A Consideration of Design Approaches Based on Cognitive Work Analysis: System Design and Integrated System Design

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ABSTRACT

This paper examines the relationships and distinctions between existing design approaches based on cognitive work analysis (CWA). Emphasis is placed on considering the use of CWA for system design, as outlined by Vicente [18], and for integrated system design, as called for by Vicente [19] and developed by Naikar and Elix [8,9]. Of note are some key distinctions in the perspectives of integrated system design. Specifically, although it was not Vicente's [19] intention to provide a comprehensive discussion, a clear difference between his approach and the one Naikar and Elix [8,9] propose concerns the level of integration. In the former, the designs of various system elements, such as the interfaces and teams, would be integrated in relation to a reduced space of possibilities for action. This shortcoming arises because the designs would be confined to organisational structures prevalent in recurring situations and potentially restricted by the design decided for the team. Such an approach could inhibit a system's inherent capacity for adaptation.

CCS Concepts

- Human-centered computing

Keywords

Cognitive work analysis; adaptation; system design; integrated system design; sociotechnical system

1. INTRODUCTION

In designing complex sociotechnical systems, a work analysis is essential because it provides an understanding or representation of the work demands that must be supported by the resulting designs. Without this understanding, designs cannot be developed that support workers in carrying out their jobs effectively. Different approaches for work analysis, however, have different implications for design, as the way in which the work demands of a system are understood is tightly interconnected with how those work demands are supported through design. This paper focuses on the use of cognitive work analysis (CWA) for design, as this framework is concerned fundamentally with promoting worker adaptation. Such a design approach is necessary if we are to create

systems that are resilient in the face of instability and uncertainty.

Specifically, this paper considers the extent to which CWA can support adaptation in complex sociotechnical systems, given the particular ideas implemented for analysis and design. After outlining the importance of designing to support adaptation, a brief overview of CWA is presented, highlighting why this framework is especially well suited for this goal. Subsequently, the paper considers how CWA can be used for system design, focusing on Vicente's [18] foundational ideas. Attention is then given to Vicente's [19] call for the need for integrated system design and how other researchers, particularly Naikar and Elix [8,9], have responded to this call. Following that, the paper focuses on elucidating the relationships and distinctions between Vicente's [18,19] discussions of system design and integrated system design as well as between the perspectives of integrated system design offered by Vicente [19] and by Naikar and Elix [8,9]. This assessment promotes greater understanding of how CWA can be extended and utilised to preserve a system's inherent capacity for adaptation.

2. DESIGNING FOR ADAPTATION

Supporting worker adaptation in complex sociotechnical systems is particularly important because these systems are open to disturbances [14,18]. As a result, workers must operate under constantly changing or dynamic conditions. This variability may arise from such common perturbations as minor technical malfunctions or staffing shortages, so that workers may have to adjust their work practices regularly, or even routinely, to handle these situations [9]. Moreover, workers may have to deal with major disturbances caused by unforeseen events, or events that cannot be fully predicted a priori, such as a new kind of military threat, an unexpected reaction of a patient to medication, or an unanticipated chain of supplier breakdowns triggered by a financial crisis. Given the novelty of these situations, workers may have to exercise significant ingenuity in their work practices to preserve or restore system safety and performance, and thus avert widespread disaster or catastrophe.

Empirical studies of workers in complex sociotechnical systems have demonstrated the importance of both behavioural and structural adaptation for maintaining system effectiveness in the face of change or novelty [9]. Behavioural adaptation involves actors adjusting their tasks, plans, goals, actions, or priorities in line with the emerging situation. Bigley and Roberts [1], for example, observed emergency response personnel adjusting standard routines for 'hose laying' or 'ladder throwing' to accommodate local contingencies. Structural adaptation, on the other hand, involves multiple actors adjusting their structure or organization, such that the particular actors involved and their roles and relationships may be constantly changing. In Bigley and Roberts's study, it was observed that, in responding to an

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emergency, pre-existing roles or positions within the system are filled with people only to the extent required, with positions becoming filled or deactivated as the situation unfolds. In addition, personnel can be assigned responsibility for multiple positions, shifted into different positions, or discharged depending on the circumstances. Thus it is clear that, to promote system effectiveness, workers must be supported in adapting both their behaviour and structure, in either routine or novel circumstances, through the system design.

