, 2014; Wilson, 2012; Woods, 2003; Woods & Hollnagel, 2006) and to look at the system as a whole, rather than its decomposed parts. The engineering of systems, cannot be based on the study of the cognitive processes that are assumed to take place within arbitrary system components, but instead on the study of the cognitive processes that emerge at the joint system – at the macro-view of the system.

JCS is not the only approach taking a "joint cognitive" view (sometimes referred to as "use-centred" or "practice-centred" approaches in the literature) for engineering complex socio-technical systems. Ecological Interface Design (EID) (Flach, Tanabe, Monta, Vicente, & Rasmussen, 1998; Rasmussen, 1999; Vicente, 2002; Vicente & Rasmussen, 1992) is an adoption of the ecological approach defined by (Gibson, 1950, 1979), and exhibits the same objectives and foundations as the JCS approach.

Feigh and Pritchett (2013) provide a new perspective on the JCS principles by proposing requirements for effective function allocation, focusing on adaptability, teamwork and collaboration. Balfe, Wilson, Sharples, and Clarke (2012) provided a similar perspective by proposing ten generic design guidelines for automation, which are consistent with the JCS principles and Feigh's requirements for function allocation. However reflecting on JCS issues by defining new terms and languages to discuss them are good but these do not resolve the issues nor do these provide solutions for practical application. One key limitation of the works by Feigh and Pritchett (2013) and Balfe et al. (2012) is that these consider cognition only and not the behaviour of the operators. Another limitation is that the focus is on interaction between human and machines, which thereby focuses on studying cognitive processes of the parts or as a binary relationship rather than as a joint system.

Explicit in the JCS theory is the fact that the technology and the people in a work system are interdependent – each affects the other (Hollnagel & Woods, 2005). The JCS approach focuses more on collaboration than coordination; where collaboration implies that each agent has knowledge about the models and state of other agents, as opposed to coordination which implies that each agent operates/acts relatively independent of each other (Murphy & Shields, 2012). Klein, Woods, Bradshaw, Hoffman, and Feltovich (2004) and Christoffersen and Woods (2002) highlight some challenges associated with designing for and achieving this interdependence and collaboration. The past few years has seen an increased focus of research in the area of interdependence, teamwork, coordination and collaboration (Bradshaw, Dignum, Jonker, & Sierhuis, 2012; Bradshaw, Feltovich, & Johnson, 2012; Bradshaw et al., 2008; Johnson et al., 2012) with the derivation of a new design approach called "coactive design" (Bradshaw, Carvalho, et al., 2012; Johnson, Bradshaw, Feltovich, Hoffman, et al., 2011; Johnson, Bradshaw, Feltovich, Jonker, et al., 2011; Johnson et al., 2014). The principles of coactive design (also referred to as teamwork-centred approach) are to address the interdependence of agents (be it people and machines) in joint activities, with a focus on observability, predictability, and directability. The coactive design approach provides some important contributions to industry by addressing a critical aspect of JCS; the importance of interdependence. The problem however is that it only address one aspect of JCS theory; interdependence. Furthermore, the coactive design approach takes a reductionist view – a micro-view – considering the cognitive processes of the human and machine rather than as a system view of cognition. That said, the coactive design approach can be seen to complement JCS rather than replace it.

Design of Automation

Numerous studies have been performed to identify deficiencies in automation design and to suggest requirements for doing things better in the future (Amelink, 2010; Balfe, 2010; Balfe et al., 2012; Gould & Lewis, 1985; Osvalder & Alm, 2014; Papantonopoulos, 2004; Woods, 1996; Woods, Patterson, Corban, & Watts, 1996). Although these requirements and guidelines to improve design are admirable, there is either a problem or resistance to their uptake as the same mistakes are being made again and again.

The design of a JCS is not easy (Norros & Salo, 2008), even when designers have good intentions to aid the operators, designs often create additional burdens rather than eliminate them (Woods et al., 1996). Studies have shown various organisational constraints (such as demonstrating progress and deadlines pressures) influence design and hinder the success of producing a JCS (Osvalder & Alm, 2014; Woods et al., 1996). According to Woods et al. (1996), the potential design errors resulting from these constraints include: reliance on unexamined folk models; shallow search of design solutions; becoming fixated on a particular solution; failure to learn from previous, similar designs; failure to learn from prototypes; and failure to monitor and learn from the performance of the released design.

Design rarely follows a textbook development lifecycle, starting from a concept of operation and then a series of design refinement to requirements specifications, detailed design and finally product realisation. The design process is not a well-order refinement, but a lengthy iteration between the development lifecycle phases (Gould & Lewis, 1985; Rasmussen, 1990; Woods et al., 1996). A salient point is that often design starts at the physical form (of products, technology, users, changing work practices, etc.) rather than at the high-level concept and goals of operation.

Design solutions are limited by the pre-understanding of the solutions space (Papantonopoulos, 2004). The designers' knowledge about the work field/domain, the relevant technologies, and of cognitive engineering principles shape the design, and when this knowledge is limited, the effectiveness of resulting design will be limited. Gould and Lewis (1985) suggest that designers should have direct contact with end users and get familiar about their work domain, rather than rely on rational analysis of how a task should be done. Gould and Lewis published their research in 1985, it is now 30 years later and there continues to be the need to re-assert the need to involve users in the design process. Part of the problems is that the phrase "involve users" is ambiguous – what does it actually means, and how do we go about doing this effectively? Besides engineering companies may have little incentive to involve users as this can negatively impact cost and schedule. In the railway industry in Australia, engineering companies follow the rail regulations and standards, and unless these prescribe human factors integration, there is limited user involvement. This has changed over the past few years with the railway regulations now explicitly calling out for human factors integration and engineering companies starting to involve users more and more in the design process. Even with this in place, the process of user involvement can still be ad-hoc and arbitrary, rather than following a structured process - one interpretation is to consult users at the start of a project and then move on; another interpretation is to involve the user towards the end, for example for a usability trial. The process of performing a work analysis includes an examination of the relationship, interaction and interdependencies of the operator and technology and provides a structure for doing.

Work Analysis

A work analysis provides a functional description of the objectives, means, and constraints of a work domain that can be used to define the work goals, activities and associated cognitive and collaborative challenges for the current and new designs (Vicente & Rasmussen, 1990).

In simplistic terms the work domain represents the field of practice, the work environment, the work space in which work takes place. The aim of the work analysis is to produce a structured model that describes the constraint, strategies and means to do work, independent of the agents (human or machine) who may be performing specific tasks. The work domain is therefore independent of the agents that operate in that environment and it identifies the invariant constraints that are required for the work system to function properly and safely. Any change (e.g. introduction of technology) must ensure that these invariant constraints are respected and remain intact. Nonetheless, making wholesale changes the nature of work may challenge some of the invariant constraints. This needs to be reflected in an updated model of the proposed system and the impact assessed, which illustrates the importance of modelling not just the existing system but also the newly proposed system. Technology that is not part of the design and integral within the work environment is classified as "fixed automation" and is included in the work analysis.

In a work analysis, data is collected through observations of and interviews with workers, and then coded in an abstract functional model. Several analysis methods have been developed to study the work domain. Burns and Vicente (2001) describe three different techniques (i.e. Abstraction Hierarchy, Multilevel Flow Modelling, and Decision Ladder Modelling) for analysing cognitive work, and their usefulness to benefit design. Naikar (2005) and Naikar, Hopcroft, and Moylan (2005) define a methodology to improve the effectiveness and efficiency in the application of a work domain analysis using the abstraction-decomposition space.

The most developed and researched method for analysing the work domain is the Cognitive Work Analysis (CWA) method (Vicente, 1999). Sanderson (2003) and Sanderson, Naikar, Lintern, and Goss (1999) analysed the effectiveness of using a cognitive work analysis, not only to influence design, but across the entire system life cycle, and claim its proven benefits in many domains, including air defence and air traffic control. Naikar, Lintern, and Sanderson (2002) have also applied cognitive work analysis to forecast the impact of new technologies on work domains.

Within the JCS framework, the work analysis is referred to as Functional Syntheses (Woods & Hollnagel, 2006) which is based on the methodology of functional abstraction as described by (Woods, 2003) and is consistent with the cognitive work analysis method.

Cognitive Work Analysis

Cognitive Work Analysis (CWA) is a systems-based analysis and modelling approach for complex sociotechnical systems that has its foundations in Rasmussen, Pejtersen, and Goodstein (1994); where it is claimed that the application of CWA leads to designs that cater for the need for users to have to adapt to unanticipated situations. Vicente (1999) describes the CWA approach as consisting of five interrelated phases of modelling:

1. Work domain analysis – purpose and structure of the system being controlled
2. Activity or control task analysis – what needs to be done in the work domain
3. Mental strategies – the mechanisms by which control tasks can be achieved
4. Social organisation – who carries out the work and how it is shared
5. Worker competencies – the set of constraints associated with the workers themselves.

