A human-interaction method for analysing design requirements for custom-built decision support tools for production control

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Abstract

A method is presented that can be used to analyse behaviour associated with production control by formally structuring field data collected from the manufacturing environment. The method links the tasks used in controlling production to the environmental factors to various levels of abstraction in regard to ends and means. It is an extension of Cognitive Work Analysis (CWA), which incorporates two different types of analysis: Work Domain Analysis (WDA) and Activity Analysis (AA). WDA uses an abstraction hierarchy (AH) - a generic framework for describing goal-oriented systems - to describe a system in a way that distinguishes its purposive and physical aspects. WDA is event independent and is quite separate from Activity Analysis (AA), which is a subsequent event dependent analysis of the activity that takes place within a work domain. The discussion lead to the expected benefits in using this method by designers of software tools for production controllers.

1. Introduction

Over the past decade, a group of researchers have been analysing human performance in production control. Central to their view is that “industrial practice and performance cannot be understood, nor can more effective processes be designed, implemented and managed without taking a holistic view of planning, scheduling and control processes” [1]. Through a discursive study of manufacturing history, McKay argues that as organisations evolve from ‘early market entry’ to maturity, they eliminate waste or non-value adding activities [2]. After eliminating internal inefficiencies, their focus shifts to the reduction of inventory by tightening the coupling to their suppliers. As the coupling tightens, the control of production becomes more complex as it is affected by the timing of deliveries from suppliers.

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In intermittent job shops or industries where there is inherent uncertainty or where human judgment is necessary, production control is generally acknowledged to be a skilled craft practised by persons who have extensive shopfloor experience [3]. The planning of capacity, routings, priorities, lead times and schedules requires practical persons, who understand the capabilities of machines and work practices within their domain. Their decision-making behaviour is mostly rational and goal directed [4]. Their decision strategies are often complex and hinge on their awareness of the subtle relationships between factors that comes from an intimate knowledge of the plant, products, and processes [5]. Knowledge and intuition, gained through years of first-hand experience, are the principal tools they use to generate and maintain satisfactory control over production. Numerous constraints imposed by environmental factors restrict the degrees of freedom on decision choices. Their goals and the means they use to assess performance depend upon context. Various cognitive factors also influence decision-making activities. Their behaviour is situated activity embedded in the particular work environment [6]. They have to make effective decisions in circumstances where there is no clear prediction of the state of the system, within an environment in which information regarding jobs, materials and resources are ill defined and scheduling goals are diverse. In Suchman’s terms, there is an “irremediable incompleteness” of instructions. They act pragmatically. In developing schedules, they don’t generate alternatives and then compare their strengths and weaknesses. Instead, they recognise typical situations and ways to respond. Predisposed towards actions that require little expenditure of time and cognitive effort, they behave like Klein’s proficient decision maker, who evaluates possible responses one at a time [7]. He argues that proficient decision makers try to anticipate what would happen if they carry out a specific action, by imagining its execution in the specific working environment. For simple cases, they easily recognise the situation and know straight away how to act. Klein calls this recognition-based reaction. It is similar to Rasmussen’s rule-based level of performance. For more complex cases, they consciously evaluate feasible choices [8].

To support their decision-making behaviour, production controllers need software tools that help them seek patterns within data, recognise familiar work situations, and explore different decision-making strategies under novel circumstances [4]. How can designers develop software tools to support them, if the environment is too complex for complete specification by rules? Make the design focus the support of situated activity. Preserve their initiative to evaluate with utmost control: place them at the centre of the decision architecture.