3. COGNITIVE WORK ANALYSIS

CWA [14,18] is especially well suited for designing to support adaptation because of its formative nature. This framework places emphasis on specifying the constraints on work practice rather than on prescribing ideal work practices or describing existing work practices, as do normative and descriptive approaches for work analysis, respectively. CWA is concerned with the constraints that are applicable not only in known, recurring, and anticipated situations but also in situations that cannot be predicted *a priori*. While these constraints must be upheld by workers, such that the constraints bound the possibilities for action available to them, within these constraints, actors still have many degrees of freedom for action. Consequently, by basing designs on a system's constraints, workers can be provided with the flexibility to adapt their work practices to a wide range of situations without crossing the boundaries of successful performance.

The five phases of CWA—work domain analysis, activity analysis (or control task analysis), strategies analysis, social organisation and cooperation analysis, and worker competencies analysis—are intended to be concerned with different types of constraint. Briefly, this framework considers the constraints of the *work domain*, including the system's purposes and physical resources; the *activities* necessary to achieve the system's purposes with a given suite of physical resources; the cognitive *strategies* that can be utilised for achieving the necessary activities; the *work organisation* or ways in which work can be allocated, distributed, or coordinated among actors; and the *workers* or ways in which work demands can be met given human cognitive capabilities and limitations. Each phase has special tools for modelling the relevant constraints, such as the abstraction hierarchy or abstraction-decomposition space for work domain analysis and the decision ladder for activity analysis.

4. SYSTEM DESIGN

In his fundamental text on CWA, Vicente [18] discusses the relationship between this framework for work analysis and system design. He makes the point that the five phases of CWA are organised so that they span from the constraints of the work domain to the cognitive constraints of workers in an integrated fashion, and that each phase of CWA can be used to inform particular classes of system design intervention. One way in which he demonstrates the logical relationships between the five phases of CWA is by pointing out that it is only once the capabilities of the system have been established (work domain analysis) that it becomes possible to define systematically what goals need to be achieved and what needs to be done to satisfy those goals (control task analysis). Similarly, only once the goals and control tasks have been established is it sensible to define the different ways in which these goals and control tasks can be achieved (strategies analysis). Then, following the first three phases of analysis, it becomes possible to determine how the work demands of the system can be allocated among human and machine actors (social organisation and cooperation analysis). Finally, it becomes

feasible to consider what skill-based, rule-based, and knowledge-based competencies are necessary for workers to meet the relevant work demands effectively.

Vicente [18] also discusses the implications of each phase of CWA for particular classes of system design intervention (Figure 1). For example, he points out that work domain analysis can be used to determine the structure of the information system database, social organisation and cooperation analysis can be used to define the role allocation of team members, and worker competencies analysis can be used to establish the training requirements of workers. He notes that his discussion isn't meant to be exhaustive. Therefore, the various phases may have applications other than those he highlights.

Consistent with Vicente's [18] discussion of the relationship between each phase of CWA and classes of system design intervention, many existing design approaches based on CWA have focused on the use of particular phases to design specific elements. For example, the ecological interface design approach, as described by Rasmussen and Vicente [15], is informed by work domain analysis and worker competencies analysis. In addition, an approach for team design described by Naikar, Pearce, Drumm, and Sanderson [11; see also 7] is based on work domain analysis and activity analysis.

Figure 1. Relevance of each CWA phase for classes of system design intervention. Adapted from Vicente [18].

Some design approaches have highlighted that the various phases of CWA can be used not just to inform particular classes of system design intervention but also to support different stages of the system lifecycle, for example, requirements definition, design, and evaluation [4,16,17]. Concrete industrial-level demonstrations of such applications include the use of work domain analysis for developing software specifications [5], for defining training-system requirements [7,12], and for evaluating system design concepts as part of a tender evaluation or source selection process [7,13].

5. INTEGRATED SYSTEM DESIGN

In the context of a review of the progress and challenges of the ecological interface design framework, Vicente [19] highlighted the need for integrated system design. He observes that a system will not necessarily be adaptive simply because it has an ecological interface, even though that is intended to promote adaptation. Instead, the designs of the different elements, such as the interfaces, teams, training, and automation, must be coordinated based on a common underlying philosophy, specifically the philosophy of promoting worker adaptation. These ideas were echoed by Naikar [6], who noted in particular that a system will not necessarily be adaptive simply on the basis of its team design, even if that is intended to foster flexibility [7,11].

