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# Integrating Domain and Worksystem models: an illustration from Air Traffic Management

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**Abstract**

This paper concerns a laboratory-based reconstruction of Air Traffic Management (rATM). A framework and model of the rATM domain, and a framework and model of the rATM worksystem are presented. The separation of domain and worksystem enables a designer to distinguish: (1) the work (performed by a worksystem), represented by a domain model, from (2) the behaviour of a worksystem (observed in carrying out the work), represented by a worksystem model . Integration of the separate models produces a single model that can be used to support the diagnosis of design problems. Problem diagnosis is considered an important stage within an evolutionary system development strategy, and one that would benefit from the support of an integrated model. Issues surrounding model integration are discussed, especially how a model of worksystem behaviours can be related to a domain model. An illustration of how an integrated model supports problem diagnosis is presented. The problem diagnosed is a discrepancy between the worksystem operator's mental categorisations of domain objects (aircraft), and the actual state of the domain objects being categorised. The model supports reasoning about the consequences of such a discrepancy.

**Keywords**

Domain, worksystem, model integration, categorisation, problem diagnosis

## 1 INTRODUCTION

This paper's aim is to illustrate the integration of two mutually informative models, one of a domain and one of an operator-device worksystem. In contrast to one software engineering view of domain analysis (Booch, 1991), domain here refers to a collection of objects (physical and informational), which are transformed by tasks performed by an operator-device worksystem. For Booch, domain analysis subsumes not only the analysis of the objects of

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work, but also an analysis of existing systems architecture and interactions. Booch's domain therefore includes elements of worksystem behaviour. Following Dowell & Long (1989), the present work on reconstructed Air Traffic Management *(rATM), separates the domain from the worksystem. Each is modelled using a different framework.

The importance of distinguishing the domain from the worksystem, for activities such as analysis of existing worksystems, can be illustrated with rATM. The goals of an rATM worksystem are expressed as the maintenance, between acceptable values, of the safety and expedition (fuel use, progress etc.) of managed aircraft as they traverse a sector. Acceptable values are set by an organisation (aviation authority). As aircraft can be more or less safe or expeditious, it is possible to express the work performed by an rATM worksystem in terms of the 'quality' of the interventions during the management task. An indexed measurement of task quality expresses the 'actual' state of the traffic with respect to a goal or 'desired' state. The value of the domain/worksystem distinction may be demonstrated by the fact that a number of different worksystems (exhibiting differing behaviours) may manage a given level of air traffic (a constant domain) equally well. For example, a worksystem, that includes a novel weather prediction device, would be considered different from one without such operator support. Models of the behaviour of the different worksystems would show variation in the ways in which interventions are planned and problems solved. However, if the same (domain) air traffic task is performed by the different worksystems, domain models may show no improvement in task quality for the worksystem with the new device. Thus, an expression of the 'effectiveness' of any worksystem should include some statement about the quality of the work it performs in the domain.

The present rATM worksystem comprises a trained human operator, a radar and Flight Progress Strips (FPSs). Generally, the prevailing strategy in ATM development is for the evolutionary integration of 'technology', automation and decision support, into the worksystem. Technological advance constitutes a reconfiguration of the worksystem. It is adopted in the belief that air traffic will be better managed with such devices than without them. A domain analysis and its product, a domain framework, can be used to construct domain models that express any resultant improvement in air traffic management. The same domain framework may be common to the analysis of the task quality achieved by a number of alternative worksystem designs. In addition to task quality, the effectiveness of an operator-device worksystem also needs to include some reference to the resource costs, incurred by the worksystem, while managing traffic at some level of task quality. Decision support technology may be understood to 'lighten the load' placed on operators managing domains. It is common for a redesigned device to bring about, not an increase in task quality, but rather a reduction in resource costs (such as 'mental workload'). System effectiveness is thereby improved through alleviation of stress, fatigue, error etc., that are induced by excessive worksystem resource costs.

Effectiveness is therefore expressed in terms of two components, one component concerns the domain, the other the worksystem. A domain framework provides a means of measuring task quality; a worksystem framework a means of measuring incurred costs in carrying out work of a measured quality. The aim of this paper is to illustrate the integration of components of separate domain and worksystem models. The measurement of overall system effectiveness will not be addressed. An illustration of how an integrated model supports problem diagnosis will be presented. The specific problem diagnosed concerns the compatibility of an operator's mental representation (model) of a domain, with the actual state of that domain.

