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Title of Paper: Developing a Requisite Analytic Trade-Space for Assessing Agile Mission Grouping - Approach Adopted For the Construction and Implementation of the DARNSTORMS Model

Topics: C2 Analysis, C2 Modelling and Simulation, Cognitive Domain Issues, Social Domain Issues

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Developing a Requisite Analytic Trade-Space for Assessing Agile Mission Grouping - Approach Adopted For the Construction and Implementation of the DARNSTORMS Model

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Abstract: The DARNSTORMS model will integrate the functionality of the Australian Dynamic Agents Representation of Networks of Systems (DARNOS) C2 model with that of the UK Socio-cultural Teamworking for Operational Research Models (STORM). The technical work is being carried out by the two nations as part of a joint initiative to extend the available C2 modelling capability. This includes encompassing those social, organisational and cultural issues that are key to any effective, network enabled, multinational coalition operation, a primary deployment mode for our armed forces. These developments will help extend the modelling tradespace available to analysts to cover all Defence Lines of Development. In particular, it will be able to address the important issues for Coalition C2, Agile Mission Grouping, Training & Experience, Rapid Deployment, Net-enabled C2 and Comprehensive Approach.

The current paper provides preliminary technical details and results on how the models are being integrated, the construction, implementation and interfacing issues that are being resolved in the process. It leads on to focus on the calibration of the model parameters, the management of the uncertainties surrounding them and the sensitivity analysis required to identify which of these uncertainties impact significantly on model performance.

1. INTRODUCTION

A key aspect of effective collaboration between elements of a (joint) force and, in particular, a coalition force is the development of a capability that can remain effective despite the challenging context of agile network-enabled (coalition) forces. Such forces are implied by the 'comprehensive approach' to operations.

The background to the development of DARNSTORMS is the recognition of the mutual benefit of collaboratively developing a sufficient representation of agile, networked, multi-national forces so that a 'requisite trade space' can be generated to support key planning processes. The collaboration will combine two extant models, DARNOS and STORM.

Australia's DARNOS provides modelling and simulation support for analysing the operational effectiveness of a networked force (a team) with special focus on the impact of social structure (command and control or networking structure).

This will be combined with the UK's STORM to give analysts the additional ability to evaluate how factors such as the prior personal experience, socio-cultural mix and work context may contribute to the overall performance of the networked force. Of particular interest is the dynamic behaviour of performance as teams form and re-form in an agile way to match emerging Coalition tasks. This collaborative effort, known as the DARNSTORMS Project, is jointly funded by the Australian Defence Science and Technology Organisation (DSTO) and the UK Defence Science and Technologies Laboratory (Dstl) for development.

The principal focus of the DARNSTORMS model will be to examine the impact that the HQ team social, cultural and organisational characteristic parameters have on the performance of the organisation

for the given task, within an NEC/NCW context [18, 19].

2. THE MODEL DEVELOPMENT APPROACH ADOPTED FOR DARNOS AND STORM

As stated above, DARNSTORMS is a collaborative effort to combine the DSTO agent based military C2 model DARNOS and the Dstl socio-cultural teamworking model STORM. The product of this union will be an agent based C2 model with the capability of addressing the social, cultural and organizational issues that are inherent in coalition operations within a NEC/NCW context.

Both DARNOS and STORM have been designed and documented using the Unified Modelling Language (UML) [17] and this continues to be the case for the DARNSTORMS model itself.

This approach has simplified considerably the developmental compatibility issues for the two models. However, more importantly it has enabled the bulk of the development effort on each model to be applied directly to the underpinning conceptual modelling activities rather than expended on coding matters. This is illustrated in Figure 1 below, which outlines the development lifecycle approach that was adopted for the STORM model.

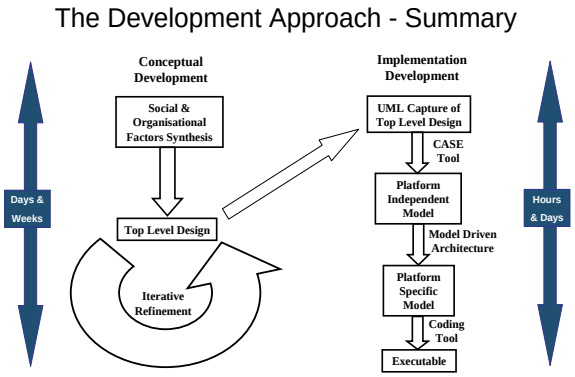

Figure 1: STORM Development Lifecycle

The efficiency of a UML based approach in both cases is due in part to the fact that both DARNOS and STORM are readily represented in terms of a dynamically changing network of interconnected components.