While Vicente [19] recognised the need for the designs of multiple elements to be integrated in order to facilitate adaptation, his consideration of how this might be achieved is brief. He clearly sees the problem as having two aspects, an analysis aspect and a design aspect. On the analysis side, he implies that the five phases of CWA, used in a coherent way, offer a basis for integration. On the design side, he indicates that the designs of different elements must be compatible with respect to the goal of promoting worker adaptation. He points to an approach for the design of alarm systems [2], which he says is highly compatible with ecological interface design because it too is based on the abstraction hierarchy. However, he also makes note of design approaches that are not based on CWA but that he regards as consistent with the ideal of supporting worker adaptation, such as the design of a critiquing system intended to provide medical technologists with decision support [3]. Overall, this discussion can be taken to mean that ideas for approaching the design of particular elements in a way that promotes adaptation can be combined with a systematic work analysis, specifically cognitive work analysis, to produce an integrated system design.

Despite Vicente's [19] emphasis on the need for integration, this topic has received little attention. One study responding to Vicente's call has been reported by Read, Salmon, Lenné, & Jenkins [16]. In this case study, the use of the CWA framework was combined with a design template that required design features associated with multiple system elements to be documented. As observed by Naikar and Elix [9], on the face of it, such a template could be helpful for ensuring that the designs of multiple elements are considered concurrently. However, based on the ratings of the four participants in the design process and the analyst's reflections, it seems that this is not a guaranteed result. More importantly, given the description of the design process, it is unclear on what basis the designs of the different elements would be integrated, assuming all elements are considered concurrently. In particular, one cannot be sure whether the constraints from all five phases of CWA would be upheld expressly in the designs of the various elements and, therefore, whether the system design would promote adaptation in a consistent fashion across multiple elements.

Also using Vicente [19] as a starting point, Naikar and Elix [8,9] consider what an integrated system design would represent in the context of promoting worker adaptation. They expand on Vicente's ideas in two ways. First, on the basis of empirical studies demonstrating the nature of adaptation in the workplace, they discuss that an integrated system design would be one in which the multiple elements are based on a common philosophy that promotes structural as well as behavioural adaptation. Furthermore, to preserve a system's inherent capacity for adaptation to novelty, or events that cannot be predicted a priori, the designs of the various elements must accommodate the full range of opportunities for structural and behavioural adaptation in the workplace rather than just a subset of the possibilities, such as those that are relevant in recurring or anticipated situations. Moreover, the range of possibilities for adaptation must be supported coherently across multiple actors in the system. Thus if a team design supports possibilities for adaptation that an interface design does not, the two elements would not be integrated, or compatible, with respect to the goal of promoting adaptation. Similarly, if an interface design for some of the actors in the system supports possibilities for adaptation that are not recognised by the interface designs for other actors in the system, such that some or all of the possibilities cannot be realised by any

of the actors, the design of this element would not be integrated across multiple actors in the system.

Second, Naikar and Elix [9] discuss that to achieve the aforementioned objectives, and thus create an integrated system design, it may not be sufficient to approach the design of multiple elements solely with the common philosophy of promoting worker adaptation. Rather, the design framework must have explicit mechanisms for binding the designs of multiple elements so that the various designs support the range of possibilities for adaptation in a consistent fashion across multiple actors in the system. Specifically, the design of each element must be anchored to a common set of constraints. Moreover, in complex sociotechnical systems, which are comprised of multiple actors, the full set of constraints that is relevant to each actor, or group of actors, in the system is dependent on the organisational structures that are possible. Hence the design of each element must be coordinated around the organisational constraints.

Thus Naikar and Elix [9] demonstrate how the set of possibilities for work organisation in a system may be demarcated independently of the situation, through extensions of cognitive work analysis, and how the resulting diagram of work organisation possibilities (WOP) may be utilised in design. This approach involves using a number of criteria that have been observed to govern shifts in work organisation in complex sociotechnical systems [14,18] in a formative manner to identify the limits—or constraints—on the distribution of work demands across actors. These criteria relate to the competencies of actors, the access actors have to information or the means for action, the requirements for safety and reliability, the need for compliance with policies and regulations, the requirements for feasible coordination demands, and the requirements for manageable workloads.

