Designing for Adaptation with Cognitive Work Analysis: Initial Conceptualisation of an Approach for Integrated Sociotechnical System Design

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This paper presents an initial conceptualisation of an approach to integrated sociotechnical system design based on cognitive work analysis (CWA). A convincing argument has already been made that the design of complex sociotechnical systems should be driven fundamentally by the goal of promoting adaptation and that a formative approach to work analysis, such as that offered by CWA, is necessary for achieving this goal. Moreover, considerable evidence exists for the value of CWA for design, for example, for designing teams and ecological interfaces that can support adaptation. It is clear, however, that a system will not be adaptive simply because it has a flexible team design or an ecological interface. Instead, to create systems that can adapt successfully, all of their various elements—such as the interfaces, teams, training, and automation—must be designed in an integrated or coordinated fashion based on a common underlying philosophy. The framework presented in this paper for this purpose proposes the set of possibilities for work organisation in a system as the central mechanism for integrating the design of the various elements and thus creating systems that are truly adaptive.

Practitioner Summary: This paper is concerned with how the design of complex sociotechnical systems, such as nuclear power plants, petrochemical plants, and military aircraft, can be enhanced to achieve high levels of safety and productivity. An approach based on cognitive work analysis is outlined for integrating various elements of a system's design, including its interfaces, teams, training, and automation, in a way that maximises the system's capacity for adaptation. By increasing a system's capacity to adapt to, and thus handle effectively, the demands of a wide range of situations, including unforeseen events, performance benefits may be expected.

Keywords: sociotechnical system, system design, cognitive work analysis, adaptation, self-organising system

1. Introduction

Designing sociotechnical systems, particularly those that are complex in nature (Vicente, 1999), is a challenging affair. Many contemporary systems, including health care, nuclear power, petrochemical, emergency management, financial, and military systems, deliver essential services for which high levels of performance must be sustained. Moreover, the untoward or disastrous consequences that could eventuate should such systems fail, or perform less than admirably, means that high levels of safety or reliability must be maintained. The decision, then, of which design philosophy and methods should underpin how these systems are conceived or formed should not be made arbitrarily.

1.1 Designing for Adaptation

Already, a strong case has been made that the fundamental objective in designing complex sociotechnical systems should be that of promoting adaptation (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). Key to this argument is the fact that the greatest threats to system effectiveness are posed by novel events (Rasmussen, 1969; Perrow, 1984; Reason, 1990). As these events cannot be anticipated, specific solutions for dealing with these situations cannot be formulated by designers and provided to workers a priori. The aim of design, therefore, must be to support workers in adapting their behaviour online and in real time—in ways that are sensitive to the details of the circumstances—and thus *finishing the design* (Rasmussen & Goodstein, 1987).

1.2 Cognitive Work Analysis

Designing for adaptation requires a special approach to analysing or modelling the work demands of complex sociotechnical systems, for the way in which the work demands of a system are understood is tightly integrated with how those work demands are supported through design. CWA offers a suitable foundation (Rasmussen et al., 1994; Vicente, 1999). Unlike approaches with normative or descriptive orientations, CWA is generally not concerned with devising solutions to support idealised or existing work practices, as these can only be formulated in relation to common, familiar, or anticipated conditions. Instead, consistent with a formative orientation, CWA is concerned with identifying the constraints that must be respected across a range of situations for a system to perform effectively.

By focusing on the analysis of constraints, CWA promotes designing for adaptation. As shown in Figure 1, the five dimensions of CWA—work domain analysis, control task analysis, strategies analysis, social organisation and cooperation analysis, and worker competencies analysis—identify different types of constraints. These constraints must be respected by a system for safe and productive operation but, within these constraints, actors have many options for action. Consequently, by basing designs on a system’s constraints, actors can be given the flexibility to adapt their behaviour to deal with the demands of a situation without crossing the boundaries of successful performance.

Dimensions	Constraints	Modelling Tools
Work domain analysis	Physical, social, or cultural context	Abstraction-decomposition space, Abstraction hierarchy
Control task analysis	Activity	Contextual activity template, Decision ladder template
Strategies analysis	Strategies	Information flow maps
Social organisation and cooperation analysis	Work organisation	All of the above
Worker competencies analysis	Workers	Skills, rules, and knowledge taxonomy

Figure 1. CWA dimensions, constraints, and modelling tools.

