An Appraisal of System Dynamics in Assessing the Impact of Computer Information Systems

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Abstract

Any attempt to impose a computerised information system (CIS) upon an organisation requires an assessment of its impact in terms of costs, benefits and procedural change. This paper briefly describes the capacity of the System Dynamics technique to capture the essence of an organisation's management structure and to assess, from a system-wide perspective, the impact of imposing a CIS. The paper employs, as a basis, two case studies set in a military context and a particular methodology developed with these applications in mind.

The efficacy of system dynamics in assessing the true impact of CIS on the enterprise and the user, is appraised, based on a set of independent criteria. The significance of the methodology for CIS development generally is considered and encompasses an elaboration of its place in the software life cycle.

Introduction

Recently, information technology has assumed a rapidly expanding role in supporting the military commander's decision-making capability and his exertion of organisational control. Frequently, however, such command, control and information systems (CCIS) fail to achieve their expectations upon implementation. Consequent user cynicism is encouraging a more diligent scrutiny of the objectives, functions and possible design options of a CCIS prior to its development.

CCIS are increasingly being employed within the military tactical environment. Procurement of these systems is frequently very complex, and usually involves several phases each of which can be protracted and expensive. A crucial task in the early phases of the procurement cycle is to obtain an estimate of the expected operational benefits and drawbacks. The primary objective of this study is to investigate the usefulness of the System Dynamics method in assessing the effectiveness of such CCIS. A secondary objective is to assess the utility of extending the System Dynamics method into other phases of the procurement life-cycle such as the evaluation of alternative system designs.

The General Approach of the Study

Unlike many traditional hard modelling environments, the aim of a System Dynamics study extends beyond providing merely a quantitative description of a system and a simulation of its behaviour within the rigid, technique-dependent constraints of a goal-directed methodology. System Dynamics is also a qualitative tool which encourages the participation of all the relevant actors in a holistic and educative debate and embodies many of the concepts associated with soft systems thinking. This appraisal of the System Dynamics technique will be based on a series of criteria having general applicability, each of which will constitute a measure of the suitability of the method in evaluating the effectiveness of CCIS.

The Applications

In order to investigate the generality of the System Dynamics technique, two candidate areas from the Land Systems tactical military environment were selected for the initial study and, correspondingly, two parallel study streams were initiated. To ensure that the study had a more universal relevance, two study streams detailed below were chosen from quite different but complementary areas.

Battlefield CCIS

A conceptual battlefield CCIS might, if deployed, assist battlegroup commanders, their staffs, battlegroup elements down to individual vehicles and associated support elements. The intent is that it will improve the present command and control process thereby giving commanders and staff more time for decision making based on accurate, relevant and timely information. This project is currently in the pre-feasibility phase and a detailed requirement has yet to be established.

Logistics CCIS

This is a possible logistic CCIS applicable to the higher levels of battlefield military command. It will support the various logistics cells by providing common computing facilities such as word processing, message handling, recording and automatic dissemination of data, data accessing, order production, calculation aids, etc. This project is already well down the development path having completed the analysis and logical design phases.

The Approach

The means of employing System Dynamics in both application areas was characterised by 3 stages:-

Stage 1 involves knowledge acquisition through discussion between the clients and modellers. It attempts to define the scope of the investigation, to identify real-world symptoms and possible causes and to capture them in the form of an influence diagram. These diagrams form a structural representation of the relationships and dependencies between the entities within the problem space and focus on the behavioural dynamics by means of an explicit realisation of the feedback processes involved.

Stage 2 involves the superimposition of CCIS representation on the base model by modelling the effects of CCIS attributes on the environment - not in their physical manifestation, but in terms of their effects on organisational activities. In general terms, the CCIS is represented in terms of the quality, relevance and timeliness of information.

Stage 3 allows the effect of changes in policy or objectives in the organisation to be explored, with the aim of optimising the application and employment of CCIS. This may include necessary changes in operating procedures brought about by adoption of the CCIS and allow comparison of the benefits and drawbacks of proposed configurations.

This approach is described in greater detail elsewhere (Wolstenholme 1990)

The Assessment as applied to Logistics CCIS

This study stream involved deriving a sufficiently detailed understanding of the military logistics organisation in terms of its objectives, structure, activities and policies, and the determination of organisational performance measures. A representative activity was selected and the policies and activities relevant to that area specified in detail. The models were designed around an acceptable level of aggregation and, in stage 2 of the methodology, included specification of the principal CCIS attributes such as comprehensibility, relevance, availability, timeliness and accuracy of information. The models, written in DYSMAP2, were driven by a selection of scenarios. The thrust of the study was aimed at providing an holistic appreciation of the CCIS on the host system in terms of high level performance measures relating to system achievement. It was concerned with assessing the need for information as a function of the way in which the information will be used. A full account of this process is described elsewhere (Watts 1990).