As an illustration, in the case of the Royal Australian Air Force's future maritime surveillance aircraft, the criterion of *compliance* with organisational regulations constrains the captaincy of the aircraft to the flying rather than tactical crew. Therefore those work demands requiring the captain's authority, such as the arming of weapons, must be allocated to one of the flying crew. The *safety and reliability* criterion constrains the responsibility of piloting the aircraft to two people, despite the fact that a single person could handle this responsibility. Thus the work demands involved in piloting the aircraft must be allocated to at least two actors. Third, the criterion of *access to information or controls* constrains the operation of four sensor systems for detecting, tracking, and identifying targets to actors at any of six workstations in the cabin. Furthermore, while the criterion of feasible *coordination* would constrain the operation of all of the sensors to one or two actors, the need for reasonable *competency* demands and manageable *workload* for crew would result in the allocation of these sensors to more than two actors.

The organisational constraints identified through this process can be represented using a WOP diagram [9]. Figure 2 depicts this diagram in a generic form to emphasise that it depicts the constraints on the possibilities for work organisation rather than describing the possibilities themselves. For instance, Figure 2 shows that Actors A and C can take responsibility for Work Demand 1. These are the constraints on the possibilities. Given these constraints, the possibilities are: Actor A has this responsibility, Actor C has this responsibility, or Actors A and C share this responsibility. Depending on such factors as the scale of the system, the number of possibilities may be very large. For

example, in the case of the maritime surveillance aircraft, the number was in the order of 10^{27} .

Figure 2. Generic diagram of work organisation possibilities.

However, for the system design to support the set of work organisation possibilities, it is not necessary for each of the possibilities to be computed and comprehended meaningfully by analysts or designers. Rather, it is only necessary for the designs of the different elements to be based on the constraints on the possibilities, as depicted in the WOP diagram. That is, as long as the designs consider the set of work demands for which each actor can be responsible, actors will be able to enact any of the possibilities for work organisation, as the situation demands.

6. RELATIONSHIPS AND DISTINCTIONS BETWEEN DESIGN APPROACHES

This section addresses the relationships and distinctions between different design approaches based on CWA. Emphasis is placed on comparing the perspectives of integrated system design provided by Vicente [19] and by Naikar and Elix [8,9]. Prior to that, the relationship between system design, as it is described by Vicente [18], and integrated system design, as it is outlined by Vicente [19], is considered.

6.1 System Design versus Integrated System Design

The question of the distinctions Vicente [19] had in mind when he called for integrated system design, after his book had focused on explaining the linkages between CWA and system design [18], is important to address explicitly, even though the relationship may be reasonably straightforward. At the outset, it is necessary to point out that given that Vicente [18,19] did not address this matter directly, his intentions can only be inferred. As noted earlier, Vicente's [18] account of system design emphasises two points: the coherency of the CWA framework and the relationship of each phase of this framework to particular classes of system design intervention, such as interface design, team design, and training design. When discussing the matter of integrated system design, Vicente's [19] focus appears to be on the compatibility of the different elements, specifically with respect to the philosophy of promoting worker adaptation, and he indicates that the five phases of CWA, used in a coherent fashion, provide a basis for integrating the designs of the different elements. The coherency of the CWA framework, then, is mentioned in Vicente's accounts of both system design [18] and integrated system design [19]. On this basis, it may be surmised that the need for integration is implicit in Vicente's [18] discussion of system design, such that the difference between system design and integrated system design is simply one of emphasis. The former focuses attention on how each phase of CWA can be used to inform the design of specific elements of the system whereas the latter draws attention to the need for integrating the designs of the different elements, using the

five phases of CWA in a coherent fashion, such that the designs are consistent with respect to the goal of promoting worker adaptation.

6.2 Perspectives of Integrated System Design

Having considered the relationship between system design and integrated system design, we can now turn to the distinctions between the perspectives of integrated system design provided by Vicente [19] and by Naikar and Elix [8,9]. These perspectives may be compared with respect to the means for integration, the method of analysis, and the process for design.