1.3 Value of Cognitive Work Analysis for Design

Considerable empirical evidence exists for the value of CWA for design. In particular, experimental investigations have shown that, for a range of systems, ecological interfaces, which are derived from CWA, promote better performance than conventional displays (Naikar, 2012; Vicente, 2002). More specifically, several studies have demonstrated that ecologial interfaces lead to better performance than existing interfaces on non-routine or complex tasks, with no disadvantage on routine or simple tasks (Duez & Vicente, 2005; Ham & Yoon, 2001; Lau, Jamieson, Skraaning, & Burns, 2008; Pawlak & Vicente, 1996; Xu, Dainoff, & Mark, 1999). This finding is consistent with the framework’s emphasis on supporting actors in situations requiring adaptive problem-solving.

The value of CWA for problems other than interface design has also been demonstrated. Detailed case studies have shown, for example, that CWA can be used for designing teams and training systems that promote flexibility (Naikar, 2013). Executed in industrial settings, where experimental investigations are typically unfeasible, these applications of CWA demonstrated their worth through the ability to impact practice. Specifically, the designs or recommendations resulting from CWA were adopted by industry on the basis of their value as judged by subject matter experts.

1.4 Limitations of Cognitive Work Analysis for Design

While it has been shown that CWA can make meaningful contributions to the design of sociotechnical systems, it has also been observed that designing for adaptation cannot be achieved in a piecemeal fashion (Naikar, 2012; Vicente, 2002). That is, a system will not be adaptive simply because it has an ecological interface or a flexible team design. A system with an ecological interface but an inflexible team design, for instance, will have limited, if any, special capacity for adaptation. Therefore, existing approaches for using CWA for design, such as ecological interface design (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1990, 1992) and team design (Naikar, 2013; Naikar, Pearce, Drumm, & Sanderson, 2003), are limited because they focus on individual system elements. Instead, to create systems that can adapt successfully,

an integrated approach to system design is required, where the different elements are "designed in a coordinated manner using a common philosophy" (Vicente, 2002, p. 75). While both Vicente (2002) and Naikar (2012) highlight the need for such an approach, neither offer a substantive perspective on the form that approach could take. In this paper it is argued that integrated system design requires that the CWA framework itself is extended.

2 Integrated System Design

This paper presents an initial conceptualisation of an integrated approach to system design that has the express intent of promoting the capacity of sociotechnical systems for adaptation. Consistent with the arguments laid out earlier, this approach is based on CWA.

The approach starts with the premise that in complex sociotechnical systems, there is usually no single or best way of organising work. Instead, as empirical studies show, the work organisation in these systems changes flexibly in response to the demands of the situation. As an example, Rochlin, LaPorte, and Roberts (1987) conducted a field study that examined how U.S. Navy personnel on aircraft carriers at sea coordinate their work activities. They found that the formal organisation of this system—that which is documented on paper—is rigid, hierarchical, and centralised, being characterised by clearly defined chains of command and means to enforce authority. Typically, this organisational structure governs operations on the ship.

During complex operations, however, Rochlin et al. (1987) found that a very different type of organisational structure is adopted. This organisational structure may be described as informal, given that it is not officially documented. The informal organisation is flat and distributed rather than hierarchical and centralised. For instance, workers at lower levels of the hierarchy have the autonomy to make critical decisions without the approval of those higher up. The informal organisation is also flexible in that there is no pre-specified plan for when it will be adopted. Furthermore, the specific organisational structure that is adopted on any one occasion is emergent, such that there is no simple or fixed mapping between people and roles and, therefore, no single informal organisational structure. Instead, the work organisation on the ship adapts to changes in circumstances. According to Rochlin et al. (1987), this adaptability contributes greatly to achieving a balance between the need for safety and reliability and the push for performance or productivity.

In line with such findings, the integrated approach to system design recognises that, in complex sociotechnical systems, flexible organisational structures that can be adapted to local contingencies are essential for dealing with the demands of a range of situations, including unanticipated events, in a way that meets both safety and performance objectives satisfactorily. Accordingly, to promote the capacity of such systems for adaptation, the approach places emphasis on understanding the range of possibilities for work organisation in a system and, subsequently, developing designs for the various elements—including the teams, interfaces, automation, and training—that can support or accommodate those possibilities. Thus this approach puts forwards the set of possibilities for work organisation in a system as the central mechanism for integrating or coordinating the design of the various elements.