In the case of DARNOS, these are in the form of military organizational and associated C2 network components. In STORM, they are the collective social, cultural, teamwork and taskwork related knowledge states possessed by the team and the dynamic interactions between them.

In addition, the STORM team and the DARNOS orgon (organizational component) are both agent entities and, as such, directly representable in object form.

As is indicated by the two vertical arrows to either side of Figure 1, the bulk of the effort on STORM has been directed at the development of the underlying conceptual model, rather than on its' implementation in executable code. The efficiency in the production of this executable code arose from taking advantage of the automatic code generation capabilities of the standards compliant Model Driven Architecture (MDA). MDA provides coding transformations from the abstract UML representation into platform specific source code ready to compile into an executable program.

The Enterprise Architect UML development tool, used to produce STORM, has been chosen for the development of the DARNSTORMS model. In addition to fully standards compliant UML model creation and MDA driven ANSI C++ code generation capabilities; it provides the necessary project QA capabilities, such as model version control and documentation facilities.

3. DARNSTORMS FUNCTIONAL ARCHITECTURE

The DARNSTORMS architecture comprises of: a simulation infrastructure; physical components; NCW components; and analyst utility components (see Figure 2).

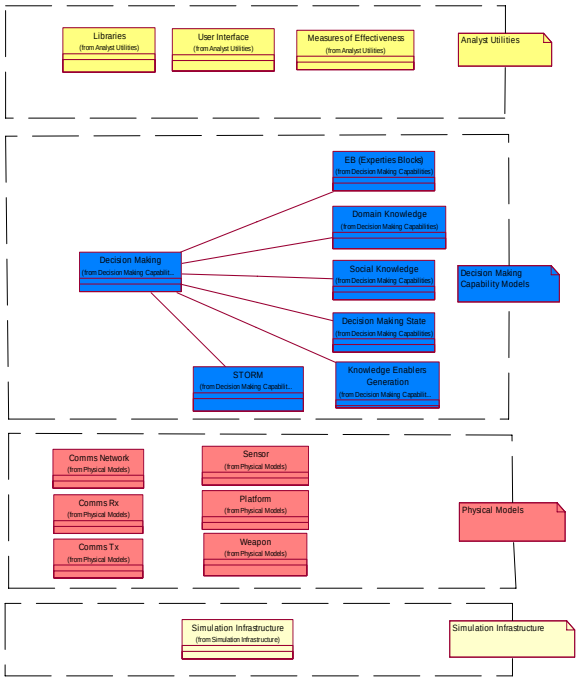

Figure 2: DARNSTORMS Architectural Components

The simulation infrastructure provides the mechanisms for the defining, running, rerunning and

replaying of scenarios by analysts. All other components in DARNSTORMS operate within the simulation framework.

The NCW Player is an element in the NCW scenario that can be considered a self contained entity in its own right. The NCW Player can play the role of multiple Nodes by considering it as a NCW Service Cluster. NCW Service Cluster is the collection of NCW Nodes that provide NCW functionality to a NCW Player. For example, an Airborne Early Warning and Control (AEWC) is an NCW Service Cluster that can perform the roles of:

- C2 Node, as a subordinate to a Regional Operations Centre (ROC), and a superior to Joint Strike Forces (JSFs);
- Comms Node, with the ability to provide data to other Players through data link;
- Sensor Node, with the ability to generate contact information based on tracks formed with its sensors, and identification determined by onboard Decision Makers.