* More commonly referred to as Air Traffic Control (ATC)

# 2 rATM DOMAIN: A FRAMEWORK AND MODEL

## 2.1 rATM Domain Framework

Dowell (1992) presents a framework for rATM within which aircraft objects and airspace objects are identified. Emphasis is placed, not on the analysis of aircraft objects *per se.*, but rather on the analysis of air traffic events, which arise when aircraft and airspace objects are associated. Five low-level attributes of air traffic events are presented, the PASHT attributes (Position, Altitude, Speed, Heading, Time). Four higher level attributes are derived from PASHT attributes: Progress (flight duration); Fuel Use; Separation; and the Number of Manœuvres (given to a particular aircraft). A hierarchy, from concrete to abstract attributes, is completed with two superordinate attributes of safety and expedition. Safety is derived from an aircraft separation value, which itself is computed from the position, altitude, heading and speed of each aircraft, with respect to all other aircraft on the managed sector. Expedition is derived from fuel use, progress and number of manœuvres, which are themselves computed from PASHT attributes (see Dowell, 1992). Interventions with particular aircraft may be viewed as a time series. Hence, an historical record of interventions, with any particular aircraft, may be viewed as an event profile. The concept of a 'profile' is of importance within the framework when considering a flight plan. Aircraft enter a sector at a given altitude, speed, heading and exit altitude. With this information, the rATM operator oversees the safe and expeditious management of all aircraft across the sector, such that aircraft leave the sector at their exit altitude and at a given 'goal' speed. A flight plan may therefore be described as presenting the operator with a desirable aircraft profile. Given the operational goals in rATM, it is possible to compare an aircraft's actual event profile with that of its goal profile and subsequently to identify any undesirable discrepancy. A profile thus consists of a series of air traffic event attribute values. Summing individual aircraft values, for separation etc., and dividing by the number of events, yields an average value for each attribute and thus superordinate values of safety and expedition are computed. Further summation of profile values for all managed aircraft may yield further values for the safety and expedition over the sector for a given worksystem.

## 2.2 rATM Domain Model

The rATM domain framework is embodied within a simulator. When the simulator is used, in conjunction with an aircraft data file (a specification for a level of air traffic, ordered in a particular fashion), the simulator records values derived from the framework, for each aircraft, from intervention to intervention. These values reflect aircraft progress (flight duration), fuel

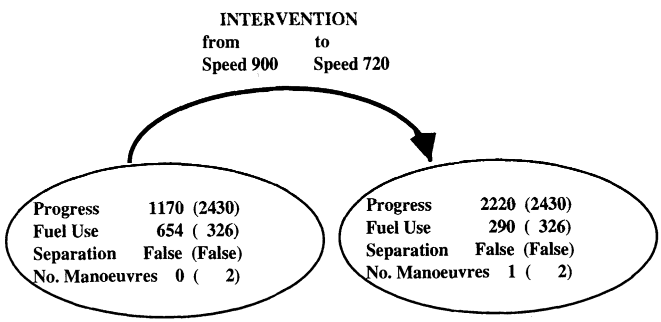


**Figure 1** Part of a domain model for a single intervention with aircraft BAN.

use, separation, and number of manœuvres (Figure 1) at the time of intervention. Post interaction analysis of these values, to compute superordinate attribute values of safety and expedition, yields a complete domain model with respect to the framework (Dowell, Salter & Zekrullahi, 1994). An rATM model is therefore a matrix of attribute values. The matrix shows how attribute values change over time, and therefore how aircraft states are transformed. Instances of desirable and undesirable task quality are thus detected by comparing values for an actual aircraft event profile with values for an aircraft's goal profile.

Figure 1 shows a small part of a domain model that records attribute value changes for an aircraft BAN, following an intervention to bring about a change in speed from 900 knots to 720 knots. This reduction of the aircraft's speed results in an increase in the projected time duration for BAN to traverse the sector, from 1170 seconds (s) to 2220s. However, a substantial saving in fuel use also results, from 654 to 290 units of fuel, as a consequence of 720 knots being ideal cruising speed for this class of aircraft. The absence of separation conflict can be seen not to change (BAN is as safe, with respect to other managed aircraft, at 720 knots as it was at 900), and the number of manœuvres given to BAN increments by one (a 'manœuvre' refers to any change in speed or altitude for a given aircraft). Bracketed values are 'goal' values derived from a goal event profile.

While such a domain model is of use in system design, it can provide only incomplete design support (Dowell & Long, 1989). In addition to information concerning 'what' changes occurred to an aircraft, and 'how well' the changes map to goal states, a model is also required to show how worksystem behaviour brought about the aircraft state transformations recorded in the domain model.

## 3 rATM WORKSYSTEM: A FRAMEWORK AND MODEL

### 3.1 rATM Worksystem Framework

The framework for modelling rATM worksystem behaviour (Figure 2) separates the operator from the rATM devices. In consequence, a worksystem model embodies a record of both operator and device behaviour. Two classes of device are used in the existing management task, radar and Flight Progress Strips (FPSs).