The crux of the matter then is how the different possibilities for work organisation may be understood. As elaborated later, the possibilities may be delineated by applying a set of criteria to examine how the work demands of the system can be distributed across actors—both human and automata. The work demands would be derived from the first three dimensions of CWA, specifically work domain analysis, control task analysis, and strategies analysis. The criteria, which are specified within the social organisation and cooperation dimension, could include the competencies of actors, the access that actors have to information or the means for action, the requirements for feasible coordination or communication, the necessity for workload sharing, the requirements for safety and reliability, and the requirements for compliance, for example, with policies or regulations. Once the possibilities have been defined, designs for each of the system elements can be developed to support those possibilities at the three levels of cognitive control that actors can bring to the performance of a task. These three levels of cognitive control, specifically skill-based, rule-based, and knowledge-based behaviour, are considered within the worker competencies dimension of CWA.

Notably, the fundamental texts on CWA by Rasmussen et al. (1994) and Vicente (1999) recognise that, in complex sociotechnical systems, different organisational structures may be adopted flexibly by actors in response to the local context, and that the social organisation and cooperation dimension must therefore be concerned with the range of organisational structures that are relevant. However, neither text proposes the set of possibilities for work organisation in a system as the central mechanism for integrating or coordinating

the design of the various elements. Both texts mention the requirement for identifying the information needs associated with the different possibilities, but even so, the ecological interface design approach developed by Rasmussen and Vicente (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1990, 1992) does not explicitly consider those possibilities. Furthermore, both texts recognise that the shifts in organisational structures that occur in complex sociotechnical systems are governed by criteria, such as the competencies of actors and the access that actors have to information or the means for action, and they describe the kinds of criteria that may be pertinent. However, neither text discusses how these criteria may be applied systematically *in a formative fashion* to demarcate the set of possibilities for work organisation in a system—and thus design systems that are truly adaptive. Vicente, as a case in point, provides examples of how CWA modelling tools may be used as a basis for examining the organisational structures that are relevant in a health care system. For instance, he discusses how the work demands in an abstraction-decomposition space may be distributed differently across a surgeon and an anaesthesiologist depending on whether the patient is in the pre-operation phase or in surgery. This is clearly a descriptive approach. Specifically, CWA is being used to describe the organisational structures that are adopted in a complex sociotechnical system in relation to recurring classes of situation rather than to understand the organisational structures that can be adopted irrespective of the situation. Thus designs based on this approach may not be suitable for dealing with unanticipated events because they may not support the organisational structures that are relevant—or that emerge—in unforeseen circumstances.

2.1 Analysis

For integrated system design, then, it is proposed that the aim of the analytic effort for any particular system is to identify the fundamental constraints that bound the possibilities for work organisation. Added to the constraints of the work domain, activity, and strategies, from the first three dimensions of CWA, are the organisational constraints from the fourth dimension of the framework. The specific approach for systematically amalgamating these constraints in a formative fashion to delineate the set of possibilities for work organisation is as follows.

First, consistent with the existing CWA framework, to identify the constraints of the work domain, activity, and strategies, a work domain analysis, control task analysis, and strategies analysis, respectively, are required. Consequently, these constraints, or work demands, will be captured in the form of a work domain model, a contextual activity model, a set of decision ladders, and a set of information flow maps. For ease of illustration, Figure 2 presents a modified decision ladder from a set of eight that was developed for the Royal Australian Air Force's future maritime surveillance aircraft. This modified model illustrates some of the decision-making demands associated with identifying targets (e.g., an enemy submarine) from the aircraft.