2. **Design requirements via modelling decision making**

To study production control behaviour as practised in manufacturing enterprises, researchers draw on diverse sources of information. A rich source of information is the shop floor. Observers may gauge much about the state of the system from the state of work-in-progress stored on the floor, the operating state of machines, etc., and through discussions with machine operators. They may also seek out informal ‘information networks’ to ascertain how they contribute to the information flow used in making decisions regarding production control [9, 10].
Development of the design requirements of software to support production control practices requires an analysis of the socio-technical system that includes the manufacturing system and the problem-solving behaviours of human decision-makers. Capturing the behaviour of human decision makers in a form that is suitable for formulating the requirements of software that can support situated activity is problematic. Ethnographic studies of situated behaviour of persons lead to rich descriptive models, full of meaning and nuance. However, they are difficult to verify and findings at a level of general abstraction are elusive. A method is needed that can realize generalised findings through abstraction, while providing the richness of descriptive models. There is a need for a structured language that describes human decision-making processes in a way that bridges the gap between descriptive and analytic models. Such a language for analysis is posited on a systems-thinking context in which the behaviour of production controllers is goal-directed and rational [4]. It encompasses both the engineering system and the problem-solving operations of the human decision-maker. It has a framework that acts as a template on which to plot the information used in the making of decisions.

3. **Cognitive Work Analysis**

Higgins [4] proposed a method for coherently marshalling and analysing diverse quantitative and qualitative information associated with production-control behaviour. This method extends Cognitive Work Analysis (CWA), which Rasmussen [8] developed and Sanderson [11] and Vicente [11] further elaborated. CWA is a systems-based approach to the analysis and evaluation of socio-technical systems. It provides a framework for generating descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states. It is a means for linking the sources and forms of information used by the decision-makers to decision activities into a high-level structural model.

There are two separate types of analysis in the standard form of CWA: Work Domain Analysis (WDA) and Activity Analysis (AA). WDA describes a system of resources in a way that distinguishes its purposive and physical aspects; its concern is “what” is being acted upon. WDA is an analysis that is independent of any specified events. AA is an event-dependent analysis that shows how activities are directed towards specific goals. These control activities correspond to “how” relationships. To extend the application of CWA from modelling behaviour associated with the control and maintenance of automated physical processes to production control, the method needs augmentation. Automated processes are designed to meet a limited set of specified goals. In contrast, production control is an intentional act in which the physical system’s configuration and purpose is under the behaviour of decision agents who have rational intent. Intentionality derives from the controllers’ purposes and values, which may include various subjective preferences of the schedulers and the organisation. For CWA to describe sufficiently such socio-technical systems, the varying goals of the decision makers need representation in the CWA framework. Thus, Higgins [4,5] added a goal structure as a third component to the analyses.
3.1 Work Domain Analysis

WDA represents the physical system in terms of constraints on the controlling activities of decision agents, either human or computer. Particular manufacturing processes are associated with certain machines. The required processes are “constrained” to specific machines and the production route is constrained by the order that processes may take. WDA describes the system using an abstraction hierarchy of means and ends. For a particular level, the level below depicts the means for achieving its ends, as depicted in Table 1. The intentions of the decision maker propagate down the hierarchy: from functional purpose of production control to the processing of jobs on particular machines. The functional purpose of production controllers is to manage production in a way that meets particular priorities and values (i.e., performance criteria). The lowest level of abstraction shows the state of the physical system (e.g., machines settings and processing variables). The next highest level represents the physical processes or functions of the various components and systems in a language related to their physical properties. In the case of the printing of stationery used for invoices etc., forms may require holes on the side of the paper: the lowest level shows the setting for a hole puncher; the level above is expressed in terms of hole production, without defining the means for its production. Above this level, concepts that are more general apply.