The radar displays data concerning aircraft: identity (call sign); position; and altitude (speed and heading data are also available upon request). As an aircraft progresses from beacon to beacon on its route, a radar trace corresponding to that aircraft is updated. To initiate an intervention, the operator highlights the relevant aircraft and issues a new speed or altitude value by menu selection. All aircraft traversing the sector pass through three beacons. For each aircraft under management, three FPS devices exist within the worksystem, one per beacon passed en-route: an entry beacon FPS; an intermediate beacon FPS; and an exit beacon FPS. Some data fields are common to all FPSs, such as an aircraft's identity (call sign). Other data only exist on entry FPSs (entry altitude and speed) or exit FPSs (exit altitude). As FPSs are paper constructs, once an intervention with a particular aircraft has been executed, the operator procedure is to update the relevant data field on that aircraft's active FPS. (An 'active' FPS is the FPS that corresponds with the beacon under which that aircraft is currently located). Consequently, the device behaviour component of rATM worksystem models should identify: the aircraft highlighted on the radar for intervention; changes in aircraft beacon position; changes to FPS data fields; and whether or not a particular FPS is active or not.

With the presented rATM domain analysis, and a description of rATM worksystem goals in terms of the maintenance of safety and expedition (within certain values), it is apparent that worksystem devices do not directly present data associated with the higher level attributes of individual air traffic events, as identified in the domain framework. If an operator wishes to know whether an intervention results in an aircraft (or group of aircraft) being more or less safe or expeditious, an estimation can be obtained only by further operator mental behaviour. This reasoning is not directly supported by the devices. The accuracy of any estimation is dependent upon the adequacy of that operator's mental categorisations (for relevant aircraft), prior to, and following, the intervention.

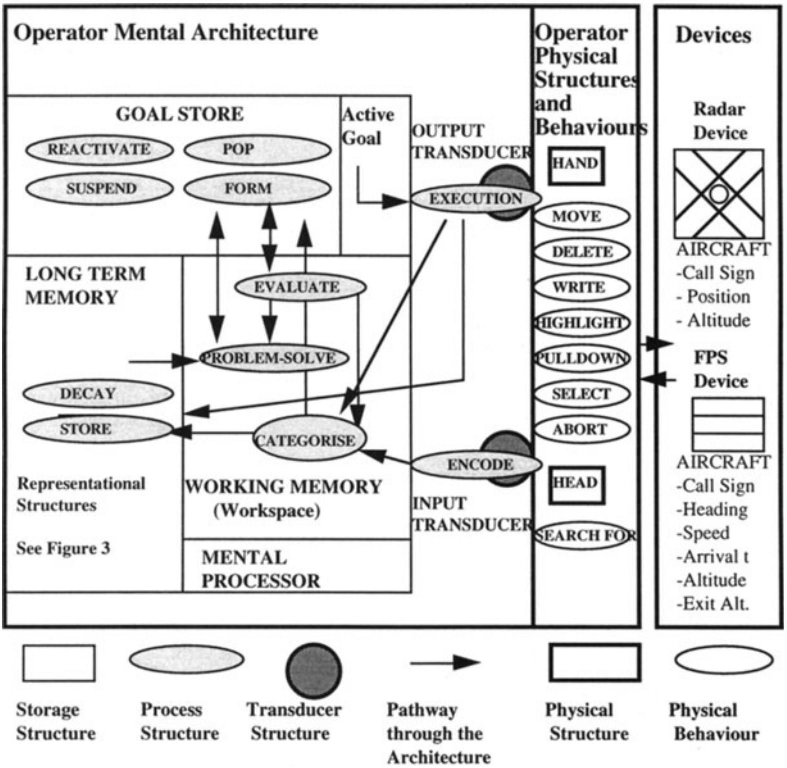


**Figure 2** A framework for modelling rATM worksystem behaviour.

The framework distinguishes the mental architecture of an operator (consisting of mental structures), from the physical structures and behaviours of that operator. Mental behaviour arises from the association of process and representational structures, identified in the architecture. The mental architecture supports modelling operator mental behaviour inferred from concurrent verbal protocol data, and head and hand movement data. It is not a computational architecture, such as SOAR (Newell, 1990) or ACT-R (Anderson, 1993), but is derivative of a computational architecture, that of the framework for induction (Holland, Holyoak, Thagard & Nisbett, 1989).

A sub-set of mental structures are identified (representational, process, storage and transducer), as required for modelling the rATM operator. A simple flow of information is shown; device data fields are 'encoded', the resultant signal then matched by 'categorisation' to a set of mental categories (Figure 3) in Long Term Memory and instances of categories 'formed' and 'stored'. A set of active category instances, present in Working Memory at any one time, constitute part of the operator's 'mental model' of the domain. Based upon this mental model of the state of the domain, goals are formed and actions executed.