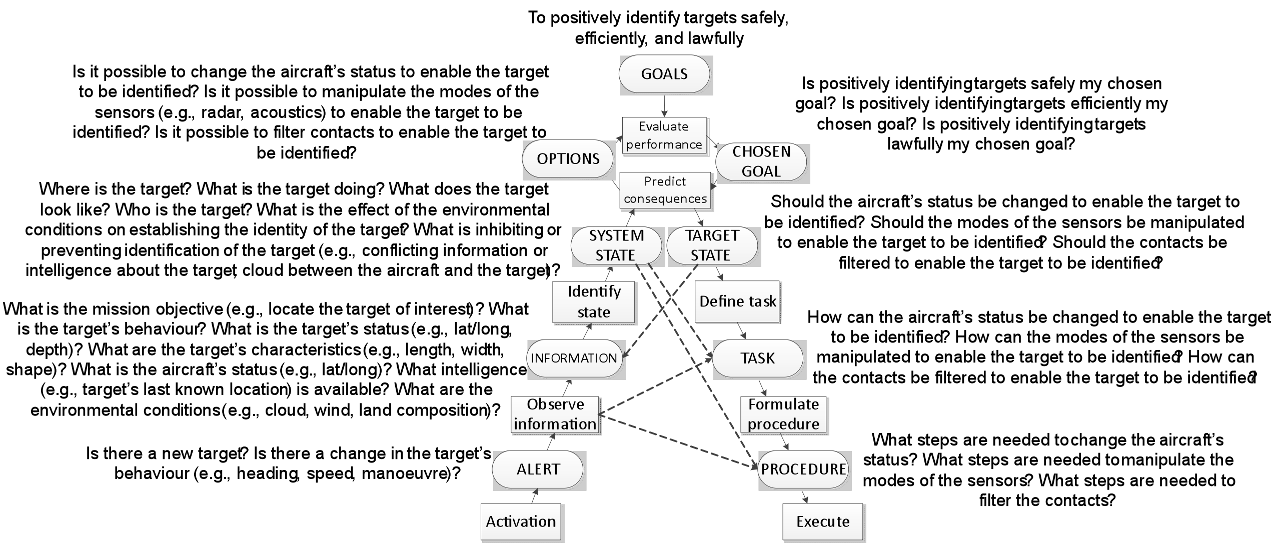

Figure 2. A decision ladder model, adapted from a set developed for the Royal Australian Air Force's future maritime surveillance aircraft.

Once some or all of the CWA models have been developed, the criteria for social organisation and cooperation noted by Rasmussen et al. (1994) and Vicente (1999) can be applied to the work demands captured in those models to examine the possibilities for work organisation in the system. Specifically, for integrated system design, the criteria can be applied by considering the following types of question in relation to each of the work demands:

- *Compliance*: Does the need for compliance with policies or regulations constrain how work demands can be allocated or distributed across actors?
- *Safety and reliability*: Does the need for safety or reliability place constraints on the allocation or distribution of work demands?
- *Access to information/controls*: Does the access actors have to information or means for action constrain the allocation or distribution of work demands?
- *Coordination*: Does the need for feasible coordination requirements place constraints on how work demands can be allocated or distributed?
- *Competencies:* Does the need for feasible competency requirements constrain the allocation or distribution of work demands?
- *Workload*: Does the need for manageable workload constrain how work demands can be allocated or distributed across actors?

For example, in the context of the Royal Australian Air Force's future maritime surveillance aircraft, the criterion of compliance constrains the captaincy of the aircraft to one of the flying crew rather than tactical crew. Hence, any work demand requiring the authority of the captain, such as the arming of weapons, must be allocated to one of the flying crew. Furthermore, the criterion of safety and reliability constrains the responsibility of piloting the aircraft to two crew members, even though a single crew member would have the capacity to handle this responsibility. Hence the various work demands associated with piloting the aircraft must be allocated to at least two crew members. Third, the criterion of access to information/controls constrains the allocation of any work demand requiring a window, such as the sighting of targets, to actors in the flight deck or actors at an observer station in the cabin of the aircraft. Furthermore, this criterion constrains the control of sensor systems (e.g., radar, electro-optical, infrared, electronic support measures, acoustics) for detecting, tracking, and identifying targets to actors at any of six workstations in the aircraft's cabin. Finally, while the criterion of minimising coordination would constrain the operation of all of the sensor systems to a single crew member at one of the workstations, the requirement for actors to be able to develop the necessary competencies and have a manageable workload would result in the allocation of the sensor systems to more than one crew member.

Figure 3 depicts generically that the application of the criteria to the constraints of the work domain, activity, and strategies, in the formative manner described above, results in an understanding of the set of work demands for which an actor *can* be responsible or, alternatively, the set of actors who *can* be responsible for each work demand. Which work demands an actor *will* be responsible for at any point in time is situation-dependent, such that the responsibilities of actors could vary over time. For example, initially Actor A could be responsible for Work Demand 1, but subsequently, this responsibility could be assumed by Actor C. In the same way, initially Actor B could be responsible for Work Demands 2, 3, and 4 and subsequently for just Work Demand 3.