6.2.1 Means for Integration

The first matter to be addressed relates to the means by which—and thus whether—integration is achieved in the two approaches. Once again, it is difficult to be sure of Vicente's [19] intentions, noting that it was not his goal to provide a comprehensive treatment, but, as already mentioned, he indicates that the use of the five phases of CWA in a coherent manner offers a basis for integration. The question, then, is how is this statement to be interpreted. While it is clear that Vicente [18,19] intended all five phases of CWA to be used to define the constraints on actors in an integrated fashion, it is not clear whether he intended all five phases to be used in the design of every element. If his intention was to base the design of every element on the constraints from all five phases, then the designs of the different elements would be integrated in that they would all be based on a common set of constraints. On the other hand, he could have meant that all five phases should be conducted to define the range of constraints on actors, and then different phases applied to inform the design of different elements. This approach would be consistent with his earlier discussion of the use of particular phases of CWA to inform particular classes of system design intervention [18]. In this case, some of the designs could be based on the constraints of the work domain, others could be based on the constraints of activity, and so on, such that the designs of the different elements would not necessarily be integrated, given that each may support different possibilities for adaptation.

In the approach for integrated system design described by Naikar and Elix [8,9], the design of each element is anchored to the organisational constraints, as specified in the WOP diagram. Furthermore, it is discussed that in an idealised implementation of this approach, the work demands of the system, from which the organisational constraints are derived, would be defined in the first three phases of CWA, namely work domain analysis, activity analysis, and strategies analysis. Naikar and Elix [8] point out that if such an extensive analysis is not possible, perhaps for practical reasons, the organisational constraints may be derived solely from the work domain analysis, as this analysis encompasses a wide range of situations, including novel and recurring events. This means that the possibilities for adaptation can never exceed those encapsulated by the constraints of the work domain. If this approach is taken, the designs of the different elements would be integrated in relation to the full range of opportunities for structural and behavioural adaptation in the workplace, such that the system design can promote adaptation to change and novelty.

Taking these ideas further, the activity analysis and strategies analysis provide a detailed appreciation of the constraints that are relevant in recurring classes of situation. Thus, if the organisational constraints are derived solely from these phases, the designs of the different elements would be integrated in relation to the opportunities for adaptation in recurring classes of situation.

Such an approach could lead to a system design that promotes adaptation to change, but not necessarily to novelty.

A valid question, then, is what is to be gained by taking the complete approach, whereby the organisational constraints are derived from the first three phases of analysis, in comparison with an approach that bases the organisational constraints on the work domain analysis alone. As implied above, the complete approach would lead to a more detailed appreciation of the possibilities for adaptation in recurring classes of situation, which are conditions that workers confront regularly. As a result, the designs of the different elements would be integrated at a more detailed level in providing support to workers for adapting to the demands of such situations. It is important to emphasise that the work domain analysis does encompass such situations, but with the addition of the two other phases of analysis, more detailed support can be provided to workers in these situations.

To further consider the distinctions in the perspectives of integrated system design offered by Vicente [19] and by Naikar and Elix [8,9], it is necessary to make some assumptions about Vicente's approach. Specifically, it is necessary to assume that his intention in stating that the five phases of CWA used in a coherent manner offer a basis for integration is that the designs of the various elements would be integrated by basing the design of every element on all five phases. Thus, having an understanding of the means for integration provided by the two approaches, albeit presumed in one case, it is possible to address the distinctions in the level of integration each approach offers with respect to their ability to preserve the system's inherent capacity for adaptation. This comparison can be approached from the viewpoints of analysis and design, although these viewpoints are interconnected.

6.2.2 Analysis

In relation to analysis, Vicente's [19] approach for integrated system design is based on the standard CWA framework [14,18]. In this framework, the analysis of organisational structures, which is carried out in the social organisation and cooperation dimension, appears to be descriptive rather than formative in orientation in some respects [8,9]. Vicente [18] states explicitly that the analysis of organisational structures is undertaken in relation to recurring classes of situation. While the consideration of such situations is important within a formative perspective, neither Vicente [18] nor Rasmussen et al. [14] provide a comprehensive constraint-based perspective for analysing the organisational structures that are relevant in these situations. Sometimes their discussions reflect a focus on describing the organisational structures that are commonly observed in these situations. Mapping these structures onto constraint-based representations, such as the abstraction-decomposition space and the decision ladder, as illustrated by Vicente [18], would highlight variations in the work organisation that are possible within the boundaries defined by the observed structures. However, there could be many other structures that are relevant in these situations, given that it is unlikely that the full set of viable structures in recurring classes of situation can be observed.