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*Table 1: Levels of Abstraction in Work Domain Analysis based on Rasmussen and Pejtersen [13].*

WDA can begin at any level of the abstraction hierarchy. An expedient starting point is the level of physical function. The upper level of Figure 1 describes the generic physical functions required in the processing of production orders at a printing plant. The level below depicts the manufacturing process in terms of physical resources (devices). The dashed arcs linking the functions and devices show potential means for achieving the functional ends. Note that for some operations, different resources can be used (e.g., folding, collating and finishing). In some cases, they are alternatives (e.g., in many cases it is immaterial which of the three collators is used). For others it depends upon the specific operation, for example, the Hunkeler collating machine can die-cut the paper and glue transparent window on envelopes and Akira printing press is the only resource that can apply ultraviolet light to cure special inks. Arcs from the ‘Special Finish’ to the Hunkeler and to the Akira indicate these ends-
means relations. Sometimes it may be useful to decompose the various processing features of a single machine, by expanding functions and devices along a parts-whole dimension: for example, at the level of physical-function, continuous printing could include, \textit{inter alia}, size and colours. Likewise, at the physical-device level, the Akira includes drum size and inks. Arcs link the attributes of a particular job at the purpose-related function level to the appropriate physical functions and devices.

The ends-means relationships between physical functions and physical resources form the levels of ‘physical function’ and ‘physical device’ in an abstraction hierarchy. For any particular job, the purpose-related level of the abstraction hierarchy consists of the specification for the manufactured components. In other words, the job specifies the purpose of the system. The attributes of a job form the intentional constraints on the physical parameters (material, geometry, batch size, etc.) for the manufacture of the final product. The purpose-related function of the manufacturing system changes with the change in jobs. Hence, in production control the WDA focuses on the configuration of the manufacturing system to meet the purpose-related function, that is, the production of a specified job.

Figure 1: Means-ends relationships between physical functions and physical resources [5]

Figure 1 forms the lower part of the more complete WDA shown in Figure 2, which shows the five levels of abstraction. The level of purpose-related function depicts the purpose of the production facility. It sets the mapping between functions and devices to the job’s specific requirements. The priority/values are the criteria used to measure the performance of the system in regard to its functional purpose. For a particular level, the level below depicts the
means for achieving its ends. Each job has its own mapping between levels as expressed by the arcs. Production controllers, in effect, instantiate the arcs by allocating the set of operations associated with each job to particular machines.

For each job, links from the set of constraints, that is, the specified attributes, to particular physical functions represent the feasible alternatives. All constraints on the purpose-related function that may map to constraints on the physical function must map to a single aggregated node for a link to exist. The temporal constraints (e.g., due date, arrival time) in the specification of the job are not physical constraints and consequently do not map between levels.

![Functional purpose diagram](image)

Figure 2: Work Domain Analysis for the production control of printing presses showing feasible means-ends links for a particular job specification

The hard technical constraints of the machines, which are causal constraints, project up to the purpose-related function level. Means-ends links only form where the causal constraints match the requirements of the purpose-related intentional constraints. For instance, the number of colours required for the job must be within the constraint boundary of the number
of colours that the press is capable of producing. As the physical system can be ‘redesigned’ by changing the set up of the machines, intentional constraints at the purpose-related level set constraints on the physical device. For instance, a press’s cylinder size is changed to meet the constraints set by the depth of paper required by the job.

As the configuration of the physical device must meet the purpose-related end, the abstraction hierarchy is redesigned for each job, because the purpose-related function is associated with a job. If the abstraction hierarchy for a job is drawn on a card, then the order of cards represents the order of jobs. Moving from one card to another denotes the changeover of jobs. By reconfiguring the system in a goal-directed way, the production controller takes on the role of system designer [13]. In effect, by sequencing jobs on a machine, the production controller orders the cards for jobs that have instantiated links to the specified machine (Figure 3). The temporal constraints (e.g., due date) may influence a job’s position in the batch of cards.