In principle there are many specific modelling techniques that could serve for each of these phases. However, the techniques most familiar to the CWA community are as follows.

1. Work domain analysis, using the abstraction-decomposition space (Burns & Vicente, 2001; Naikar, 2005).
2. Activity or control task analysis, using decision ladders (Burns & Vicente, 2001; Chin, Sanderson, & Watson, 1999; Hoffman & McCloskey, 2013; Naikar, Moylan, & Pearce, 2006).
3. Mental strategies analysis, using flowcharts (Hassall & Sanderson, 2012).
4. Social organisation, using annotations of the models produced at other phases, indicating actors and their roles (Jenkins, Stanton, Salmon, Walker, & Young, 2008).
5. Competencies, using the skill-, rule-, and knowledge-based behaviour distinction; often via annotations on a decision ladder (Jenkins et al., 2008; Naikar, 2006; Vicente, 1999).

The first phase determines the work objectives and the means to achieve these. This is a core part of describing the work domain. Phases 2 and 3 are used to determine how work is done, within the work domain constraints, to achieve the work goals. Phase 4 allocates functions to agents, and is traditionally referred to in the literature as function allocation. The last phase specifies the competencies required by the agents to perform the allocated tasks/functions. For simplicity, in this thesis the first three phases are referred to as work analysis, and phases 4 and 5 are referred to as function allocation.

The abundant research in cognitive work analysis methods has highlighted many benefits of applying these techniques for the development of JCS (and alike). Mazaeva and Bisantz (2003) detail the benefits of applying work domain analysis to both describe the work domain, as well as for modelling the introduction of automation into a work domain. Chin et al. (1999) and Memisevic, Sanderson, Choudhury, and Wong (2005) describe the improvements in control quality of a monitoring, command and control system as a result of the design influence from the work domain analysis. Naikar and Sanderson (2001) detail the usefulness and feasibility of applying a work domain analysis based framework for the evaluation of design proposals for complex systems. Dinadis and Vicente (1999) have applied cognitive work analysis to visual display design to improve the aircraft cockpit displays for the C130J. Lintern (2002) describes the unique benefits of a work domain analysis for the design of complex distributed systems. Naikar and Sanderson (1999) describes the benefit of using work domain analysis to define and evaluate training systems.

The research has converged to an understanding that the work domain is critical for the development of JCS, and moreover that the functional synthesis of the domain analysis is a necessary prerequisite for making sound and effective human factors design recommendations (Moray, Sanderson, & Vicente, 1992).

It is without a doubt that there are many benefits of conducting a work domain analysis and that it is critical in conceptualising and designing an interface for a complex, time-pressured command and control domain (Cummings, Guerlain, & Bass, 2004).

It is however not all smooth sailing, as the application of work analysis could be associated with several potential hidden problems and challenges. What is lacking in the research is due consideration of potential negative effects on design, rather than a bias towards highlighting benefits of and the importance of applying a work analysis. This is further elaborated in the next section.

Work Domain Analysis – Potential Challenges

Several researchers have found that in spite of good intentions, it has proven difficult and time consuming to apply work domain analyses in practice (Hugo, 2015). One challenge with performing work analyses is that the methods are not fully developed and suffer from methodological and conceptual issues. Skilton, Cameron, and Sanderson (1998) describe that for the application of cognitive work analysis is time complex and consuming, and that adequate tool support is required for it to be viable. Another problem, with the conduct of a work analysis, is determining where to draw the system boundary and knowing the implications of this. The boundary must be draw between the JCS under evaluation and the environment in which the JCS functions (Hollnagel & Woods, 2005). Care must be taken to ensure that the boundary encapsulates the necessary system structures based on the essential system functions, rather than on physical differences. Amelink (2010) defines an extended work domain analyses to address and overcome some of these problems.

Indeed, examining and understanding the work environment is critical for teasing out the work goals, constrains and means-end relationships. However the research is not clear on how the results of the work analysis inform or be applied to the design process since the introduction of new technology will transform the nature of practice (Woods et al., 1996). In addition, "workers are generally not aware of the deficiencies in their mental models, and if designers use these models as the basis for the interface design, then these deficiencies are almost sure to be transferred to the resulting interface" (Vicente, 1999, p. 55); this poses a fundamental challenge for designers trying to understand and decode user's needs and perspectives. Examining the work environment will highlight and focus on problem areas, which takes the examination to a micro-level (a user-centred view) and potentially result in the allocation of functions to technology (i.e. a machine-centred view) without due consideration. For these reasons, it is suggested that work analyses should be applied but not to the existing work space, rather it should be applied to a generic abstract model of the work space (Amelink, 2010).

Another approach to studying the work field is the multi-level structure defined by (Sharples et al., 2002). This approach operationalises the work analysis by breaking it into four levels which leads to a more detailed investigation. The concern with this approach is that there is emphasis on analysing the problem areas and conflict, and less focus on how work is achieved in the presence of uncertainty.

A further challenge of performing work analyses is that each user may only know a small part of the work domain, and hence multiple user need to be observed/interviewed in order to paint a more complete picture of the work domain. The obvious challenge then becomes determining when the picture is complete enough and hence when to stop the analysis. Although some techniques have been proposed to verify and validate the work domain model (Bisantz, Burns, & Roth, 2002; Rechard, Bignon, Berruet, & Morineau, 2015), the model is only as good as the quality of the input data.

THESIS QUESTION

The literature review has shown the importance of understanding the work domain, as well as describing the various deficiencies, challenges and inconsistencies associated with using the outcomes of the work analysis. Given that work analysis underpins the JCS (and EID) approach, it seems crucial to the success of designing a JCS to understand:

1. how the outcomes from work analyses inform and influences design;
2. what design influencing factors conspire against the utilisation of work domain knowledge;
3. how does the work domain knowledge help with the design of collaboration;
4. what types/aspects of work domain information is necessary for a positive design;
5. what types/aspects of work domain information could have negative influences on the design; and
6. how to ensure that the positive aspects of the work analysis are maximised.

In other words, how can and should the outcomes of a work analysis influence the design of Joint Cognitive Systems? As already mentioned, the past decades have seen automation and complexity increasing in the railway industry. This in turn has seen an increasing interest to investigate the practicalities of applying JCS in the railway industry to tackle the challenges faced with automation in complex systems. The thesis research will therefore focus and be scoped within the context of automation in railway systems.

The question that this thesis aims to answer is:

What is the role of a work analysis in the design of Joint Cognitive Systems?

METHOD

Given that the research question posed is seeking to produce findings about the role of a work analysis and that this knowledge is not known in advance, the most appropriate research methodology is a qualitative approach. A qualitative approach is commonly applied to explore a phenomena which is the case for the posed thesis question – to elicit and categorise information. A case-study approach is well suited if we are examining a single example of a class of phenomena (Flyvbjerg, 2006), and we applied this approach to elicit data from two studies (i.e. case studies). A quantitative approach was not applied as this type of approach is better suited for exploring and confirming a hypothesis about a phenomena. For these reasons, a qualitative method using case studies with higher order analysis was selected (Dekker & Nyce, 2004). Higher order analysis is required to give the gathered data meaning – to transform it into a higher level abstraction or model. The higher-order analysis decomposed informant categories and patterns into conceptual guidelines for designers for the creation of future work (Dekker & Nyce, 2004; Dekker, Nyce, & Hoffman, 2003).

Gathering of Data

Data was gathered, over several months between September and November 2015, through semi-structured interviews and participant observations, in relation to the two case studies described below. All interviews and observations were written down as transcripts/ field notes and then coded in order to identify patterns and themes that can be used to reason about and draw conclusions – noting that at least two independent data points were required to identify patterns and common themes. The same coding schema (shown Appendix A) was used for both studies to allow the coded data to be combined for triangulation of the data. The coding of the data was also performed by two different people as a means to validate the coding of the data.

The source of the data came from studying two development projects in order to understand and identify how work domain knowledge was gathered and what work domain factors influence the design and how. These two projects involve the design and introduction of new technology (i.e. automation) for railway operations, and involved:

1. A cab display unit (CDU) which provides the interface between the train driver and the signalling system. The CDU is used to provide the train driver with a continuous indication of the state of the track ahead and with awareness (e.g. train speed and location, track speed restrictions, and limits of the train's movement authority).

2. A hand-held computer-based device (HHD) which is used by railway track maintenance workers to interface with the central railway interlocking system to vitally notify their location on track and to obtain permission to access the track.

The two projects were at different stages of the development lifecycle with the CDU towards the end of the lifecycle and ready to commission, and the HHD at the beginning of the lifecycle in the prototyping stage.