In other places, the discussions by Vicente [18] and Rasmussen et al. [14] appear to reflect a focus on describing the organisational structures that are reasonable rather than possible. In other words, rather than being concerned with defining different possibilities for distributing the work demands of the system across actors, they seem to be concerned with identifying a distribution that is reasonable. For example, they suggest distributing the work demands across actors such that the coordination requirements are

minimised. However, as Naikar and Elix [9] observe, there may be circumstances in which it is necessary for actors to adopt organisational structures with greater coordination requirements, perhaps because of the workload of particular actors at that point in time. If these organisational structures are excluded from consideration in the analysis phase, they won't be supported in the design phase.

Lastly, given the focus on recurring classes of situation, the analysis of organisational structures in the standard CWA framework does not properly account for the organisational structures that may be relevant, or that may emerge, in unforeseen circumstances. Yet, as Rasmussen et al. [14], Vicente [18], and others have established, novel events pose the greatest threats to system effectiveness. Consequently, supporting worker adaptation in these situations is particularly important.

Overall, then, given the approach for integrated system design suggested by Vicente [19], the designs of the different elements would be integrated on the assumption that the design of every element is based on all five phases of CWA, as noted previously. However, given the reliance on the standard CWA framework, the designs would be integrated in relation to a reduced space of possibilities for action relative to the system's inherent capacity for adaptation. This is because the designs would not account for the organisational structures that are possible either in recurring classes of situation or in unforeseen circumstances.

In contrast, in the approach for integrated system design described by Naikar and Elix [8,9], emphasis is placed on integrating the designs of the different elements in relation to the set of possibilities for work organisation in the system irrespective of the circumstances. As indicated above, these possibilities can be delimited by defining the organisational constraints that are applicable in any situation. Thus these constraints will rule out the organisational structures that are never feasible, but within these constraints, there are likely to be many remaining possibilities for work organisation that are applicable to a wide range of conditions, whether novel or recurring. Which of these possibilities will be most suitable at any moment will depend on the intricacies of the situation, which may not always be known a priori, such that the organisational structures actors should adopt cannot be pre-specified. Instead, the problem can only be resolved in situ by actors, assuming they are supported in doing so by the system design.

6.2.3 Design

As alluded to above, the effectiveness with which an approach for integrated system design preserves a system's inherent capacity for adaptation is dependent not only on the method adopted for analysis but also on the process followed for design. Thus, having considered the perspectives of integrated system design suggested by Vicente [19] and by Naikar and Elix [8,9] in relation to the method of analysis, it is worth comparing the two approaches with respect to the level of integration afforded given the design process employed.

Once again, as such matters are not considered in detail by Vicente [19], it is difficult to be clear about his intentions. However, based on his earlier discussions of the use of CWA for system design [18], one potential implication of his approach is that the team design would be established before the designs of the other elements are considered. In particular, he discusses that once the actors in the system have been organised into groups or teams, it becomes possible to develop designs for the interfaces, training, automation, and so on that are tailored to particular workers. The

risk with this approach is that certain possibilities for work organisation in the system, assuming these are identified, may be ruled out if it is deemed that they cannot be supported by the team design, when in fact the possibilities could have been supported if the team design had been considered in conjunction with the design of other elements (an example is provided in the following discussion). In this case, then, the designs of the different elements would still be integrated, as the designs of the interfaces, training, automation, and so on would be tailored to the responsibilities of particular actors, given the team design. However, the designs could very well be integrated in relation to a reduced space of possibilities for action. Therefore, as before, such a design approach could restrict a system's inherent capacity for adaptation.