Arrows between processes show 'legal' pathways through the operator mental architecture, for example, encoding a stimuli from the environment is always followed by the categorisation of that stimuli. Such pathways are essential to modelling operator mental behaviour.

The final part of the worksystem framework relates to overt physical behaviour of the operator. Two physical structures are involved, the operator's head and hands. Head movements are necessary because they signify 'search for' behaviour ('Search for' Aircraft BAN's speed value on BAN's entry FPS). Hand movements are necessary to cover a wider set of physical behaviours, including the 'delete' and 'write' behaviours, that alter the configuration of worksystem FPS devices.

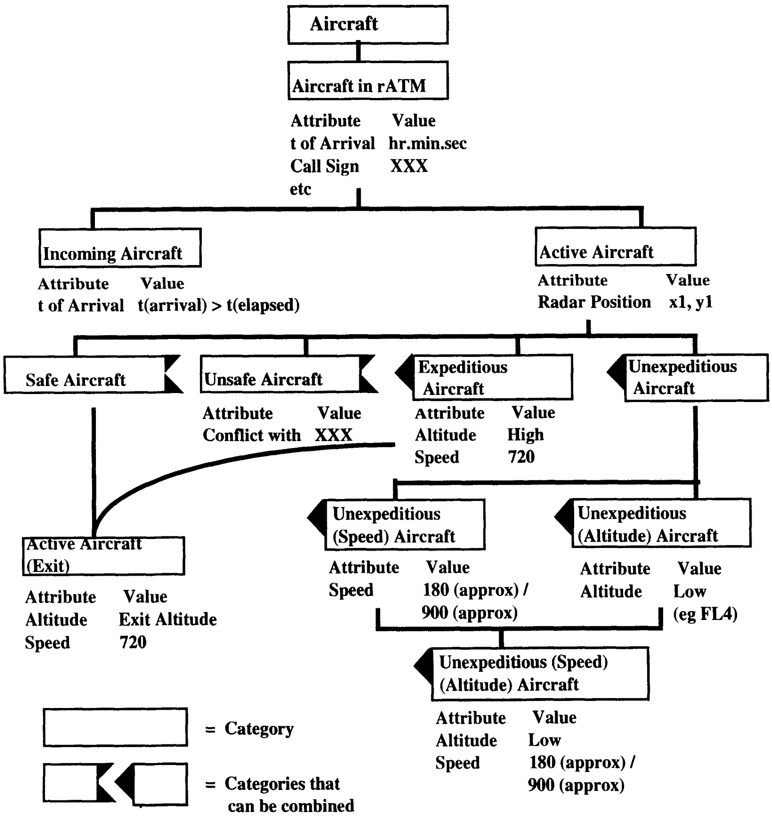


**Figure 3** rATM operator mental categories in Long Term Memory (representational structures).

The design problem diagnosed (Section 6) is a discrepancy between instances of mental categories formed by an operator, that correspond to the states of domain objects, and the actual states of domain objects, as shown in a domain model. A set of mental categories are proposed as part of the framework for modelling worksystem behaviour (Figure 3). From these categories mental representations of aircraft states are formed (category instances). The mental category of an 'Active Aircraft' is differentiated from that of 'Incoming Aircraft', based upon whether an operator has encoded a radar position for that aircraft, from the radar device, or whether elapsed simulation time is greater than time of arrival, as specified on an aircraft's entry FPS. A change in proposed mental category is established observationally, based upon overt behavioural evidence that a radar trace has been encoded. This evidence may take the form of verbal behaviour or head movement to the radar, with accompanying 'search for' behaviour. Observed behaviour results in a column of a worksystem model recording changes in an operator's mental category instances. In the case of an aircraft arriving on the sector, such a category instance change would be from 'Incoming Aircraft' to 'Active Aircraft'. If following this particular change in category, further overt search behaviour is observed, for example, for that aircraft's speed data field on an entry FPS (if that aircraft's speed value is 900 knots (therefore not goal speed of 720 knots)), this behaviour would result in a further recategorisation of that aircraft. The aircraft would no longer simply be represented as an instance of the 'Active Aircraft' category, but as an instance of the 'Active Unexpeditious (Speed) Aircraft' category. A goal may then be formed to intervene and reduce that aircraft's speed to 720. Using the framework in this way leads to the creation of models such as that shown in Figure 4.