The physical components model the physical characteristics of the NCW Players that exist within an NCW scenario. These in effect model elements defining the Sensor Grid (through the Sensor Nodes, which determine what information I can provide) and Engagement Grid (through the Weapons Node, which determines what I can attack). The physical elements considered include:

1. Platforms (aircraft, ships, …);
2. Sensor Node: including sensors such as radar, electro-optical…
3. Weapons Node: including weapons such as AAM, SAM…
4. Comms Node: including the onboard transmission (Tx) and reception (Rx) communications systems (radio, data link …).
5. Communications Network, which models the communication infrastructure through which the Comms Nodes communicate.

The Decision Making Capability models the decision making of the NCW Players that exist within an NCW scenario, which includes:

1. Decision Maker behaviour of the NCW player.
2. The STORM model of organisation maturity process, which impacts on the Decision Maker's behaviour.
3. Team Characteristics Generation, which calculates the STORM Settables for the NCW player.
4. EBs are the Expertise Blocks of the NCW Player. EBs are discrete modules of decision-making capability that encapsulate procedural knowledge.
5. Domain Knowledge contains the domain knowledge of the NCW player.
6. Social Knowledge contains the social knowledge of the NCW player.
7. Decision Making State contains the decision making state of the NCW player.

The Decision Maker models are developed to provide both generic behaviours and scenario specific decision making capabilities required for DARNSTORMS scenarios.

The NCW components model the command and control, and information sharing responsibilities of the NCW Players.

The STORM model of organisation maturity process is integrated with DARNOS. This allows the evaluation of the organisations maturity, at different stages of their maturity process, as organisations are formed dynamically during the scenario execution.

DARNSTORMS development concentrates on developing these components that are specific to the integration between STORM and DARNOS.

The Analyst Utilities components include:

1. User Interfaces (UI) used by analysts to examine a running scenario;
2. MOE components to capture the data to be recorded and/or displayed during the scenario execution;
3. Libraries support utilities to manage the entities to be incorporated in NCW Scenarios.

The primary interfaces of the architectural components are presented in 3 below.

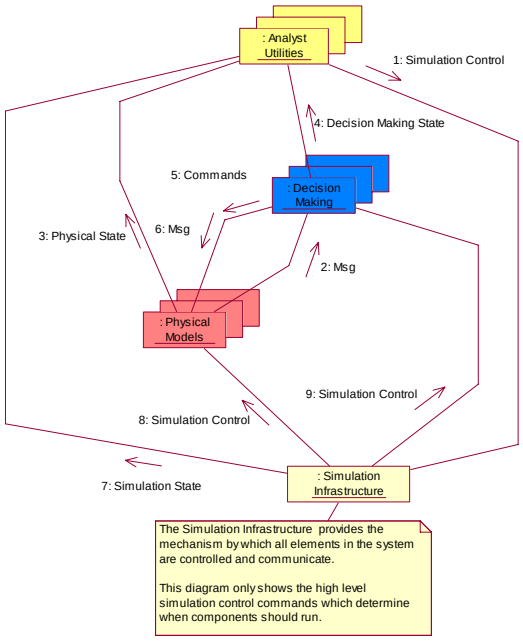

Figure 3: DARNSTORMS Architectural Interfaces

The primary interfaces to the Analyst Utilities component provide facilities to: present data to the user through the User Interface; capture data for processing Measures of Effectiveness; and controlling the simulation. The utilities to create scenarios from libraries of models are also managed within the Analyst Utilities component.

The Analyst Utilities component obtains data from: the DARNSTORMS components, which provide the: Decision Making State; Physical Component States; and Simulation State.

The Decision Making State provides data describing the information flow, command flow, and internal state of the Decision maker.

The Physical Model components present state information about the physical components including: position, speed etc of platforms; state of the communications system; etc.

The Simulation State presents information about the simulation including simulation time and runtime performance of the simulation.

The Analyst Utilities component also provides the interface by which the user can control the simulation infrastructure, for example by running faster or slower than real time.

The Simulation Infrastructure provides the mechanism by which all data is passed between components and determining the execution order of the components. All data that is passed through the Simulation Infrastructure is also available to the Support component, for display, recording or manipulation.

This infrastructure functionality is not explicitly presented in the diagrams below, i.e. if the diagram presents information flow between components, the flow is implicitly available to the Analyst Utilities components.