The CDU project allowed for reflection of the processes and influences that resulted in the final product. The HHD project on the other hand provided a unique opportunity to explore how a prototype design can be influenced by knowledge of the work domain.

The CDU was developed by a large global engineering company with capability in multiple industries, including railway, aviation and defence. The HHD was developed by a small engineering firm specialising in high integrity railway systems and technology.

Case Study 1: Train Driver's Cab Display Unit (CDU)

The objective of this study was not to assess whether the CDU design is good or bad, but instead to understand the key inputs used to derive at the final CDU design, and to determine how the knowledge and inputs from the work domain and end-users influenced the design – particularly the design of the CDU layout, the information that is required to be displayed, and how the CDU fits into the greater joint cognitive work system.

A key event during the design of the CDU were a series of workshops which was held with end users and other stakeholder to analyse the work domain and to derive at the CDU display design. This case study interviewed a representative of each stakeholder group, including the system architect, a designer, an end-user representative, and a management representative, who participated in these workshops.

Rather than ask generic questions about the CDU design, the interview questions focused on particular key aspects of the design to help participant recall decisions and inputs from the workshops. The interview questions were structured into six parts. The first part was a general inquiry about influences on the design; key inputs; and the level of knowledge about work as done. Parts two to five asked more directed questions with each part focusing on a particular design aspect of the CDU; specifically on the following aspects:

1. Horizontal vs Vertical Layout

2. Display of speed profile
3. Display of adjacent authority[1] information
4. Display of points status

The interview questions (which are detailed in the "Interview Questions" Section below) for parts two to five asked questions about how the knowledge of work as currently done influenced the design; what inputs the end-users provided; what the end-users main concerns were; which input were beneficial and which hinder the design; what problems were encountered with regards to forecasting how work may/could be done with the new technology. The last part of the interview questions asked slightly more directed questions about which input were considered to be beneficial and which hindered the design.

The interviews were documented as transcripts and provided to participants to validate that the transcripts were a true reflection of the interview. The validated transcripts were then subjected to a post-interview analysis (e.g. data coding and analysis). The first phase of the analysis worked through the transcripts using an open-coding approach with most of the coding terms pre-defined. Using the concepts and categories from the open-coding activity, a second pass axial coding analysis was performed to identify patterns that can be used to reason about and draw conclusions.

Case Study 2: Handheld Device (HHD)

This case study was comprised of three distinct but related parts:

1. To interview the designers of a prototype HHD (which was developed prior to the conduct of a work analysis);
2. To perform a work analysis of railway maintenance workers taking possessions of a section of track; and
3. The outcomes of the work analysis was provided to designers. After the designers had consumed this information and potentially re-designed the HHD, a second round of interviews was conducted with the designers to determine how the knowledge of the work domain influenced and changed their initial design.

[1] Authority here means the access permission given to a track worker or train to have exclusive use (or track ownership) of a section of track. The Authority includes details of the location, usually a kilometre post, where the authority starts, and the end location. The start and end locations of the authority are referred to as the Limits of Authority.

Part one of this study reviewed the prototype HHD design documentation and then drafted interview question for the informants. The system architect, engineer and management representative, involved in the prototype design, were then interviewed in turn.

Part two of this study involved the conduct of a work analysis of the process used by railway track maintenance workers to obtain and release a possession of a section of track (i.e. to reserve the section of track for exclusive use in order to perform maintain work on that section of track). This process, of obtaining and releasing possessions, is safety critical on a railway, as it needs to ensure that track workers are on the correct section of track and that this section of track is protected (i.e. the signalling interlocking prevents routing trains into that section of track). The results of the work analysis were documented in an abstraction hierarchy (Vicente, 1999) to model the work domain goals and constraints. Data for this work analysis was sought firstly through review of the possession management procedure, then through semi-structured interviews with a maintainers (including possession manager, protection officer, track worker) and network controllers, and then through observation of work as done. The work domain model was initially drafted from the information obtained from the procedures and interviews. This draft model was then used during the observations to compare how work was done, and to annotate any differences. The noted differences were then taken back to the relevant user for clarification. The work domain model was then finalised and presented to the informants for validation.

The objective of the work analysis was to produce a functional description of the objectives, strategies, and constraints of the work domain that can be used to define the associated cognitive and collaborative challenge in relation to possession management. The key purpose was to ensure that the work domain constraints to work effectively and safely are respected and remain intact after the introduction of the HHD.

The outcomes of the work analysis were then presented to the HHD designers to allow them to re-design the HHD prototype, at their discretion.

Part three of this study conducted a second round of interviews with the same three designers to determine how the knowledge of the work domain influenced and changed their initial design and why. The data was again transcribed and then coded using the same coding schema as used in Case Study 1. The additional benefit of this inquiry is to elicit some information about how designers convert the domain knowledge into design requirements, and what problems and challenges the designers experienced during this process.

Following the open and axial coding of the data from the interviews, the data was combined with that of study one (i.e. the CDU study) for further analysis to confirm patterns identified during the first study and identify any additional patterns. Similar to the Case Study 1, higher-order analysis was applied to decompose these patterns into conceptual guidelines for designers for the creation of future work.

Interview Questions

The interviews are semi-structured as participant responses affect how and which questions are asked next. The interview structure was iterative, that is, data collection and questions are adjusted according to participant responses and what was learned.

The interviews used open-ended non-leading questions, and the information sought was not asked directly (at least initially) to avoid leading and influencing participants answers. Both exploratory and explanatory questions were asked. The interview questions were drafted and then given to a colleague for review and a dry run, to fine tune the direction and scope of each question.

Case Study 1: Train Driver's Cab Display Unit (CDU)

For the CDU study, the end objective was to identify what work domain factors/inputs influenced the design and how, in order to understand why the design ended up the way it is and what role the work domain played in this. Consequently the following questions were derived.

Case Study 1: CDU	
General questions	1. What inputs did the end-users provide? 2. How did the end-user participate in the design decisions? 3. What was the context of the end-user discussions? 4. What were the end-user's main concerns?
Specific questions about each of the following: • Horizontal vs Vertical Layout • Speed Profile vs Clock Display • Addition of Adjacent Authority Information • Display of Points Status	1. What were the driving forces and influencing factors for the design decision? 2. What stakeholder group had the most influence? 3. How was information about the work domain gathered and used in design? 4. What problems were encountered with regards to forecasting how work may/could be done with the new technology? 5. What aspects of the design were most relevant/important to the end-user?

Case Study 1: CDU	
Closing questions	1. Users often do not want to think about re-training and doing things differently. Does that restrict and limit design options? 2. Which input were beneficial to the design? 3. Which inputs hindered/constrained the design?

Case Study 2: Handheld Device (HHD)

Similar to the first study, one objective was to identify what work domain factors/inputs influenced the design and how. The interesting question for the second round of interviews was to identify what changed from the concept prototype to the new design, and why. Answering this question provides insight into how the knowledge of the work domain changed/influenced the new design.

Case Study 2: Handheld Device	
Interview 1	1. What were the driving forces and influencing factors for the design decision? 2. What stakeholder group had the most influence? 3. How was information about the work domain gathered and used in design? 4. What problems were encountered with regards to forecasting how work may/could be done with the new technology? 5. What information about the work domain was missing from the initial design? 6. What consideration is given as to how the new product would change the way user will work?
Interview 2 *(post work analysis)*	1. What has changed from the concept prototype to the new design, and why? 2. What were the driving forces and influencing factors for the re-design decision? 3. How was the work analysis incorporated into the design process? 4. What aspects of the work analysis were used as inputs in the re-design? 5. Which input were beneficial to the design? 6. Which inputs hindered/constrained the design?

Research Ethics

The research in this thesis was done strictly for academic purposes.

Permission from the design and end-user organisations were sought and obtained prior to engaging any informant. For Case Study 1, the design and end-user organisations were external organisations. The work analysis of the track worker possession management process, for Case

Study 2, was undertaken at an external railway operator organisation. The interviews in relation to the HHD for Case Study 2 were undertaken at my workplace, however, I have had no involvement and I am independent of the HHD project and the designers involved.

Each informant, from whom data was gathered, was voluntary and was asked to consent freely to the process.

There was full disclosure to each participant of the objectives and aims of the study, the type of data collected, the methods of collecting data, confidentiality, time commitments, rights to decline, opportunities to withdraw, and opportunities to have supplied data destroyed (if requested).

Participant's confidentiality has been protected and not shared or disclosed such that others could guess the identities of people who played a role in the research.

All informants provided consent to having the interview transcribed and to being quoted anonymously.

RESULTS

The results section is broken up into four themes that emerged from the coded data:

1. Understanding the Work Domain – this section reiterated the importance and benefits of conducting and using a work analysis in designs.
2. Difficulties – this section describes some identified difficulties of using a work analysis.
3. Influencing factors – this section describes some identified factors that influence design.
4. Using a work analysis to influence design – this section reports on the results of using a work analysis to influence the HHD design.