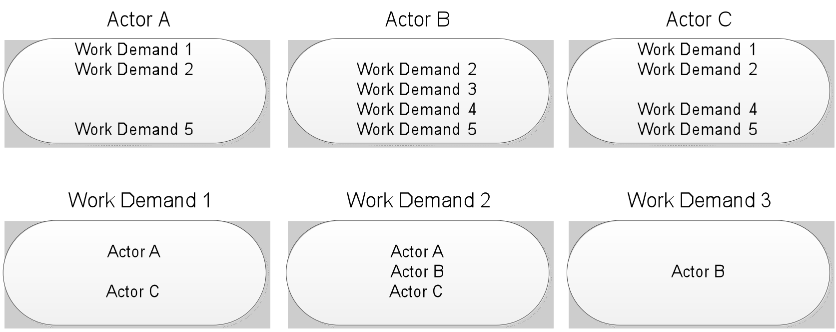

Figure 3. Boundaries on the allocation of Work Demands 1 to 5 across Actors A, B, and C.

It should be emphasised that the formative mapping of work demands to actors, as shown in Figure 3, demarcates the set of possibilities for work organisation but does not portray or describe each possibility. That is, it depicts the fundamental boundaries on the allocation or distribution of work demands, from which the various possibilities may be derived, but it does not elucidate each possibility. This distinction may be clarified further with a simple example. Figure 3 shows that Actors A and C can take responsibility for Work Demand 1. These are the fundamental boundaries or constraints on the possibilities for work organisation. Given these boundaries, the possibilities for work organisation are: Actor A has responsibility for the work demand, Actor C has responsibility for the work demand, or both Actors A and C have responsibility for the work demand.

To draw a parallel with the Royal Australian Air Force's future maritime surveillance aircraft, previously it was noted that, based on the criterion of access to information and controls, any one of the actors at each of six workstations could control any one of five sensors for detecting, tracking, or identifying targets. If we assume, for the sake of simplicity, that these are the fundamental boundaries on the possibilities for work organisation in this system, it would mean that each of these actors can take responsibility for controlling any of these sensors. Within these boundaries, then, there would be many possibilities for work organisation. For instance, to list just a few possibilities, the actor at Workstation 1 could control just the radar and the actor at Workstation 2 could control just the acoustics sensor and vice versa. Alternatively, the actor at Workstation 1 could control the radar, electro-optical, and infrared sensors or any of the five other actors could control all of these sensors. Thus, in a given situation, if the criterion of safety is emphasised, one of these possibilities may be adopted, whereas if priority is given to the criterion of workload sharing, another of these possibilities may be adopted. Which possibility is adopted could be emergent. That is, it could depend on the details of the situation, which may not always be known a priori, such that the problem can only be resolved online and in real time by actors.

Clearly, then, depending on the scale of the system and the level of granularity at which the work demands are modelled, the number of possibilities may be very large. While it may not be impossible to specify all of the potential combinations of work demands and actors, it may not be feasible to do so and, more importantly, it is unnecessary. Rather, to support adaptation, the design of the various system elements must simply take into account the fundamental boundaries on the possibilities for work organisation. That is, as long as the design takes into account the full set of work demands for which actors *can* be responsible, actors *will* be able to handle those work demands effectively if the need arises.

It is also important to emphasise that the fundamental boundaries are independent of situation. In other words, from a practical perspective, when analysts step through the process of applying the criteria to the work demands, they are likely to find that the allocation or distribution of work demands to actors cannot always be established conclusively. In some cases, these 'ambiguities' may be resolved by analysts in relation to certain classes of situations, such as the work situations in a contextual activity model (Naikar, Moylan, & Pearce, 2006). However, in many cases, these uncertainties can only be resolved by actors in relation to the particularities of a situation, which cannot always be predicted a priori. For example, while actors may generally seek to minimise coordination requirements in enacting organisational structures, there may be circumstances in which they adopt structures involving more coordination because of the workload of particular actors at that point in time. The criteria, then, may be invoked by actors online and in real time in response to local contingencies. Therefore, by providing actors with appropriate support through the design of the various system elements, actors should be able to enact—flexibly—particular possibilities for work organisation from the fundamental set, in response to the local context, and thus finish the design.

Finally, it is important to address explicitly why, within the context of this methodological perspective, the possibilities for work organisation are regarded as emergent, consistent with the observations of Rochlin et al. (1987). Specifically, while the potential combinations of work demands and actors could be computed, the number of possibilities for a complex system is likely to be so large that it is not feasible for all of the possibilities to be considered meaningfully by analysts or designers. Certainly, this is the case with the Royal Australian Air Force's future maritime surveillance system. Therefore, the possibilities for work organisation can only be enacted meaningfully in situ by actors responding to local contingencies. Moreover, the possibilities are regarded as emergent because it cannot be planned a priori which of the possibilities will be appropriate in unanticipated situations, as the details of these situations cannot be known ahead of time.