## 3.2 rATM Worksystem Model

Figure 4 is part of an rATM worksystem model, for an operator identifying the presence of an aircraft (WAL) on the sector and amending relevant worksystem FPS devices accordingly. The model separates into different columns: the goals of the worksystem; the operator physical and mental behaviour; two sets of operator mental category instances (for domain and devices); and device behaviour. The separation of operator mental category instances, according to whether they refer to a domain object or a worksystem device, reflects the distinction between the operator's mental representation of the state of aircraft in the domain, and the operator's representation of the configuration of worksystem devices that reference those aircraft.

The 'Device Behaviour' column of the worksystem model (Figure 4) records that aircraft WAL has become visible ('Show') on the radar at beacon Gamma ($\gamma$). The 'Operator Behaviour' column, records that the operator's physical behaviour at this time is to search the radar for WAL, with the subsequent encoding of the trace (of WAL) at Gamma. The trace is categorised as referencing an aircraft, and particularly WAL, due to an encoding of WAL's call sign, shown next to that radar trace. Prior to this behaviour, the operator possessed a representation of WAL, as an instance of an 'Incoming Aircraft'. In consequence of the operator identifying the presence of WAL on the sector, WAL's mental category instance is changed to that of 'Active Aircraft'. The alteration in operator mental category instance for WAL (a representation of the domain), from 'Incoming' to 'Active' leads to a requirement to update worksystem devices to reflect this event. When an aircraft arrives on the sector, as in the case of WAL, the operator's behavioural procedure is to change the physical position of that aircraft's entry FPS on the FPS board, to the 'active' section under the relevant beacon.

The FPS will remain inactive, despite WAL's presence on the radar, until this updating procedure has been carried out. Such a 'reconfiguration' of worksystem devices is to reflect the fact that WAL is now under worksystem management, and to maintain the accuracy of the worksystem's device configuration with respect to a change of aircraft state in the domain. Hence, the second goal shown in the model is for an updating procedure to be carried out. The entry FPS is searched for, found (encoded) and moved to the active position. In the process of carrying out this task, data fields on the FPS for WAL's speed and altitude are encoded.

| Worksystem Goals | Operator Behaviour | Operator Mental Representation of Domain | Operator Mental Representation of Worksystem Devices | Device Behaviour |
|---|---|---|---|---|
| Establish presence of Aircraft 'WAL' on Sector | ***SEARCH FOR :*** *WAL, Radar (γ)* | | | Radar/Gamma, Show, WAL |
| | ENCODE / CATEGORISE: WAL<br>POP GOAL :<br>FORM GOAL:<br>Amend WAL FPS (Entry), Status | WAL, Position, Gamma<br>WAL, (from) Incoming Aircraft (to) Active Aircraft | WAL, Radar/Gamma<br>WAL FPS (Entry), Status, Inactive, OLD | |
| Amend WAL FPS (Entry) Status | ***SEARCH FOR :***<br>WAL FPS (Entry) Gamma / Inactive | | | |
| | ENCODE / CATEGORISE:<br>WAL FPS (Entry) | WAL, Speed, 280<br>WAL, Altitude, 50<br>WAL, (from) Active Aircraft (to) Active Safe Unexpeditious (Speed) (Altitude) Aircraft | | |
| | ***MOVE :*** WAL FPS (Entry), Active | | WAL FPS (Entry), Status, Active | WAL FPS (Entry) to Gal |
| | POP GOAL :<br>FORM GOAL :<br>Establish WAL, Exit Altitude | | | |

**Figure 4** Part of an rATM worksystem model.

This encoding leads to a further refining of the operator's mental representation for WAL. WAL is no longer merely mentally represented as an 'Active Aircraft', but 'Active Safe Unexpeditious (Speed) Aircraft'. Evidence for WAL's categorisation as active and safe is gathered by encoding the radar trace. Evidence for WAL's lack of expediency, with respect to goal altitude (undesirably low), and goal speed (undesirably slow) is gathered from encoding the entry FPS's data fields. While this change in mental category instance will have implications for future worksystem behaviour, the immediate goal of changing the state of WAL's entry FPS is completed and reflected in the operator's mental representation of device configuration, and also in the device component of the model itself.

## 4 DOMAIN AND WORKSYSTEM MODEL INTEGRATION

Frameworks and models for both the rATM domain and worksystem have been presented. Before discussing the utility of such a model in problem diagnosis (Section 6), three issues will be raised concerning the integration process: temporal alignment of models; mapping category instances to domain states; and mapping of worksystem and domain goal expressions.

### 4.1 Temporal alignment

First, the domain model shows air traffic event attribute values for: progress; fuel use; separation; and number of manœuvres, after each intervention with an aircraft. The worksystem model in contrast, shows a continuous stream of worksystem behaviour. It is necessary, therefore, to insert each set of domain model values, following an intervention, into the worksystem behaviour stream at the point at which that intervention took place. In the instance of rATM and Figure 5, this insertion presents no significant difficulties.