Understanding the Work Domain

It is no surprise that the results have identified and confirmed (as detailed in the literature review) the importance of work domain knowledge in design.

Work as done

Interestingly both studies, of the CDU and the HHD, identified that one of the most important things to the end user was being provided with information and awareness of what is happening around them. The end users wanted this awareness so that there were no surprises (i.e. no unexpected events). The train drivers expressed the importance of knowing if there is a work crew on adjacent tracks – "*The worst thing that can happen is driving around a bend and suddenly you see a work crew. You don't know if they are on your track or an adjacent track and you have to make a split second decision whether to apply emergency braking which could derail the train or continue. This sort of scenario can seriously stress the driver.*" *(Informant A)*

Similarly, the work crews (comprised of protection officer and track workers) on the track, do not want to get any nasty surprises of a train unexpectedly coming towards them. Acquiring this knowledge of how important this awareness is can only be obtained by talking to and observing the end-user. The end-users rules and procedures do not discuss this, and hence the work as imagined does not fully capture important aspects of the work domain.

The Importance of Context

One of the key principles of Joint Cognitive Systems is to take a systems perspective (Hollnagel & Woods, 2005; Woods, 2003; Woods & Hollnagel, 2006). This means that a macro ergonomic view is taken to decompose the goals and objectives of the system in order to interactions and collaborations between the agents (i.e. humans and technology) of the system. It follows from this that taking a piece of technology from on work domain to use in another work domain would not provide the same collaborative environment unless the goal, objectives and constraints of the work domains are equivalent. In fact, taking a piece of technology from one domain to use in another takes a micro view rather than a macro view.

This scenario was encountered during the CDU design, where the initial design proposal was to utilise an existing ERTMS CDU (more commonly referred to as ERTMS DMI (2012)), which is designed for and proven-in-use for high-speed operations, and not for the targeted regional freight train operations. The problem here was that there are several fundamental differences between ERTMS high-speed train operations and freight train operations, which resulted in the train drivers rejecting the design. Some of the core differences are that for high-speed operations, the train driver's focus is fixated on the display rather than to look out the window ahead – because at speeds of 300+km/h the driver cannot see much out the front window and even if the driver did, there would not be enough time to react. The freight train operators drive the trains by looking out the front window and only glance at the display at regular interval or when they are notified that information has changed. The train drivers said that they use the display to assist them in driving the train rather than the display being their primary and only source of information. Consequently, the type of information to provide to the driver and the way it is presented is quite different between high-speed and freight train drivers. The freight train drivers specified that design must ensure that important information stands out and that changes are highlighted because they only glance at the display when required. For example, the CDU sounded a brief alert tone, when a more restrictive speed restriction entered the display horizon. This is similar to a car navigation system, where the display horizon moves forward as the vehicle moves forward, and as new information comes into view, the driver is alerted to this – "*I want to know when things ahead of the train change; particularly if I need to slow down or stop. You know stopping a train does not just happen, a full train can take up to 1.5km to stop so you need to plan ahead*" *(Informant B).* When alerted, the user can then glance down at the display and see the upcoming speed profile for several kilometres ahead of the train. Similarly, if information about a track crew enters the display horizon, or if there is a problem detected ahead of the train that requires the driver to stop sooner, then the driver is alerted to this.

The following two images show the differences of the ERTMS DMI (2012) and the Australian Rail Track Corporation (ARTC) Advanced Train Management System (ATMS) DMI. Figure 1 shows the initially proposed design prior to the workshops with the end-users, and Figure 2 shows the design that resulted from the workshops.

Figure 1: ERTMS/ETCS Driver Interface Display (source ERTMS DMI (2012))

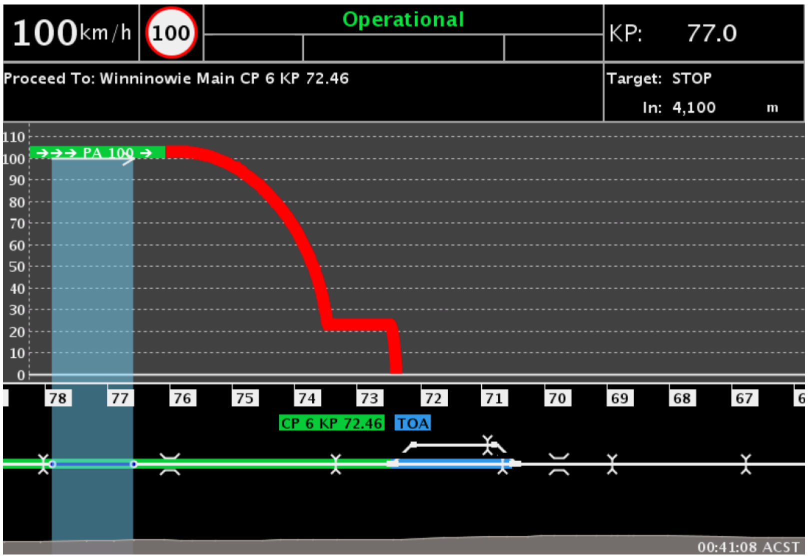

Figure 2: ARTC ATMS Driver Interface Display (source ARTC (2011))

About one third of the ERTMS DMI display (i.e. the top left corner of the display) is consumed by a speed dial showing both current speed and the maximum allowed speed. For the ATMS DMI, the current speed and speed limit is still in the top left corner but much less prominent. As mentioned above, of more importance to the driver is the look ahead of what speeds they need to be doing several kilometres ahead – anticipation.

Anticipation

One of the recurring themes identified during the interviews was that the assistance the end-users were interested in from the technology was to provide anticipation and readiness. The collaboration from the end-user was to be provided with information to assist with forward planning – "*I know what I am doing now, I need to know what is coming up*" *(Informant C).* The designers overly focused on providing information about now and underestimated the users need to plan ahead. The reason for this was because of the gap between the work as imagined by the designer and the work as done by the user. An example of this can be observed comparing the information displayed in Figure 1 and Figure 2, particularly that the second figure focuses much more on what is ahead of the train, showing a detailed speed profile, track gradient and adjacent authorities. This example highlights the need to elicit the user knowledge as part of the work analysis in order to communicate and translate this knowledge into design requirements.

National Culture

The layout of both the CDU and HHD had the information organised in order of critical (specifically to operate safely) from top-to-bottom, left-to-right. Moreover, the most critical information was placed at the top of the screen. It is natural for western cultures to read and hence scan information, top to bottom, left to right, and hence the screen is laid out this way. This all works well if all users are from Western cultures, but people from Eastern cultures read right-to left, and Asian cultures read bottom to top. The designers and user representatives did not intentionally focus on any particular culture, in fact they did not give it any attention at all as their own culture was second nature to them.

The designers were also unaware of another culture related issue raised by the train drivers in relation to the CDU – they said "R*ed means stop. Don't put up anything on the display that is red, unless you want us to stop.*"*(Informant B).* Colours can have special meaning in many industries, and in railways green, yellow, and red are standardised colours which have specific meanings. The designers did not fully appreciate this during the initial prototype design. Figure 2 shows an example of where the designers made the speed profile red to indicate that the train should be slowing down, but the red had a different meaning to the drivers, and the final design changed the red to orange.

Difficulties

Prior Knowledge and Preconception

A user is not a blank slate but they bring past experience and culture to a situation. Although it makes sense that prior knowledge and experience shapes a user's requirements and perspective for a design, the concept of preconception was the most surprising result from the interviews. Many of the inputs provided by the end-user during design CDU workshops were directly shaped by the users prior knowledge of another CDU design that they were familiar with (i.e. the Freightmiser Driver Advice System (Coleman, Howlett, Pudney, Vu, & Yee, 2010)), and even prior to the workshop the end-user participant had a strong preconception of the design they wanted – they wanted something similar to the Freightmiser product. This preconception was exposed during the workshops by breaking the workshop attendees into five groups with key stakeholders in each. Each group discussed and drafted a concept design. When the five concept designs where put up next to each other at the end of this activity, they were almost identical. This was not coincidence, as the end-user in each group was the most influential and the end-users had a preconceived design in mind, which was based on an existing product. Throughout the design workshops, the end-user repeatedly referred to the existing product.

Although it is good for a user to know what they want, being fixated on a single pre-conceived idea, limited the ability to explore alternative and potentially better design options during the workshops. There may be very good reasons why the user has pre-conceived ideas, and it is the challenge for the designers to understand the basis for this.

The end-users may also have limited vision of what could be done with technology. The extent of the end-users inputs regarding technology was limited to the prior knowledge of what they had seen or were aware off rather than what may actually be achievable. This prior knowledge can be a source of a pre-conceived idea or otherwise limit the exploration of alternative design options. Clarifying the work goals and objectives in the functional synthesis of the work domain provided a means for the designers and users to engage in discussions about some alterative design options during the workshop by relating these options directly back to the work goals and objectives.