4. DECISION MAKING INFRASTRUCTURE

DARNSTORMS models the dynamics of team formation and the subsequent effect on team performance. DARNSTORMS will represent and allow variation in the key Settables associated with the dynamic organisation formation (e.g. activity awareness, mutual understanding, co-location etc.) measuring the organisation performance according to their roles and capabilities (using the information received and based on which decisions are made) for achieving the mission objective.

Figure 4 presents the flow of information through the Decision Maker.

The activities which take place include:

- The Decision Maker receives inputs from STORM organisation maturity level [1], communication messages from other Decision Makers (NCW players) [2], own sensors state [3] and platform state [4].

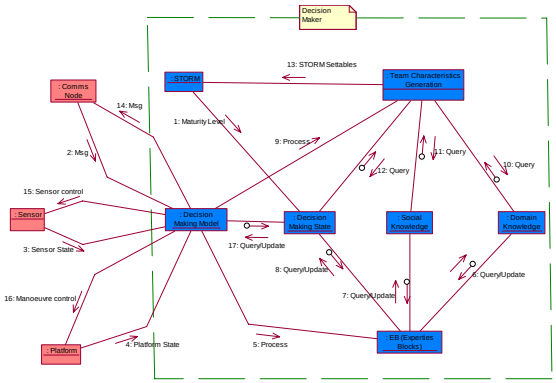

Figure 4: Decision Maker Infrastructure

- The Decision Maker, using its EBs, performs processing for the current simulation tick [5].
- This processing may include the Decision Maker's EB's:
  1. Querying of the Decision Maker's Domain Knowledge [6], Social Knowledge [7], and the Decision Making State [8]; to gather information required to make decisions;
  2. Performing the updates to the Domain Knowledge [6], Social Knowledge [7] and the

Decision Making state [8], to change their internal state or view of the world; and

3. Issuing messages to the other Decision Makers [14], issuing sensor control [15] and platform manoeuvres [16]

- Using the Team Characteristics Generation component, the Decision Maker determines the STORM Settables for the current simulation time step [9].
- This processing may include the Team Characteristics Generation:

1. Querying of the Decision Maker's: Domain Knowledge [10], Social Knowledge [11] and the Decision Making state [12]; to gather information required to determine the STORM Settables;
2. Issuing STORM Settables to the STORM component [13].

5. ORGANISATION MATURITY LEVEL

The Organisation Maturity Level is part of the interface between DARNOS and STORM. The Organisation Maturity Level is calculated by STORM (as the equivalent task-specific Team Maturity Value) and is provided by it to DARNOS, in order to influence the way in which, and the extent to which, the task is performed.

The Team Maturity Value is generated by the STORM implementation of the Tuckman-Jensen small group maturity model [16]. This model is implemented in STORM as a finite state machine, with the transitions between the various maturity states triggered by the internal knowledge variables exceeding a relevant set of task-specific threshold values.

The Decision Maker in DARNOS makes use of the Organisation Maturity Level, which it receives directly as an input from STORM. Within the Decision Maker, the Organisation Maturity Level can influence the decision making process in one or more of the following ways:

1. Different level of maturity can determine the different interaction structures that the Decision Maker can adopt. For example a mature organisation may allow free flow of information between sub-organisations; while an immature team requires information to be flowed and filtered through "more experienced" sub-organisations.
2. Different level of maturity can determine the selection of EB (EBs) that the Decision Maker can use. For example, a mature team may have a wide range of EBs to choose from to accomplish a goal, while an immature team may have fewer options.
3. Different level of maturity can influence which groups of EBs are executed to achieve a goal. For example, an immature team may execute additional EBs (eg to gather and evaluate additional information) to achieve a goal, compared to a mature team.
4. Different level of maturity can influence the execution of EBs. For example if the Organisation Maturity Level is low it may take longer to make a decision. For example, which structure to adopt under in a changing situation?

6. STORM SETTABLES

The STORM Settables are part of the interface between the DARNOS and the STORM components of DARNSTORMS. The scenario-dependent STORM Settables are calculated by the Team Characteristics Generation module in DARNOS.

Figure 5 summarises the current set of 15 STORM Settables, which were developed to accommodate the range of factors that need to be able to be modified to address C2 modelling within the NEC/NCW context.