## 4.2 Mapping category instances to domain states

A second, and more complex issue, concerns the mapping of common terms of reference between domain and worksystem models, specifically the relationship between mental categories and domain states. The domain framework expresses the transformation of aircraft states, brought about by air traffic events, as a hierarchy of attribute values (Section 2). At the most primitive level, this expression is in terms of PASHT attribute values. However, higher level abstractions, such as fuel use and progress are also provided by the domain model. Worksystem devices display only the primitive PASHT attribute values. Hence, there is a difference between the domain model description of object transformations, in terms of levels of fuel use etc., and the empirical evidence from worksystem modelling, showing that operators predominantly categorise aircraft using PASHT attribute values. PASHT attribute values are those directly manipulated by operators when making interventions. An example of this difference is a domain model showing the primary outcome of an air traffic event to be a reduction in fuel use, while a worksystem model shows the outcome of the event to be a recategorisation of the aircraft as travelling at its goal speed. While a strong relationship exists between fuel use and speed, the operator lacks data, embodied within worksystem devices, for higher attributes (such as values for 'fuel use') identified in the domain framework. In consequence, operators seem unable to form adequate representations of the states of aircraft with respect to such higher level attributes. Further operator mental behaviour is required to derive higher level data from more familiar PASHT attributes, a time consuming and mentally 'costly' behaviour. Such inadequate technological support leads to a simplified 'mapping' by the operator, between the highest level air traffic event attribute of expedition, and the PASHT attributes with which the operator carries out interventions, namely speed and altitude.

In contrast to the simplified mapping observed with the complex attribute of expedition, the safety attribute values of domain models may be seen to map more directly to an operator's mental categorisation behaviour in the worksystem model. This more direct mapping may in part be because safety is a important and familiar concept for operators to act upon - avoiding the collision of objects in three dimensional space over time. Additionally, the attribute value is derived from a simple relationship between aircraft altitudes, positions, speeds and headings, i.e. PASHT attributes directly presented by worksystem devices to the operator .

In addition to attributes that are directly mapped between models, and those for which a simplified mapping exists, there are attributes of the domain framework that seem to have little possibility of being mapped to worksystem models. There is little evidence to suggest operators have any mental representation that equates with the 'number of manœuvres' given to a particular aircraft. Such data are distributed over a set of three FPSs. Further, in comparison to the attribute 'safety', the number of manœuvres appears inconsequential to the operator. As a result, the 'number of manœuvres' attribute and its value appear not to be treated as an important constraint upon worksystem behaviour. Integration may thus produce well-mapped attributes across models, as with 'safety'. Poorly mapped attributes such as expedition also occur, along with attributes that appear not to be mapped at all.

The final issue in integrating the rATM domain and worksystem models, concerns how domain model attribute values for progress and fuel use, which lie on a linear and hence relative scale (an aircraft may consume more or less fuel, progress faster or slower than planned), may be mapped to the mental categories modelled in the worksystem, which are absolute (a safe or unsafe aircraft; a fuel efficient or fuel inefficient aircraft). It is thus necessary to resolve how many units, for example, of fuel use, either side of a given goal value (for fuel use) may be tolerated, before it is expected that the operator should have mentally represented an unacceptable discrepancy and made an intervention. For the purposes of this analysis, the level of 10% (of the goal value) was established for progress and fuel use, and 50% for number of manœuvres. Safety, as it takes a Boolean value, does not require such treatment.

| Worksystem Goals | Operator Behaviour | Operator Mental Representation of Domain | Operator Mental Representation of Worksystem Devices | Device Behaviour | Goal Transformation | Domain Object Transformation |
|---|---|---|---|---|---|---|
| Establish, TAW, Speed & Altitude | ***SEARCH FOR***:<br>TAW, Radar ( γ)<br>ENCODE /<br>CATEGORISE: TAW →<br>***HIGHLIGHT***: TAW<br>***PULLDOWN***:<br>Request Speed<br>ENCODE /<br>CATEGORISE: → <br>POP GOAL :<br>FORM GOAL :<br>Establish TAW, Exit Altitude | TAW, Position, Gamma<br>TAW, Altitude, 55<br><br>TAW, Speed, 720<br>TAW, (from) Active Safe Aircraft (to) Active Safe Unexpeditious (Altitude) Aircraft | Radar/Gamma, Show, TAW<br>Radar, TAW, Selected | Radar/Gamma, TAW, Highlighted | | TAW<br>Progress 2700 (**2460**)<br>Fuel Use 374 ( **317**)<br>Separation FALSE (**FALSE**)<br>Manœuvres 2 ( **2**) |
| Establish TAW, Exit Altitude | ***SEARCH FOR***:<br>TAW FPS (Exit), Alpha / Inactive<br>ENCODE /<br>CATEGORISE :<br>TAW FPS (Exit)<br>POP GOAL :<br>FORM GOAL :<br>Intervention, TAW, Altitude, 135 | TAW, Exit Altitude, 135 | | | | |
| Intervention, TAW Altitude, 135 | ***PULLDOWN***:<br>Change Altitude<br>***SELECT***: 135<br>CATEGORISE: TAW<br>POP GOAL: | TAW, Altitude, 135 (changing)<br>TAW, (from) Active Safe Unexpeditious (Altitude) Aircraft, (to) Active Aircraft (Exit) | TAW FPS (Entry), Altitude, 55, OLD | | Improve quality of TAW, Fuel Use | TAW<br>Progress 2910 (**2460**)<br>Fuel Use 330 ( **317**)<br>Separation 1830 (**FALSE**)<br>Manœuvres 3 ( **2**) |