Trust in Technology

The interviews revealed that on several occasions the users demonstrated a lack of trust in technology, which statements like "*Given that I am responsible for the train, I need to make sure that it is safe for me to move the train and will want to be able cross check the information*" *(Informant D)*. Part of the problem was accountability – clarifying and understanding who is responsible if the technology fails. Another part of the problem was that the end-user had some difficulty in grasping how an existing functionality would be implemented in the technology and they kept on referring back to how work is done currently, rather than how work would be done with the technology. For example, in the current system the drivers had to stop at each set of points (sometimes referred to as turnouts or switches) to inspect that they are correctly set for the desired route. In the new design the movement and setting of points was done automatically but the users firstly did not trust the technology and secondly they did not quite understand how the new system would work in practice. Although the workshops provided the users with mock-ups to illustrate how the technology might interact with their work using realistic scenarios, it took time – by the fifth workshop users were starting to understand.

Influencing Factors

There are many factors that influence design, and many of these conspire against the joint cognitive systems design principles, particularly that a top-down macro ergonomics view should be taken to design the system.

Technology and Design Driven Requirements

Good design practices in systems engineering are to apply a top down approach starting with a concept, going to requirements, and then refining these requirements into a system architecture and design. The designs of the systems studied did not follow this idealistic process. Instead the requirements are driven by a concept or abstract design with the utilisation of particular technology already in mind. In fact the separation between requirements engineering and design is artificial (Maiden, 2013). As soon as stakeholder and engineers think about requirements, they immediately think about solving design problems. This is where the work analysis can help to ensure that the work goals, objectives and constraints are captured and respected.

The introduction of new technology on a railway network in Australia, particularly for safety critical technology, requires regulatory approvals. It is hence inherently difficult and time consuming for a railway operator to introduce novel technology without proven-in-use data due to the potentially lengthy process to gain regulatory approval. Consequently tenders for upgrades and improvements on a railway network prescribe to use of proven-in-use technology to mitigate cost and schedule risks by minimising new development and the regulatory approval process. It follows that when the business analysis think about a new concept of operations, they immediately think about architecture and existing technology (Maiden, 2013).

The CDU hardware was from a respected manufacturer, was proven-in-use in railway application, and was supplied with safety certificates. The chosen hardware thereafter influenced the design. Requirements were restricted and reduced to what the technology was capable in terms of both functionality and layout. For example, given that the physical dimensions of the display was a rectangle with the long side horizontally, it made more sense to layout much of the information horizontally because this allowed the designers to provide a longer look ahead of what speeds and gradients are ahead of the train.

Regulatory Approvals

Aspects of the regulatory approval requirements were already discussed above regarding the needs to utilise proven-in-use technology. The regulatory framework is always in the back of the designer's mind, and several design decisions are taken to ensure regulatory approval rather than ensuring usability.

> *"I originally did not plan to put a schematic onto the display but I knew that this is something that the regulator would want, and hence added it to the design." (Informant E)*

The regulatory framework requires the design to comply with the CENELEC EN5012x standards, which shapes the design towards safety assurance, and sometime at the detriment of usability – for example, by requiring the users to perform additional interactions, cross checks and confirmations which are required on the CDU and HHD. The compliance with the CENELEC EN5012x standards is a double edged sword – on one hand it is tedious for the designers to comply but on the other hand designers use the need to comply with these standards as a means to argue against end-user usability requirements and concerns.

Reality vs Implementation

The requirement for a system design to model reality as closely as possible is well understood and researched (Hollnagel & Woods, 1999; Woods & Dekker, 2000; Woods & Hollnagel, 2006). However, modelling the complex dynamic nature and behaviours of aspects of a complex system can at times be difficult and hence there is a trade-off between reflecting reality and how practical it is to implement. On several occasions during the CDU workshops, the designers argued against requests from the end-user to change the way information is displayed. The general premise of the argument by the designers reduced down to "*this is too difficult to implement*" *(Informant F).* An example of this is the speed profile on the CDU. The users wanted to see the speed gradually reduce down in a curve as this reflects reality, and the driver can see exactly what speeds they should be travelling at which locations. This was however difficult to implement, and particularly difficult to make it reflect reality. This means that the designers can provide a curve, which gives the users the perception of being accurate, where in fact it may not reflect reality at all.

These trade-offs are ongoing throughout the design process and both designers and users must give and take, and find common ground where both parties can work effectively; this is further elaborated in the Analysis Section.

Using a Work Analysis to Influence Design

As previously mentioned, the HHD project was in the early prototyping stage which provided a unique opportunity to study how the knowledge of the work domain could change the prototype design. Specifically, the prototype design was developed without user involvement. As part of this study, a work domain analysis was conducted for possession management by interviewing and observing both network controllers and track workers. The outcomes of this work domain analysis was then provided to the HHD designers who were in the process of designing the device. Once the designers had time to consume the work domain data (after a period of one month), interviews were conducted with the designers to identify how and what had changed in the design.

Work Analysis of Track Possession Management

Before getting into the details of the work domain analysis, let us clarify what is meant by a track possession.

> A 'track possession' or 'track closedown' is where a section of railway corridor is restricted from everyday rail operations for a specified period of time. By closing the corridor to normal rail activity, it enables the rail infrastructure manager to conduct essential track maintenance in a fast, efficient and safe environment. The work performed can involve both major and minor tasks, which in turn will improve overall network conditions and ensure both the reliability and safety of rail operations in the designated area.

The primary objectives of track possession management are both to protect the staff in the railway corridor from getting struck by a train, and to protect trains from derailment (as for example a piece of rail has been removed as part of the maintenance works).

The work analysis revealed several aspects of the work environment that the designers were not aware of. Most of the track maintenance work is classified as "as traffic permits" which means that the maintenance works needs to be slotted in between train movement such that there is minimal interruption to the train running timetable. Moreover, a track work crew often gets a possession for a period of time, then they need to get all the gear and people out of the rail corridor, make the track safe for a train and let a train pass. After that they get back on track to continue work. In order for this to work, the protection officer (i.e. the person in charge of the people in the rail corridor) needs to be aware of when trains are due to arrive. The track workers also need to be aware of train movements on nearby tracks. Although there are designated people located at the boundary of a track possession to lookout for trains, if an unexpected train starts to approach, the people do not know whether the train is on their track or an adjacent track, and they have to quickly and swiftly make sure all staff get off the track. From all the end-users interviewed, this awareness of knowing the train movement around them, was the number one concern and most important feature of the HHD device. The designers were not aware of this, nor were they aware that track workers who work at remote sites sometime rely on trains to take them home at the end of their shift.

The primary focus of the initial prototype design was location determination – ensuring that the track worker is at the correct location and that they are within the section of track that is blocked for rail traffic. This is a critical function, as there have been incidents where track staff were at the incorrect location, and it were these incidents that influenced and drove the direction of the initial prototype design. The situation of incorrect location is compounded by the use of more and more contractors who have limited or no geographical knowledge of the rail network. A network controller said "*Sometime they get to site and ring the network controller for track access permission but they do not actually know where they are*" *(Informant G).*

The goals, objectives, constraints and means-end relations were captured in the abstraction hierarchy shown below.