Specifically, the current group of Settables is designed to address those factors of importance to modelling the impact of the following capabilities:

- Coalition C2;
- Agile Mission Grouping;
- Training & Experience;
- Rapid Deployment;
- Net-enabled C2 and
- Comprehensive Approach.

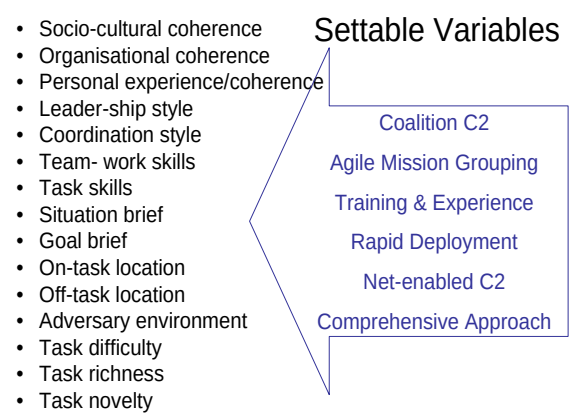

Figure 5: The STORM Settables

The Settable variables, in conjunction with the nature and degree of their influence on the set of internal knowledge variables of the STORM model, directly shape the overall behaviour of the model in any given scenario. Therefore,

capturing the specification of the Settables, along with the precise nature of their interactions with the internal STORM variables, is key to the effectiveness of the sensitivity analyses performed on both STORM alone and also on DARNSTORMS.

It should be noted that the final 3 Settables (Task difficulty, richness and novelty) differ from the other 12 in the way that they impact upon the model. Whereas the other 12 Settables determine the capabilities of the team, these specify the nature of the task and the requirements that this makes of the team. As these increase in value, it becomes more difficult for any given team to perform the task effectively.

The relationships between the various STORM variables and those between them and the 12 capability determining Settables are all represented by a generic functional form, based on the sine wave.

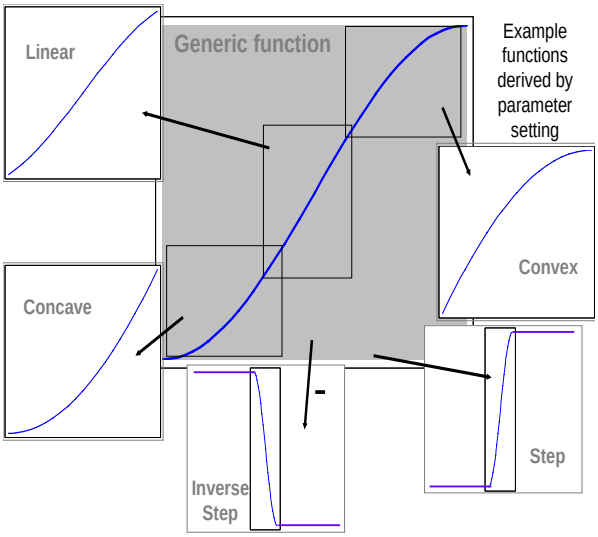

Figure 6: Generic Sine Wave Function Relationship between STORM Variables

Figure 6 shows how different types of monotonic relationships can be derived by mapping the input and output variable ranges onto different sections of this curve.

This flexibility of form is essential in permitting an exploration of the impact of different relationship forms on the model predictions, as part of a more general parametric sensitivity analysis.

A natural extension of this approach, across more than one cycle of the sine wave, addresses more complex functional forms, e.g. as indicated in **Figure 7**. This extension will primarily accommodate unimodal and inverse-unimodal forms of relationship between variables.

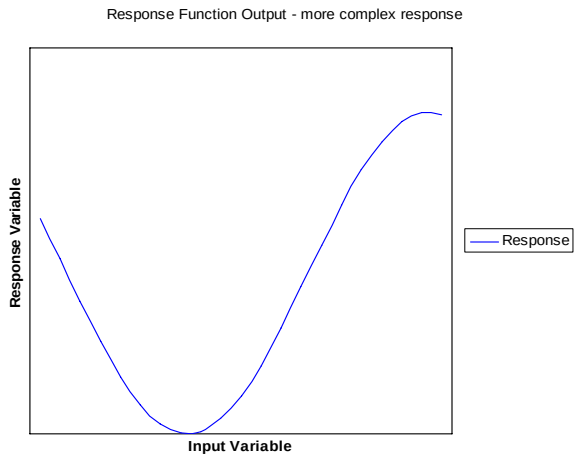

Figure 7: Extension Of The Sine Wave Function Beyond Monotonic relationships

7. SENSITIVITY ANALYSIS

From the outset, STORM has been developed to encompass, as far as possible, a requisite set of variables for modelling socio-cultural teamworking within a military OR context.