![Figure 3. Structural sequence of Abstraction Hierarchies](image)

### 3.2 Activity Analysis

Activity Analysis (AA) is an event dependent analysis of the control activities associated with decision behaviour directed towards specific goals. To analyse activity in decision terms, Rasmussen classified reasoning behaviour in supervisory control into three distinct types: skill-based, rule-based, and knowledge-based reasoning [14]. Rule-based behaviour consists of a sequence of subroutines in a familiar work situation, which the person consciously controls [15]. It is directed towards the meeting of goals. Very often, the goal is not even explicitly formulated, but found implicitly in the situation releasing the stored rules. As controllers develop skill, they do not apply rules mindfully; their behaviour rolls along without conscious attention. The boundary between skill-based and rule-based behaviour is not well defined, as it depends on the level of training and on the person’s focus of attention. During unfamiliar situations for which no rules for control are available, the control must move to a higher level that is goal-directed and knowledge-based.
Rasmussen’s SRK (Skill, Rules and Knowledge) framework for decision-making consists of cyclic activities of recognition and action, from the initiation of a decision maker’s response to the resulting action [15]. Rasmussen “bent” a flowchart of these cycles from a linear sequence into the “decision ladder” shown in Figure 9 and then added shunts and leaps to the basic sequence [16]. The left leg, upwards, represents analysis of the situation and the right leg, downwards, signifies the planning of action directed towards the goal, shown at the top of the ladder. The shunts and leaps reflect the behaviour of experienced decision makers: unlike novices, they do not have to move through all the steps in the sequence. A shunt from the left to the right leg of the ladder represents rule-based behaviour. An associative leap links two states of knowledge that are directly associated with each other. Rasmussen makes it clear that the decision ladder is not a model of the decision process itself, but a useful map for representing the structure of such a model [8]. Vicente, going further, asserts that it is not even a template of human information processing activity, but is a generic template for identifying the demands associated with particular activities [11]. In activity analysis, the ladder is merely a frame on which to sketch activities: consequently, it is not necessary to use every element.
Field studies reveal that the goals of production controllers vary over time [4, 17, 18]. Their goals depend upon the hour or the day and constraints change: “what is a ‘good’ schedule generated Monday morning may be considered a ‘bad’ schedule if generated Monday afternoon” [17]. Each goal has its own decision ladder. Figure 5 demonstrates the usage of the ladder for mapping activity directed towards an ultimate goal of the minimisation of average tardiness and machine utilisation. An associative leap across the ladder occurs when the production controller recognises that Earliest Due Date is a scheduling policy that meets this goal under the observed conditions. If the decision maker recalls the procedural steps for the rule, then they can directly execute the steps, otherwise, they first have to determine the steps. If no rules are clearly pertinent, then they must draw upon their deep knowledge of production practice within their domain. Mapping the AA for these steps onto the ladder requires a deeper understanding of the decision-maker’s mental context.

Figure 5: The decision-making activity in developing and maintaining a production schedule [5]
is currently unallocated, then the output of the decision ladder would be the instantiation of a means-ends chain in the abstraction hierarchy. Another ladder would concern scanning and shuffling. When abstraction hierarchy ‘cards’ are juxtaposed, the state variables required for a job are compared to those of its predecessor. If the set up of the machine has to change, then the controller has to map these changes of state to value measures associated with the goal structure.

3.3 Goal Structure

A structural relationship exists between the various goals that production controllers may pursue at different times in their decision-making activity (Figure 6). They do not pursue all goals simultaneously: different goals are active at different times. The operational objectives are directly at the focus of their attention and are associated with the ‘ultimate goals’ in the various decision ladders. An ‘ultimate goal’ will consist of one or more these objectives. For these goals, it is clear when they have been satisfied. The operational objectives have a structural relationship to goals at higher levels of abstraction. The higher that a goal is up the hierarchy, the less directly it relates to immediate operational activity. Nevertheless, by satisfying low-level goals, production controllers will tend to meet the high-level goals.

![Figure 6: The decision goal structure [5]](image)

Figure 7 shows the relationship between a decision ladder, the goal structure and the abstraction hierarchy. The high-level goals of the goal structure are linked to the functional purpose and the priority/values in the ‘means-ends’ abstraction hierarchy. The apex of the goal structure coincides with the functional purpose level of the abstraction hierarchy, and the
level immediately below coincides with the highest-level priorities in the abstraction hierarchy.