**Figure 5** Part of an integrated model of rATM worksystem behaviour and domain object transformation.

## 4.3 Mapping of worksystem and domain goal expressions

The third integration issue concerns the expression of goals. An examination has already been made of the complex relationship between the attributes manipulated by the operator, and the attribute values contained in a domain model. Because of the discrepancy between mental categories and a domain model description of aircraft states, it is important that worksystem goal expressions are separated from domain model goal expressions. A simple example is the alteration of a speed value. While a worksystem may express a goal at the level of the PASHT attribute, 'allocate a new speed value to aircraft BAN', a domain model expression of that goal would be in terms of an attempt to improve the quality of BAN's fuel use or progress (see Section 4.2). In addition, there are worksystem goals, such as checking that all FPS data fields are accurate, that have no direct correspondence with domain object transformations, and hence need to be expressed separately.

## 5 INTEGRATED rATM WORKSYSTEM AND DOMAIN MODEL

Figure 5 illustrates part of an integrated model. It shows worksystem components (worksystem goals; operator behaviour; mental representations of domain and worksystem; and device behaviour) taken from a worksystem model The figure also shows domain components (goal transformation; and domain object transformation) taken from a domain model. The initial state of an aircraft TAW is shown in the domain object transformation column (top). Changes in TAW's attribute values for progress, fuel use etc., as a consequence of an intervention that alters TAW's altitude from 55 to 135, are also shown (bottom of column). With respect to worksystem goals, an altitude of 55 is considered unacceptably low, the consequences of which are evident. Fuel use increases for aircraft at low altitude, and TAW's fuel use at altitude 55 is 374 units, 57 units more than the 'goal' level shown in brackets, or 18% in excess. TAW is safe as a 'separation' attribute value of 'false' is visible in the domain object transformation column. ('False', as a Boolean value within the domain model, signifies no projected separation conflict with other managed aircraft at current altitude). The operator behaviour column shows that TAW is identified as active on the radar, and categorised as being an instance of an 'Active Safe Unexpeditious (Altitude) Aircraft'. This category instance is compatible with the domain object transformation column's account of the state of TAW. The operator allocates TAW a new higher altitude of 135, based upon a search for TAW's exit altitude. There is no overt behavioural evidence that the operator was aware that another aircraft already occupied this altitude. Hence the intervention changes the operator's mental category instance for TAW to that of 'Active Aircraft (Exit)', a safe and expeditious aircraft in its goal state. The domain model, however, shows that at this new altitude TAW is in separation conflict with another aircraft in 1830 seconds. Hence, there is a discrepancy between mental category instance and domain state. Unpresented parts of the worksystem model indicate the erroneous mental category for TAW is due to the operator not having an active mental representation, at the time of deciding TAW's new altitude, of BAN already occupying altitude 135. The integrated model, therefore, relates the states of aircraft in the domain, and the changes in those states, to worksystem behaviour and mental representation.

## 6 DESIGN IMPLICATIONS OF MODEL INTEGRATION

It is proposed that reasoning in design (about alternative worksystem configurations and potential software tool assistance), will be better supported by an integrated model, than without such a model. Figure 6 summarises over a management scenario, for one aircraft ZEN, changes in operator mental categorisations of ZEN, and changes in domain state values for ZEN. How such a model may be used to diagnose problems associated with discrepancy will be shown.