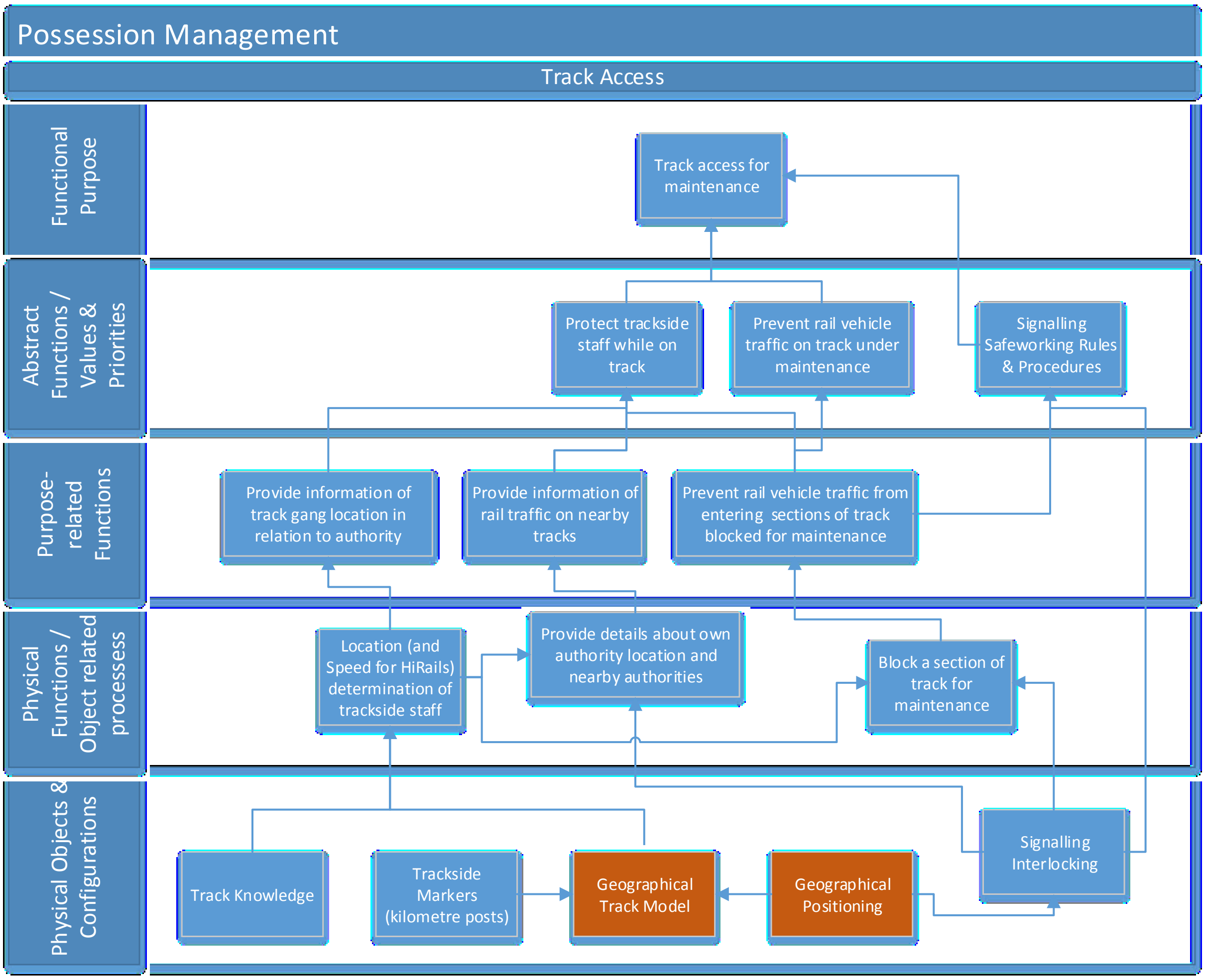

Figure 3: Possession Management Abstraction Hierarchy

Other aspects of the work environment the track workers highlighted, which may not have been obvious to the designers is that it is a harsh environment with lots of dust, sunlight and thermal extremes, and "*You know, the guys on site are pretty rough and the device needs to be tough to survive.*" *(Informant G)*. Being outdoors under direct sunlight provides additional challenges for the devices, as it not only has to be readable in direct sunlight, but readable while wearing polarised sun glasses.

How did the Design Change?

Once the work domain data was presented to the HHD designers, it became apparent that the prototype design (shown in Figure 4 below) did not really address the end-users needs, because the prototype design did not address the end-users primary concern to be provided with awareness of the rail traffic around them. The prototype design's primary focus was to display the current location, the location of the authority and the limits of the authority.

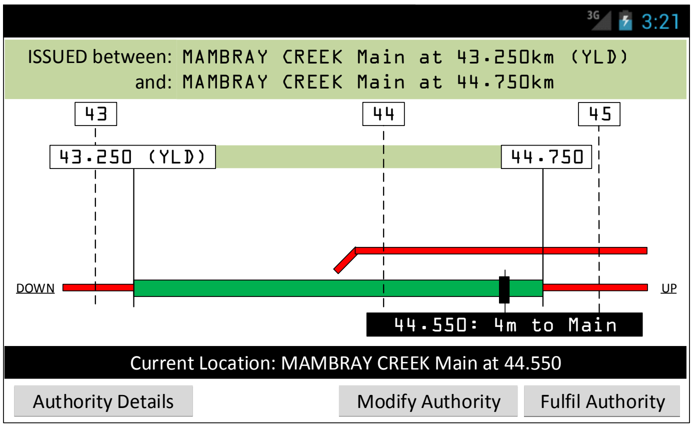

Figure 4: HHD Prototype Display

The HHD designers found the work domain information relevant and considered it critical for the success and user acceptance of the product, as the work analysis highlighted how important awareness was to the user and provided the designers with better awareness of the work environment. The information was assimilated by the designers and then incorporated into the design through changed proposals and new requirements. The designers were also cautions about some of the information provided by the end-users, particularly relating to the provision of more detailed situational awareness. The designers pointed out that we could easily get carried away and provide too much information. The end-user may want to see everything but this can easily lead to problems in that critical information may get lost in the noise and more importantly we do not want the track workers to focus too much attention on the device, and forget about doing their job on site – in the end the device needs to be effective and safe which is an invariant constraint. This highlighted the importance of distilling the end-user information down to the goals and objectives documented in the functional synthesis of the work domain, and focusing the design on that, rather than taking the demands from the end-user at face value. This also highlighted the importance of ongoing user involvement in the design, and to ensure that designs and user work together and balance trade-offs to reflect the needs of both.

After analysis of the work domain information to clarify the goals and objectives, the means-end relationships were defined to derive the requirement for the device. As the functional synthesis focuses on the essential functions of the joint cognitive system rather than the physical objects and how these functions are realised, the designers, in conjunction with the users, can transform the model of the current work into a model of future work. This transformation is carried out by introducing the new technology into the model and determining what else needs to or could change as a result in order to achieve the work goals and objectives.

The figure below shows the revised layout of the HHD. The first thing to notice when compared to the prototype is that the display is significantly larger to provide more information. The other main thing that changed with the design was the provision of information about train movements near the area of track work, as this was a primary concern of the end-user. On the right-hand side of the screen is an area allocated to provide information about approaching trains, including specifying on what track and the approximate arrival time. The device was further amended as a result of the work analysis to not only show their location relative to their authority but also how far they were from the limits of their authority. Another thing that was learned from the work analysis was that a possession authority can span up to 10 kilometres of track, so the schematics has been extended to ensure that the entirety of a possession can be shown on the display.

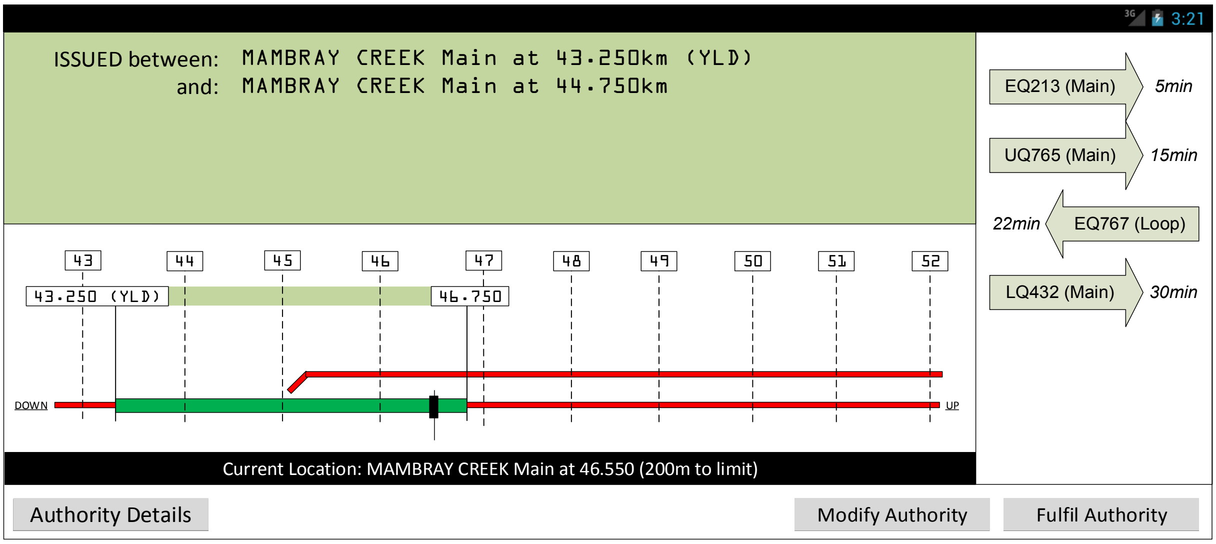

Figure 5: HHD Revised Display

The other thing that became apparent during the discussion with network controllers, was that it was crucial for the effective movement and continued throughput of rail traffic for the network controller to continue to grant access to track workers, irrespective of the technology and changes in process. The reason for this is that only the network controller had the overview and foresight of all train movements on the network and they had the knowledge where, when and for how long track crew could be granted access to the rail corridor without interrupting rail movements. The network controller reiterated that "*We cannot have a track crew rock up to site, and simple block a section of track. They do not know when the next train is expected and they could cause major delays.*" *(Informant G)*. This resulted in a substantial change in the interactions model between track worker, HHD and network controller.