In contrast, in the approach described by Naikar and Elix [8,9], the team design need not precede the design of the other elements. Instead, the objective is to develop designs for each element that support the set of possibilities for work organisation. As indicated earlier, the possibilities for work organisation in a system take account of the full set of work demands for which each actor can be responsible, regardless of the position each actor may occupy within a group or team. Placing the focus, then, on designing each element to support the set of work organisation possibilities means that it is not necessary for the actors to be organised into groups or teams before the designs of the other elements can be considered. Rather the designs of the various elements can be considered in conjunction with each other, in relation to the set of work demands for which each actor can be responsible, which would increase the likelihood of the range of possibilities for work organisation in the system being supported.

As an illustration, it may be found that the set of work demands for which an actor can be responsible requires considerable competencies. If the team design is considered on its own, the possibility of this actor having responsibility for the full set of work demands might be ruled out. However, if the team design is considered in conjunction with the design of the training program, the full set of work demands might be accommodated. It may be feasible, for instance, for the actor to serve as a deputy to a more senior position within the team, following some basic instruction, such that the full set of competencies for the job can be matured gradually over time through on-the-job training. Such a design approach, which is anchored to the organisational constraints, rather than the team design, has a better chance of preserving a system's inherent capacity for adaptation.

7. CONCLUSION

In conclusion, this paper has highlighted some of the relationships and distinctions between existing design approaches based on CWA. Its focus was the use of CWA for system design, as outlined by Vicente [18], and for integrated system design, as discussed by Vicente [19] and by Naikar and Elix [8,9]. It was surmised that Vicente's [18,19] discussions of system design and integrated system design reflect differences in emphasis, with the former focusing attention on the relevance of each phase of CWA for particular classes of system design intervention and the latter emphasising the need for integrating the designs of different system elements, so that they are compatible with respect to the goal of promoting adaptation.

It was also found that there is some ambiguity about Vicente's [19] intended approach for integrated system design, which is not surprising as it was not his goal to provide a comprehensive description. In particular, it is unclear whether the designs of different system elements would be based on all five phases of

CWA and therefore on a common set of constraints. If they are not, then the designs of these elements would not necessarily be integrated in that they may not support the same possibilities for adaptation. Alternatively, assuming that they are based on all five phases, the designs would be integrated in relation to a reduced space of possibilities for action compared with a system's inherent capacity for adaptation. One reason for this shortfall is that the designs would be based on organisational structures that are commonly observed or judged to be reasonable in recurring classes of situation, rather than on organisational structures that are possible regardless of the situation. Another reason is that the designs of particular elements could be limited by the design decided for the team.

By heeding Vicente's [19] call for the need for integration, Naikar and Elix [8,9] have suggested an approach that increases the likelihood of preserving a system's inherent adaptive capacity. This approach involves defining the set of possibilities for work organisation in a system, irrespective of the situation, and coordinating the design of each element around the organisational constraints. As a result, the design of multiple elements can be integrated around the full set of possibilities for action available to each actor, such that the system design supports the range of opportunities for structural and behavioural adaptation in a coherent fashion across multiple actors.

The present consideration of design approaches based on CWA fosters greater understanding of how this framework may be extended and utilised to promote adaptation in complex sociotechnical systems. With respect to analysis, it highlights that the social organisation and cooperation dimension of the framework should be extended to account for the set of possibilities for work organisation in a system regardless of the situation. As the organisational constraints encompass the full range of opportunities for action available to each actor, whether structural or behavioural, this extension would significantly expand the capacity of CWA to support worker adaptation. In relation to design, this paper highlights that, irrespective of whether the focus is on a single element or multiple elements, the design of every element should be coordinated around the organisational constraints. Otherwise, the designs may not account for some of the possibilities for adaptation available to particular actors, such that the resilience of the system in the face of change or novelty is compromised.

Further work, however, is necessary to develop Naikar and Elix's [8,9] proposed ideas for integrated system design into a fully-fledged approach for facilitating adaptation in complex sociotechnical systems [10]. In particular, it is necessary to establish systematic processes for respecting the organisational constraints in the design of each element, such that the possibilities for adaptation are upheld expressly by the system design. For example, it is necessary to ascertain how the organisational constraints can be incorporated into the design of the interfaces, teams, training, and automation. Finally, some other key objectives of future research should be to validate the various ideas constituting the proposed approach, either through experimental studies or case studies, and to establish the feasibility of implementing this approach in industrial settings.

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