Because of this fact, there will be a varying degree of knowledge available to specify each of the selected variables. This is both in terms of available empirical data for specifying the value taken in any given context and also in the overall range of values that they may conceivably take.

A number of modelling issues arise from this variability in data quality and availability, in particular the impact of the resultant parameter uncertainties on the team maturity and performance measures of team effectiveness produced by STORM.

In addition, the variation of these measures of effectiveness over time is one of the most important of these issues, particularly within the context of agile mission group operations. This dynamic can, however, only be tested effectively within a closed loop sensitivity analysis, requiring the gearing with taskwork that the DARNSTORMS model provides. Hence, it can only be addressed effectively once the combined model has been developed.

A combined process of calibration of the STORM variables and sensitivity analysis on the parameterisation of their inter-relationships has been devised to minimise the impact of these uncertainties where possible and to quantify the residual impact that remains thereafter.

This process also enables a focusing of future research onto those remaining variable and parameter uncertainties that are of pivotal importance to military C2 modelling within the NCW/NEC context.

A first, open-loop calibration and sensitivity analysis performed on the standalone STORM model during May and June 2006 provides an initial uncertainty and sensitivity bounding for the model parameters.

This first calibration and sensitivity analysis process will be followed by further, closed loop sensitivity studies on the full DARNSTORMS model, at appropriate points during the course of the model development programme. This will provide further, context-specific information to help fine tune the model parameters and also to focus future research efforts onto pivotal variable data.

These latter require a suitable scenario to provide the necessary C2 related context for these analyses, particularly the dynamic interactions with the DARNOS C2 task working activities, as outlined in Figure 8 below.

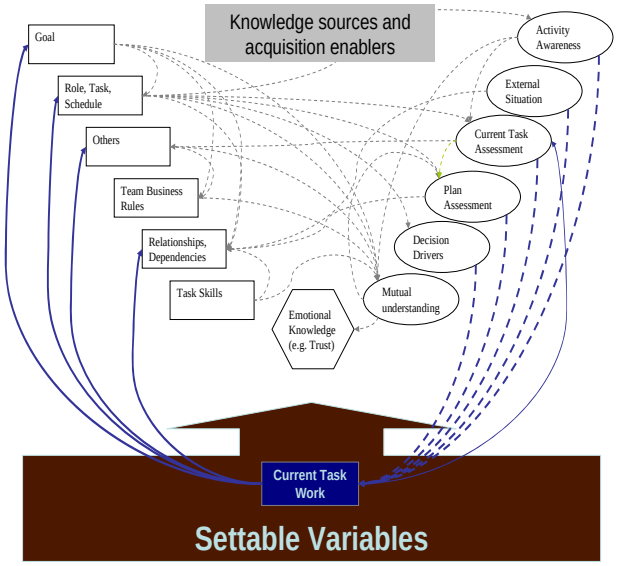

Figure 8: Interaction of STORM With DARNOS C2 Task Working Activities

To characterize the range of values to adopt for each of the various STORM variables, a sensible range approach was adopted. In this, a uniform 0 to 10 scaling is adopted and indicative sensible minimum (2), sensible average (5) and sensible maximum (8) values are characterized in terms of the relevant team properties and associated context information. The range of each variable can then be scaled up or down according to its required relative influence within the model.

The SIMLAB sensitivity and uncertainty analysis package [13] is used to undertake the specification of the STORM variable and parameter set sampling scheme and for the generation of all the input datasets for the sensitivity analysis. It also runs the STORM standalone executable and harvests the output data for subsequent statistical analysis.

SIMLAB can also perform a range of statistical analyses to identify the pivotal variables, inter-relationships and parameters in the model.