The observation from this process is that designers should not just accept requirements from the user. The designers need to analyse and understand what the users need to perform their job and determine the most effective means to provide this information. The end-users are not designers and their demands are often expressed indirectly or related to how things used to be done. For example, the track workers said that they want open radio back. They used to have open radio where they picked up lots of information (i.e. the party line effect) and they want it back. After more investigation it became clear that the requirement was not for a radio but the need for awareness of rail traffic. The open radio might be one means to provide this but there are other potentially more effective means to provide this through the HHD. The work analysis helped to distil the user request into the goals, objectives and means-end relationships.

Observations from the application of a Work Analysis

The analysis of the work domain proved to be invaluable. There was information discovered that was a surprise to myself and the designers. Even if you think you know how the users work, "*you just don't know what you don't know*" *(Informant E)*. One example of this, was the importance of the awareness of knowing what trains and work crews are nearby was important to both train driver and track workers, albeit for slightly different needs but in pursuit of the same goal.

The use of the abstraction hierarchy and the derivation of means-end relationships was a useful way to clarify the core goals and objectives of the work domain. Notwithstanding, there were environmental constraints identified, like operating in direct sunlight, in dusty conditions, and wearing polarised sunglasses, that did not directly fit into the abstraction hierarchy. The last layer of the abstraction hierarchy, named "Physical Objects and Configurations" was extended to "Physical Objects, Configurations, and Environmental Constraints". This allowed the environmental constraints to be captured and traced to the physical objects that these constrains related to.

Analysis

It is now time to reflect and relate the results from the previous section back to the thesis question posed, as well as the six sub-questions. These sub-questions are distilled and paraphrased into themes here rather than repeating them verbatim. Each of these themes is then discussed in turn.

1. Utilising a work analysis to influence design
2. Benefits and challenges of using a work analysis
3. Balancing conflicting influencing factors
4. Design of collaboration

Utilising a work analysis to influence design

You don't know what you don't know

The research studies conducted reaffirmed, what was described in the vast research literature, that a work analysis and user involvement provides critical insights into the work domain that need to be taken into consideration when designing joint cognitive systems. Both case studies highlighted that the work analysis identified user needs that were unknown and indeed a surprise to the designer. As mentioned in the Literature Review the need to involve users is nothing new, and despite this, operationalising it has been slow. Using a work analysis however gives this process structure and helps alleviate some of the identified difficulties and challenges.

From Work Analysis to Requirements

The overarching challenge that remains is how to effectively translate the work analysis information into design requirements. Specifically, the challenge is to determine how the work analysis can inform design when the introduction of new technology will transform the nature of practice (Woods et al., 1996). The high-level layers of the abstraction hierarchy of the work analysis should not change with the introduction of the new technology unless there are wholesale changes to the nature of work. The core goals, objectives and constraints should be mostly constant in the work domain and independent of the tasks performed by agents in the domain. In order to model how new technology will transform work, the work analyses should not only be applied to the existing work space, but also to an abstract model of the future work space (Amelink, 2010). This was done for the HHD Case Study, where the possession management abstraction hierarchy in Figure 3 shows the work domain with the new technology in place.

For the product design of the CDU and HHD, design requirements came from the "Physical Functions / Object related processes" and "Physical Objects & Configurations" layers in the abstraction hierarchy. The former layer provided the functional requirements and interface requirements, whereas the latter layer imposed a pseudo architecture. When the change to the system does not differ significantly from current operation, as was the case for the two studies conducted, then the translation of the work analysis into design requirements seems to be straight forward as the work domain is stable and well understood and hence provides a basis for design. Where the change to the system is significant, then requirements must be elicited from the entire abstraction hierarchy, with the "Abstract Functions / Values & Priorities" providing the basis for a Concept of Operations. The challenge here is that the abstraction hierarchy is hypothetical and only as good as the information gatherer and documented. Building an abstract model of a complex system will not be complete and will be restricted to the limited information and knowledge from the people who participated in the analysis. The key is to have all stakeholders involved in the work analysis to not only ensure that all aspects are covered but to ensure that the work domain is viewed from different perspectives. Furthermore, as observed during the case studies, the goodness and completeness of the work analysis is enhanced by having a good cross section of motivated users.

Ongoing Re-Design

A common problem faced by designers, including the CDU designers, is changing requirements. Although end-users may think they want a particular feature or they want information presented in a particular way, once they see a prototype they realise that they want something else, or something in addition to what is provided. As a product undergoes several cycles of re-design, the product can diverge quite significantly to its original form and possessing added design complexity. It is important to not lose track of the work analysis – don't just use the work analysis to elicit the initial set of requirements and then put it away in the back of a cupboard. The CDU study showed that reflecting back to the work domain goals, objective and constrains (particularly safety constraints), helped guide re-design requests to ensure that these complemented and supported to information from the work analysis. This ensured that there was cohesion of the information provided to the end-user, and hence minimised added design complexities.

Benefits and challenges of using a work analysis

The previous section already highlighted some benefits and challenges associated with utilising a work analysis and user involvement in design, which is expanded in the following discussion.

Common Ground

Users and designers speak a different language. Users tend to express their needs and goals in terms of how they work rather than in terms of requirements that the designers understand. These communication problems and misunderstandings between designers and users lead to design conflicts. From the designers perspective it might come across as the user not knowing what they want and constantly changing their mind. It is hence crucial to reach *common ground* – i.e. pertinent knowledge, beliefs and assumptions that are shared among the involved parties. This can be achieved by the designers having a good domain knowledge so that they understand how work is done and what the issues and challenges are. Both research studies revealed that the conduct of a work analysis, particularly the parties involves in performing the work analysis, provides a means to bridge the potential misunderstandings and to reach common ground.

The common ground laid out by the work analysis was also useful for guiding end-users preconception of a particular design to an alternative design option. The ability to normalise end-user requests to the goals and objectives of the work domain, allowed designers to open a dialogue with the end-users and to justify an alternative design option to possibly better serve the end-user to achieve their goals and objectives.

Where the system is significantly different from the current operation, there is no accurate data on how work is done, only hypothetical questions about how work might be done. A work analysis of the future system is a means to allow users and designers to agree on how the hypothetical work environment might work and thereby to discuss and negotiate design options using a common language.

The Users-Designer Relationship

The main problem between users and designers is that their objectives are not always aligned and can be in fact be opposing. Designers are driven by cost and schedule, and hence will drive to minimise complexity, novelty, and aspects that are time consuming to implement. The end-user on the other hand wants something that is usable, effective and helps them achieve their work goals and objectives. The designers and users need to build a relationship where there is understanding and awareness of each other's goals and objective, and an understanding that there are constant and ongoing trade-offs required to balance conflicting demands. Both users and designers need to be open-minded and flexible to explore and discuss design options.

Users who face problems and challenges in their everyday work are eager and motivated to participate and help identify solutions and explore design options. This was evident in both the CDU and HHD studies where the exiting process was manual intensive and tedious and/or there was important information not easily/readily available to the user. The train drivers and trackside workers had a positive attitude about the new technology and were motivated to help and contribute. On the flip side, users who are content with what they have and how they work are reluctant to change. The network controllers, for example, were less eager to contribute. From the observations, it follows that a positive outcome from a work analysis is pivotal on the motivation of the user. In addition, the inputs from users of different level of experience is also a factor as, for example, expert users tend to perform their tasks differently to novice users.

Similarly, designers must not be fixated on a particular design ad must be motivated to help the user, and not just design a product. There was an example of this in the CDU case study. The original prototype design was done by a different design house who wanted to convince the user that the ERTMS DMI design was right for them, rather than work with the user to identify what the user actually needs to do their work. This relationship broke down and a different design house was engaged to develop the final CDU design.

The conclusion then is that a positive outcome from a work analysis is dependent on and requires that a good cross section of motivated users is selected with varying levels of experience from expert user to novice, and designers who are interested in understanding the work domain and are willing to work with the users rather than impose their design on them.

User Acceptance

One overarching challenge associated with introducing new technology into a work environment is that if this results in radical changes to the way the end-users work, then there is less chance of the change being accepted by the end-users.

Furthermore, designer's and user's ontology is influenced by their depth of knowledge and experience of a particular problem or solution. This prior knowledge and preconception sets and restricts design possibilities and options. An example of this was the CDU users' prior knowledge of the Freightmiser system.