Figure 7: The relationship between the goal structure, decision ladder and abstraction hierarchy

Above the operational objectives are the functional goals, which production controllers may also directly attend, but, in practice, they are less likely to do so. These goals, which are those typically addressed by operations research (e.g., minimisation of tardiness or flowtime), are outside their immediate focus as they respond to situations arising within their environment. Generally, functional goals are far too abstract and remote for persons making decisions under both organisational and time pressures. At the higher levels are goals that indirectly relate to shop floor parameters. The focus is on short-term financial viability and customer patronage. At the top of the goal structure is the raison d’être of the company, the maximisation of long-term financial return. It depends upon short-term financial viability and customer patronage, which are the goals that are immediately below it. The higher a goal is up the hierarchy, the less it directly relates to immediate shop floor activity. High-level goals tend to be attained through satisfaction of low-level goals, rather than by the direct attention of the production controller. Nonetheless, the controller sometimes directly considered them when making scheduling decisions. Directed arcs into a goal indicate that as its underlying sub goals move towards satisfaction, it will also tend to move towards satisfaction. They do not depict direct causation. Violation of underlying sub goals linked to a goal does not mean necessarily that the goal is unachievable. Humans interacting with complex systems commonly seek multiple goals. Some goals may be in competition while others may constrain each other [19]. Arcs linking goals within a level of the hierarchy depict such constraints.
4. **Dynamics of goal setting and attainment**

Production controllers often consider multiple objectives, as multiple links from the ultimate goal in the decision ladder to the goal structure in Figure 7 demonstrates. In printing, a production controller’s primary intention may be to extend the queue of jobs at a particular press. In doing so, the controller may also try to meet as the ancillary objective, minimisation of time lost in setting up the press. Yet, in striving to follow the rules for reducing set-up time, the controller may need to consider additional constraints. For example, a change in set up may violate the requirement that there is a press configured for the instant processing of premium jobs, if they arise. The controller would have to decide whether to follow this soft intentional constraint strictly, on the off chance that unanticipated premium orders would appear within the current schedule horizon. These scenarios accord with Klein’s Recognition-Primed Decision (RPD) [7]. In considering potential moves, the controller may evaluate possible responses serially, reflecting on plausible goals, critical cues, expectancies, and typical actions. For this hypothetical case, the goals change as the controller considers the flow-on consequences of moving jobs. The goal at the top of the decision ladder varies.

The goals that are at the focus of a controller’s behaviour vary over time. As goals change, so do the activities. One type of behaviour is serial switching: as controllers recognise the pertinence of other goals, they redirect their activities, as a series of decision ladders portrays (Figure 8). In the printing case study, the following behaviour occurred. While organising work allocation, the controller observed insufficient jobs allocated to a particular press to cover the scheduling horizon. He started with activity 1 that had as a goal, ‘extend the queue length’ with a ultimate goal as ‘the minimisation of changes to the press set up.’ As he carried out this activity, he identified some jobs that he definitely wanted finished by their due date but would be tardy under activity 1. His behaviour then changed to activity 2; to resolve the relative importance of competing goals, decision activity then moved to the top of the ladder,
and the new goal extended the previous goal to include specific jobs are to meet their due
dates. Yet again, during this activity, he became aware that this activity violated the
operational constraint: ‘at least one press is prepared for the immediate processing of
premium jobs.’ Activity 3 represents the behaviour for including this modification to the goal.
In this example, changes to the system state act as alert for other goals that the production
controller needs to consider. Although Figure 8 shows serial switching between activities
directed towards different goals, scanning for patterns that trigger a new activity occurs
concurrently with the search for jobs that meet the constraints of the current procedure.
Therefore, the left side of the decision ladder (activities dealing with analysis) with an
associative leap to the ‘ultimate goal’ (e.g., activity 2 in Figure 8) runs concurrently with the
extant activity (e.g., activity 1). The right side of the ladder (planning and execution) becomes
active only when the production controller decides to direct activity towards the new goal.