A Latin Hypercube Sampling (LHS) scheme [14, 15] is applied to the system for the generation of the input datasets, thereby ensuring a fully representative sample set is employed in the sensitivity analysis. Unless otherwise indicated from the relevant available empirical evidence or theory, a uniform distribution of uncertainties was assumed for each of the STORM variables.

Unlike for the STORM standalone model, the use of SIMLAB to provide a sensitivity and uncertainty analysis framework is not feasible for DARNSTORMS, due to its closed form. It needs to provide its own batch run sample generation capability.

Therefore, in order to facilitate the undertaking of such sensitivity analyses on it, a required capability of the DARNSTORMS model is to record measures from batches of runs for offline analysis. This is the primary mode for the sensitivity analysis and calibration of STORM parameters and variables within the DARNSTORMS model. This facility provides analysts with the capability to:

1. specify a set of variant scenario parameters, as required by the STORM model for the process of dynamically forming organisations,
2. run the scenarios to completion
3. capture the effects of these settable values on the organisation maturity process and team performance measures of effectiveness.
4. save the model output in a form suitable for offline statistical analysis

8. THE INITIAL OPEN-LOOP SENSITIVITY ANALYSIS ON STORM, WITH PRELIMINARY FINDINGS

An initial open-loop sensitivity analysis was undertaken during May and early June 2006. This took the form of a screening analysis, to identify the sensitivity of each of 14 key STORM knowledge variables to changes in the values of the 15 Settables. The variables are key in that, in combination with each other, they determine the team maturity state and hence, effectiveness. Figure 9 identifies these 14 key variables (to the right), as well as listing the 15 Settables (to the left).

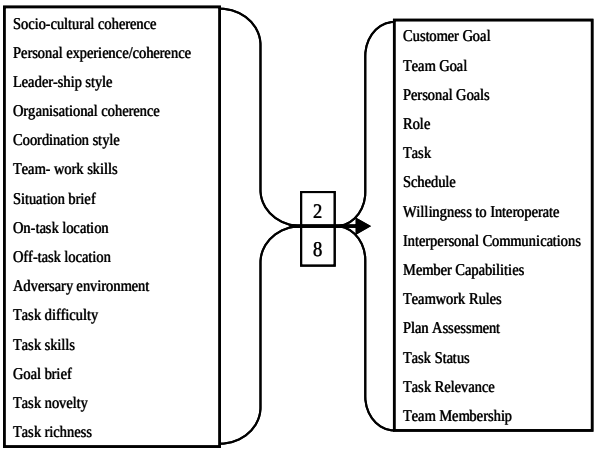

Figure 9: The Input Settables and the Output Knowledge Variables Used In the Initial Sensitivity Analysis

For this analysis, it was assumed that all of the variables adopted the same 0 to 10 scale as one another. This equalisation of the effect sizes simplified the subsequent analysis of the results, permitting the direct comparison of all of the inputs to each key variable.

A two level factorial design approach was adopted, using the sensible minimum (2) and maximum (8) values as the two levels. As this was a screening analysis and a full 15 factor 2 level design would require 32,256 runs of the STORM model, a 1/16th fraction was used (i.e. 2048 runs). This design resulted in 3 pairs of two-way interactions being confounded. In mitigation of this, the settables were assigned to the factors in such a way as to ensure that at least one of each pair of interactions was scientifically infeasible.

Measures were derived for the sensitivity of each of the 14 STORM knowledge variables to the variation applied to the values of the settables. We determined both the size of each effect and also the associated statistical significance of it.

A preliminary assessment of the results obtained from the sensitivity analysis indicates that the STORM model behaves in a stable manner, supplying sensible results for each run.

Each of the 14 key variables showed the expected sensitivity to variations in those Settables that are direct inputs to them. For example, apart from the Team Initiation activity variable, the Team Membership knowledge variable has two direct inputs, both Settables (On-Task Location and Off-Task Location). As one would expect, the variation in this key variable in the sensitivity analysis is characterised fully by the equivalent variation in these two Settables.

A more detailed programme of review of the results from the open-loop sensitivity analysis is currently underway. This assessment is being undertaken in conjunction with the relevant project scientific Subject Matter Experts.