Having a good cross section of users to participate and provide multiple perspectives, as mentioned above, helps, but this does not necessarily help if the users are aligned with the same preconception of the design. Although users may show reluctance to contemplate an alternative design, the real hurdle to overcome is to get the users to trial the new design. Something that looks unfamiliar will not initially make sense to the user, but with many of these designs, once the user actually starts to use the product, they find that it might actually make their work easier. This is a never ending challenge, but having some novice users involved (i.e. ones which are not set in deep roots and do not have a long history of doing something a particular way) helps, as these users are generally more easily persuaded to consider something different. Even without the availability of novice users, the challenge for designers is to identify a champion within the users group who is willing to trial an alternative design, and if the design is good, this user will convince the rest of the user group. For the HHD product, the end-users were highly motivated and eager to explore design options because they expressed that they had several challenges with their current work.

The work analysis helps by making designers aware of the goals, objectives and challenges of the end-users, and by proving a common language to raise and discuss design options.

Balancing conflicting influencing factors

Technology Driven

Throughout this thesis, it was highlighted that the design changes and improvement in the railway industry is primarily technology-driven. Even when an organisation has visions to make radical changes to their operations, the focus immediately turns to what current technology is capable of (Maiden, 2013; Papantonopoulos, 2004). This should be no surprise to the user, as economic constraints and tight market competition, does not allow railway operating companies to invest in research and development, and instead focuses on available and proven technologies.

Nonetheless, this does not mean that a joint cognitive system, macro-cognitive, systems engineering approach cannot be applied to the system design. The technology limitations are merely constraints in the work domain, and should be modelled as such in the work analysis. This reiterates what was already mentioned above that the work analyses should not only be applied to the existing work space, but also to an abstract model of the future work space.

Regulatory Approval

The discussion has highlighted that although the compliance with railway standards and regulations may be tedious for the designers to comply with. The need to comply provides a means for designers to negotiate conflicting requirements from the end-users. Provided that the regulatory constraints are included in the work domain abstract model, the work analysis thereafter provides a common ground for designers, end-users and even regulators to discuss and negotiate conflicting design requirements.

Reflecting Reality

Modelling the dynamic nature and behaviours of a complex system is difficult and hence there is a need for designers to trade-off requirements between providing information that reflects reality more closely and the practicality to implement this feature. Similar to what was mentioned above, the common ground achieved through the work analysis allows designers and end-users to discuss these conflicts while respecting the goals, objective and constraints of the work domain.

Design of collaboration

It is not necessarily the work domain knowledge from which collaboration emerges, but it is the structure and boundary of the work domain model which is based on the essential functions of the joint cognitive system rather than physical objects or agents. It is effectively the inclusion of users within the system boundary and the top-down systems engineering approach that is ingrained in the JCS approach. The work domain knowledge plays a pivotal role by documenting and clarifying the goals, objective and constraints, which in turn are translated to functional requirements for collaboration that are independent of any allocation to agents.

The work analysis provides the foundation from which the collaboration develops – it starts with the collaboration between designers and users during the design of the joint cognitive system, which in turn provides a stepping stone for developing collaboration and team play in the joint cognitive system.

Discussion

The scope of this research project was limited to the investigation of two case studies involved in the design of automation in railway systems. Accordingly, the conclusions drawn regarding the role of a work analysis in the design of joint cognitive system is restricted to automation in railway systems. This is not necessarily a limitation of the research and rather is a statement about the scope of the research.

Nonetheless, many of the themes and outcomes seem to not be unique to the railway industry, and hence it would be of interest to determine how transferable the themes and outcomes of this research are to other industries. In addition, if they are not transferrable, then determine why not.

If there was more time, it would be interesting to conduct a work analysis of the train drivers' work while driving trains. This analysis can then be used to evaluate the final design of the CDU to check if there are any gaps, and if so, trace the design process back to identify some potential causes of these gaps.

The issues and challenges identified in relation to users, or more specifically the selection of users and managing the users is quite interesting. The data indicates that the selection of users is critical to the success of a work analysis, given that the analysis is only as good as the inputs provided by the user. Some further research would be of benefit to develop a criteria for user selection, and what aspects would make up a good cross section of users.

The issue of user prior knowledge is potentially a major issue from a designer's perspective, and further investigation into techniques on how to counter and overcome this bias is required.

Lastly, getting user acceptance of a change or new technology is challenging in the best of times, however getting user acceptance when there are significantly changes to the way a user works is painfully difficult. Investigations into strategies to successfully introduce significant changes would benefit designers.

The conduct of the work analysis as part of Case Study 2 was interesting on multiple facets. During the analysis, there were environmental constraints identified that did not directly fit into the abstraction hierarchy, and the physical layer of the abstraction hierarchy was extended to allow for these the environmental constraints to be captured and traced to the physical objects that these constrains related to. Secondly, drawing the system boundary for this work analysis was more challenging than expected. Even so there was awareness of this potential issue, as highlighted in the literature review, the system boundary was drawn to include only the maintainers and network controllers. This is very much a designer's view of the possession management function and consequently resulting in this defining the scope of the analysis. However, during the data analysis work of this thesis it was noted that train drivers have an interface with maintainers and network controllers, and interviewing the train drivers could have provided yet another perspective to further enhance the functional synthesis of the possession management process.

CONCLUSIONS

The goal of this thesis was to clarify the role of a work analysis in the design of joint cognitive system, within the context of designing automation in railway systems. The role and influence of a work analysis was studied in the context of Joint Cognitive Systems through the conduct of two case studies involving the design of automation in railway systems.

The need to study, analyse and understand the goals, objective and constraints of the work domain is essential to the JCS approach. Masses of literature is available to highlight and demonstrate the benefits of using the work domain information to influence and evaluate design. The literature is however much more scarce when it comes to studying potential deficiencies, challenges and inconsistencies associated with using the outcomes of the work analysis. This thesis has attempted to bridge this gap in the literature.

The work analysis is only as good as the inputs and information gathered, which consecutively is contingent on selection of the users involved in the work analysis. A good cross selection of motivated users with varying levels of experience is pivotal for a successful outcome. A user is not a blank slate but they bring past experience and culture to a situation, this can in some circumstances be of benefit and in others a hindrance. The challenges identified during this study included:

- User with strong preconceptions tend to be reluctant to consider design alternatives and trial new options.
- User with limited trust in technology tend to be reluctant to consider automation options.
- Users tend to be only motivated to consider change, when they face challenges, problems and tedious tasks in their everyday work.
- Users and designers speak a different language, and common ground most be established in order to effective communicate.

Although several difficulties, challenges and pitfalls emerged from the case study, the results have at the same time reaffirmed the benefits and importance of using a work analysis to influence design. An observation with the designers was that "they don't know what they don't know" about the work domain. On several occasions, the designers were surprised to learn about aspects of work as done they were not aware off – aspects that were critical to the users but not necessarily documented in procedures. The work analysis provides awareness and understanding to the designers of work as done, rather than work as the designers think it should be done. In fact it provides awareness and understanding between user and designer – the communication and relationship between user and designer is critical and this is where collaboration and team play in the JCS evolves, as during the design stage, the designer represents the technology agent and builds and develops the collaboration with the user.

The work analysis is no doubt a crucial ingredient in the design of a JCS, however there are other design goals and objectives that will influence the work analysis and potential conflict with the goals and objectives of the JCS approach in the design of railway systems. Designs are influenced by economic and schedule constraints, which in turn manifests in that upgrades and changes in the railway industry are technology driven. Although this imposes constrains on the system design, it does not mean that systems engineering and a JCS approach cannot be applied. In fact these can work well together provided the constraints (whether economic, schedule, safety, or technology limitations) are detailed and integrated into the work analysis.

The results have shown that the work analysis, with the required user-design relationship and common ground, contribute and support the laws that govern joint cognitive systems at work – particularly common models, collaboration, and balance trade-offs and dilemmas.

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APPENDICES

A. Coding Scheme

The table below provides the coding scheme applied to the interview transcripts.

Topic	Coding
What stakeholder group most influenced design	End-user
	Designer
	Management
	Regulator
How was end-user and work domain information gathered	End-user consultation
	Workshop with end-user
	User trials & evaluation
	Perceived knowledge
	Rules and procedures
Design inputs from end-user	Work problems
	Work environment
	Task breakdown
	Interfaces
	Time-critical tasks
	Dependencies
	Goals/objectives
	Things that make work difficulties
	Things that make work easy
Main concerns of end-users	Change of job
	Change of role
	Change of process
	Why change
	Nothing
Factors that shaped design	User familiarity (i.e. wants current system)
	Better consistency
	Better observability (graphically over textual)
	Usability / ease-of-use
	Better user forecasting
	Better historical information
	Safety
	Technology
	Cost& schedule

Topic	**Coding**
Aspects most relevant to end-user	Layout orientation
	Layout size
	Colours and fonts
	Type of information
	Awareness and Anticipation
	Usability
	Consistency
	Better reflect reality
End-user ability to see how work could be done in the future with the new technology	Fixated on a solution (restrictions to look/consider alternatives)
	Stuck in the present (inability to escape current work as done)
	None (user could picture how work may be done in the future)