2.2 Design

Following on from the analytic effort, the aim of design—of each of the system elements—becomes to support the range of possibilities for work organisation that are feasible, or permissible, given the system's constraints. For example, the team design should be such that the range of possibilities for work organisation can be adopted. Similarly, the interface design should also support or accommodate this set of possibilities. In this way, the set of possibilities for work organisation provides the fundamental basis for anchoring, and thus coordinating, the design of the various system elements.

Specific to this principal design objective is the idea that the design of any particular element should seek to capitalise on the strengths and minimise the limitations of the various possibilities. In addition, the designs should not introduce or impose extraneous constraints on the possibilities for allocating or distributing work in the system. In other words, the designs should not introduce constraints beyond those that are fundamental to the system, as this would limit the possibilities for work organisation. In line with this thinking, the redesign of an existing system could include removing extraneous constraints that were introduced previously through the design of the various elements. Thus this approach preserves the capacity of the system for adaptation.

Within this overarching framework, existing, complementary design approaches or principles may be extended to create the various elements. For instance, the existing approach for using CWA for team design (Naikar, 2012, 2013; Naikar et al., 2003) can be extended to include the social organisation and cooperation dimension as described in this paper. Consequently, the goal of this approach would become to devise a form or structure for the team that enables workers to adopt the full set of possibilities for work organisation. Similarly, the ecological interface design approach (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1990, 1992) can be extended to include the delineation of the possibilities for work organisation. The aim, then, would be to provide a worker, or team of workers, with the information necessary for fulfilling the work demands associated with the range of responsibilities they can adopt, not just those they are allocated or usually adopt. Finally, a key objective of an existing approach to automation design is facilitating effective human-automation coordination (Dekker & Woods, 2002; Klein, Woods, Bradshaw, Hoffman, & Feltovich, 2004; Woods & Hollnagel, 2006). This approach can be extended so that it addresses systematically the coordination requirements associated with the range of possibilities for work organisation in complex sociotechnical systems.

2.3 Limitations

One criticism of the integrated system design approach is that, in practice, opportunities to influence the design of an entire system are rare. Typically, one works on only one or two elements, such as the interface design or the team design. However, even then, the approach of supporting the range of possibilities for work organisation as best as possible is worthwhile, as it would preserve or promote—rather than limit—the capacity of the system for adaptation. Additionally, championing the need to take an integrated approach to system design in workplaces is important, and the goal of promoting a system's capacity for adaptation with the intention of enhancing safety and productivity has the potential to capture the attention of decision makers.

Another potential criticism of the approach is that it is time consuming. The ideal strategy would be not to take shortcuts in executing the approach but to find ways of being involved upfront of the industrial design cycle, which in most cases is fairly lengthy anyway. Nevertheless, it is worth acknowledging explicitly that typically every analytic and design effort must be tailored in some way to meet the needs of a project (Naikar, 2013). In the case of the integrated system design approach, the criteria for social organisation and cooperation may be applied, at a minimum, solely to the constraints of the work domain, as the possibilities for action, or work organisation, can never exceed those constraints. The constraints relating to activity or strategies, however, can be useful for resolving some of the ambiguities in the work organisation and the design of the various system elements. Another option, therefore, may be to adjust the level of granularity of the analyses to the time constraints of the project; less detailed analyses take less time to complete.

Finally, while this paper demonstrates that CWA can be extended to support an integrated approach to system design at a conceptual level, further research is necessary to clarify the viability of this approach in practice. In particular, the theoretical and methodological ideas, in relation to both the analysis and design stages, must be refined and validated, and the feasibility of applying the ideas in industrial settings must be established.

3 Conclusion

This paper provides an initial conceptualisation of how CWA can be extended to support an integrated approach to system design. Specifically, it proposes that the central mechanism for integrating the designs of the various system elements is the set of possibilities for work organisation. Accordingly, it demonstrates how the set of possibilities may be delineated in a formative fashion and it highlights how the design of the various system elements may be centred, or coordinated, around these possibilities. This lynchpin is necessary for creating systems that are truly adaptive.

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