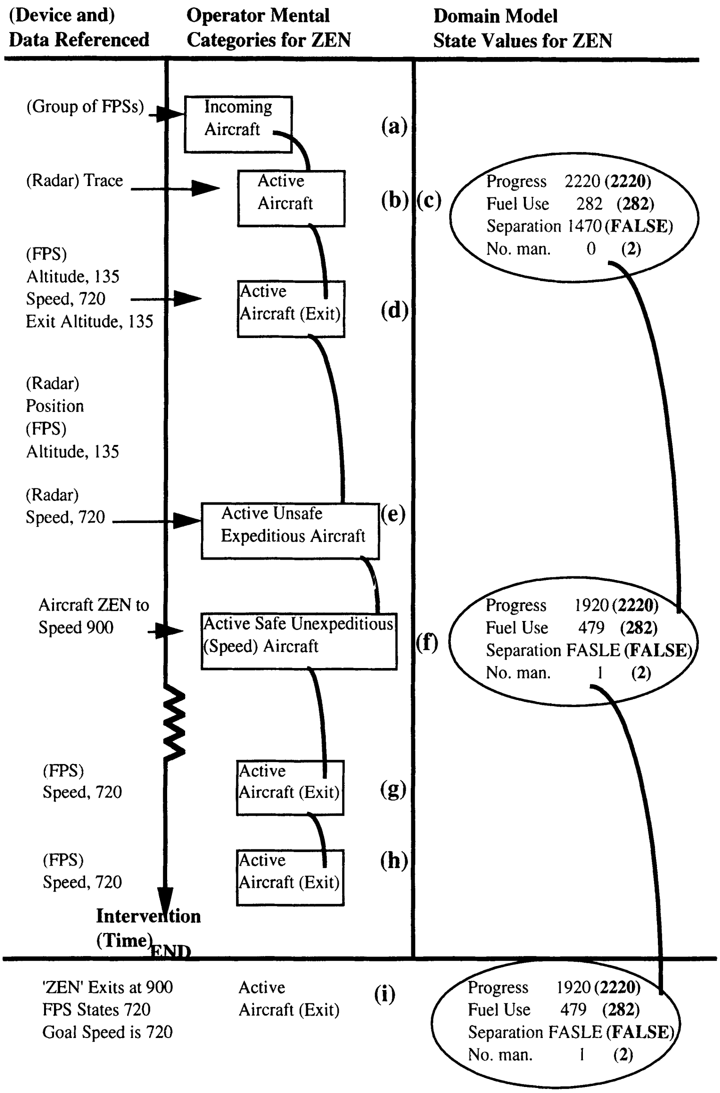


**Figure 6** Summary model of mental category changes and domain state changes for aircraft ZEN during a scenario.

An rATM worksystem that manages air traffic, such that aircraft incur 70% more fuel than is desirable, and traverse a sector in 13.5% less time than planned, may be considered to be an instance of an ineffective worksystem. ZEN is an aircraft that exited a managed sector with these (index) values of task quality. The model seeks to align, from transformation to transformation, the operator's mental category instances for ZEN, with the changing domain model values that reflect the actual state of that aircraft. Two important parts of this model will be commented upon, (c) when aircraft ZEN enters the sector, and (f) the only intervention made with ZEN. When the aircraft becomes active on the sector (c), the domain model identifies a projected collision with another aircraft 'X' at altitude 135 in 1470s. The worksystem model shows the operator is initially only aware that aircraft ZEN has arrived on the sector (b), a little later the operator becomes aware that, with ZEN's given speed and altitude, it is already in its exit state (d). The operator is not aware of the altitude conflict with 'X' until (e). The conflict is resolved with an intervention to ZEN that increases its speed to 900 (f), with a plan to slow ZEN back to 720 (goal speed), when the conflict is past. The usual procedure of updating ZEN's FPS speed data field is not carried out, due to a requirement for other interventions to be made. The radar device does not display speed data except upon request (query), and as a result of not updating ZEN's FPS immediately after intervention, the incorrect speed value is copied by the operator over to other FPS devices used during management, until ZEN exits the sector at 900. The failure to update the speed data field results in the operator never questioning the old value (720). Consequently, ZEN's speed is not reduced to the goal speed, because the operator repeatedly sustains an erroneous mental category for ZEN, that of 'Active Aircraft (Exit)' or an active safe and expeditious aircraft in its exit state, based upon an incorrect FPS data field (see '(Device and) Data Referenced' column at stages (g) and (h)). The integrated model supports such diagnostic reasoning about system ineffectiveness, based upon an understanding of the worksystem behaviours that result in an aircraft consuming excessive amounts of fuel, and progressing across the sector at a speed greater than is desirable.

As stated earlier, the speed attribute is a low-level PASHT attribute, involved in the computation of superordinate attribute values for both progress and fuel use. The operator has no device support for the construction of mental representations of the progress and fuel use of ZEN. Failure to update a speed value has effects that percolate up the hierarchy of abstraction used in the domain framework. Reasoning about alternative worksystem configurations may take the form of reasoning about decision support tools that reflect higher level attributes of aircraft, and their relationships with PASHT attributes, such that operators manage air traffic with more varied data sources than just PASHT attributes. In such a manner may design be supported.

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