An activity analysis for production control shows the dynamic aspects of goal setting and
attainment. There are clearly two phases in moving to a new goal. Production controllers first
evaluate whether they should redirect their attention to the new goal. If they perceive that
behaviour in this direction is propitious, they may then shift their attention. In some
situations, controllers may know their final goal but do not know at the outset the path of
action for its accomplishment. They may instead seek a subgoal that seems nearer to their
final goal and then plan actions for its attainment.

5. Design of production-control support tools

Cognitive Work Analysis represents the human and technical system through a triad of tools:
Work Domain Analysis to model the physical system; Activity Analysis to capture actions
associated with decision behaviour; and Goal Structure for representing complex relationships
between goals. It provides a foundation for software design in environments that are too
complex for standard requirements analysis to be unequivocal. By integrating the attributes of
people and computer systems, it provides a means for realising human potential and human
performance [20]. In applying this method, the aim is not to embody in the computer all
implicit procedural and structural knowledge from domain experts, but to enhance specific
human competencies. It replaces technology orientation in software design with a problem-
solving orientation [21]. The design focus is to support humans in recognising cues and
strategies from the context of the situation. This support must be such that their problem
solving behaviour is not constricted by support tools that are inflexible. To preserve their
initiative to evaluate situations and to control outcomes, the human decision-maker must be at
the centre of the decision architecture.

A human-centric tool allows an opportunistic approach to production control. Figure 9 gives
an example of human-centred decision architecture, in which the domain expert controls the
decision process. The knowledge-based adviser offers advice, which may be rejected. Human
decision-makers govern when the software applies procedural knowledge: which scheduling
rules to use on which sets of jobs. Humans act as intermediaries between the real-world
manufacturing environment and the abstract and simplified world of operational models. They
deal with conflicting goals that they can clearly express or just know tacitly; they resolve
how to use information that is incomplete, ambiguous, biased, outdated, or erroneous; they select when and how to apply selected heuristics.

CWA provides an analytical structure for the development of software requirements. For the rule-based level of activity, shown by the shaded region in Figure 10, computer-supported procedural rules are expressed on the right. On the left is the analysis process for recognizing the state of the system. It shows what information production controllers use to decide which, if any, computer-supported procedural rules are pertinent for the current state of the system and the cues they use to select the set of jobs they shall apply the rule. To help production controllers experiment opportunistically with various strategies, the displays should depict this information in ways that help users visualise relations between jobs and the effects of decisions on performance [11, 22].

Where no established procedures apply, production controllers decision activity is knowledge based. Information used for recognizing the state of the system under these conditions is expressed by the nodes further up the ladder on the left. The information includes recognition of performance relative to the goal. Therefore, to support activity directed towards the goal, displays include the performance measure and cues that show which actions would improve performance.

While a tool may be designed so users can follow familiar practices, improvements to production-control behaviour should be encouraged. Often production controllers are preoccupied with immediate operational objectives, which are at the lowest level of the goal structure. Occasionally, their attention may be drawn to high-level goals. If their focus could be generally raised to higher-level goals, then the performance relating to these goals may improve. To encourage them to lift their purview to higher-level goals, appropriate performance metrics should be included in displays.
7. Conclusion

The paper presents a method for analysing behaviour associated with production control. It provides a means for structuring the behaviour of practising production controllers. It links the tasks used in controlling production to the physical system and situational context at various levels of abstraction in regard to ends and means. The method consists of three interlinked analytical tools: Work Domain Analysis, Activity Analysis and Goal Structure. WDA describes a system in a way that distinguishes its purposive and physical aspects. AA is an event dependent analysis of the activity that takes place within a work domain. The discussion lead to the expected benefits in using this method by designers of software tools for production controllers.

8. References