When complete, the review will provide a full assessment of the scientific plausibility of the current STORM implementation, as this is characterised by these sensitivity analysis results. This will be especially important in ensuring the correct representation of the Settables where they are indirect inputs to the key variables.

The questions to be answered in this context are:

- Is the representation complete?
- Has all duplication of this representation been eliminated?

As an example of this concept of Settables as indirect and as direct inputs to the key variables, consider the Team Goal knowledge variable.

This variable is central to the team maturity development process, crucial to progress from Forming to Storming and thence to Norming. Figure 10 shows both the direct inputs to the Team Goal variable and also the indirect inputs to it (i.e. the direct inputs to the direct inputs).

Figure 10 below shows that, in total, Team Goal has 7 Settable variables as inputs to it. Two of these (Task difficulty and Task richness) are demands placed on the team by the task, 4 are team capabilities and the other (Off-Task Location) is a team behaviour moderator. Of these inputs only the two demands and Organisational Coherence are direct inputs, the remaining 4 are indirect inputs via the Customer Goal and Personal Goals knowledge variables.

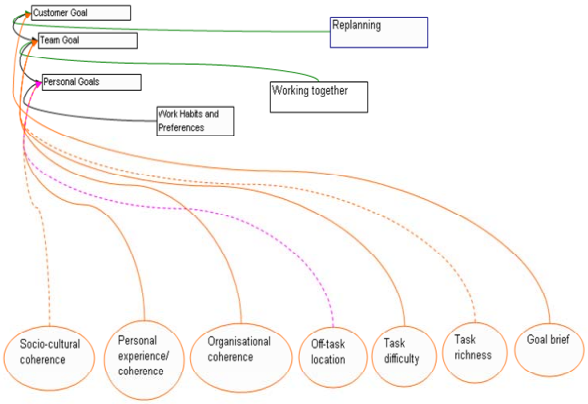

Figure 10: Direct and Indirect Inputs to the STORM Team Goal Knowledge Variable

If the STORM model represents the indirect inputs to Team Goal correctly, they should have similar effect sizes and statistical significance levels to those obtained for the direct inputs. For the Team Goal knowledge

variable, this is precisely what was found from the open-loop sensitivity analysis.

9. CONCLUSION AND FURTHER WORK

From a modelling standpoint, the open-loop sensitivity analysis undertaken on the STORM model indicates that it is both stable in operation and that it produces sensible results. Without this, it would not be possible to interpret the results of the sensitivity analysis as being due solely to the relationships between the STORM model variables.

The relative sensitivity of the key knowledge variables to variations in the Settables values is very much as would be expected, when these Settables are direct inputs.

A rigorous evaluation of the cases where the Settables are indirect inputs to the key knowledge variables is being undertaken at the time of writing, to ensure the scientific plausibility and completeness of the representation of these.

This examination of the results from the open-loop sensitivity analysis will result in an appropriately calibrated STORM model, which is a prerequisite for any subsequent closed-loop sensitivity analyses of the DARNSTORMS model.

A suitable case study is being developed jointly by Dstl and DSTO to explore the range of values that may realistically be adopted by each of the main STORM Settables. This will form the basis for the closed-loop sensitivity analyses to be performed on DARNSTORMS.

The primary difference between these and the open loop sensitivity analyses performed to date is that the case study will provide a clear C2 context to the closed loop analyses. This will result in a more precise alignment of the behaviour of DARNSTORMS with that required for the effective modelling of HQ teams within the overall military C2 context.

So, the DARNSTORMS model will be further calibrated within the context of this case study and additional model parameter sensitivity analyses will be performed. The method to be employed for undertaking this process has already been designed, but development of the DARNSTORMS model takes precedence over it in the collaborative work programme.

The STORM model itself has already been refined from its first version through the consolidation of the Settable variables, now both fewer in number and more practical in nature. STORM will be refined further in the light of the experience gained from the scenario-based variable calibration and parameter sensitivity studies to be undertaken on the DARNSTORMS model.

We intend to iterate over this calibration, sensitivity analysis & refinement process during the course of the DARNSTORMS model development process. In fact, two full iterations of DARNSTORMS model development and testing are planned to be undertaken during the course of the current collaborative programme.

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