The Assessment as applied to Battlefield CCIS

This study stream began by attempting to conceptualise and structure the analysis of the CCIS problem area through discussions with the client. The model construction and its subsequent development provided a means of structuring the debate and stimulated insight by study of the model's output. By employing System Dynamics as a data capture and knowledge structuring aid, the study stream highlighted some of the soft systems aspects of the method. The use of influence diagrams as a communications medium was particularly significant, instigating discussion on modes of functional representation. The construction of a baseline model, using the STELLA package, was based on these representations and subsequently enhanced by the superimposition of the CCIS. Interpretation of the measures of organisational effectiveness as output during model execution yielded additional insight into the identification of critical functions and their response under varying patterns of CCIS support. A full account of this process is described elsewhere (Henderson 1990).

Assessment of System Dynamics Against Qualitative Criteria

The efficacy and suitability of System Dynamics was appraised by reference to the following qualitative criteria:-

a. Flexibility and Generality

System Dynamics models systems in terms of five distinct conceptual entities: processes, organisation structure, information structure, strategies and delays. These entities form a basic primitive set which facilitate easy translation to System Dynamics modelling constructs. The generic nature of these elements allows considerable flexibility and generality in model construction.

In the model of ammunition supply the following elements were represented. The physical process of interest was the movement of ammunition. The model displayed the underlying hierarchical structure associated with military command and incorporated the strategies which controlled the movement of ammunition. The strategies were effected by monitoring the physical flows (such as ammunition in transit) and information flows (such as perceived ammunition stock levels) and executing the appropriate policies (such as stock or resource allocation). The delays were employed in simulating the transit of various entities such as supply transport.

In the model of battlegroup functions the primary physical flow represented the availability and attrition of opposing combat units. The strategies were effected by monitoring the physical flows (such as number of available active units within range) and information flows (such as perceived enemy strength) and executing the appropriate policies (such as advance or "shoot and scoot"). The delays were employed in simulating such variables as repair times or movements.

The model can be graphically presented in either of two formats. Flow Diagrams link the building blocks with arrows representing the direction of flow and are useful in demonstrating the assumptions with reference to the physical processes. Influence diagrams link the building blocks with arrows showing the direction of influence of one variable on another and are useful in determining the underlying feedback structure of the organisation and in forming a basis for quantitative model development.

b. Ease of Problem Formulation and Development of Models

Within System Dynamics, models are formulated through iterative interaction with the client. However, the iterations result in the formulation of both a conceptual model (i.e. in the form of a structured analysis on paper) and an executable model (normally created using a specialist System Dynamics tool).

In the case of the logistics model the the System Dynamics concept of stocks and flows mapped naturally to the physical nature of the application. The development of the strategies and information sources and sinks was built on this base model in a relatively straightforward top-down manner.

In the case of the battlefield CCIS the disparate functionality of a battlegroup was modelled by establishing concepts underlying each separate function and then defining their interdependency by means of influences.

The ease with which conceptual models are formulated is dependent upon the investigator's skill at knowledge elicitation, capture and structuring, upon the enthusiasm and responsiveness of the client and upon the efficacy of the graphical and other tools employed. In the case of System Dynamics, influence and flow diagrams provide an accessible and easily intelligible medium for expression of the colloquy. In similar future studies model development effort may be mollified by employing a set of guidelines formulated for this type of problem which will help in overcoming the inexperience of modellers new to the technology.

The formulation of executable models is eased by selection of an appropriate dynamic modelling software package which automates many of the tasks involved in model development and obviates the need for a technical computer specialist. Accessible, user-friendly packages such as STELLA which exploit the full range of contemporary MMI capability are particularly valuable.

c. Ability to Cope With Complexity

The ability to cope with complex issues is a concern of all analysis/modelling techniques. The model constructor can quickly lose track of the interactions of the various elements within the model, and cognitive limits are soon overrun.

The logistics function is an extremely complex organisation encompassing many commodities, modes of transport, routes and locations. A model including detailed representation of the processes associated with all services and commodities would be expensive to develop, both in man-hours and hardware requirements. It is likely that the complexity of such a model would render the interpretation of its behaviour relative to the nature of the supporting information system extremely difficult. Consequently only a representative activity of the logistics operation (the ammunition supply function) was modelled. The impact of the CCIS on this activity was assessed in relative isolation. The assessment could subsequently be extrapolated to the whole organisation.

In the case of the battlefield CCIS the resolution of the primitive functions was only taken as far as necessary to assess the system-wide impact of a CCIS. The granularity of the model was controlled by appropriate aggregation of functionality. For example the reinforcement of a force may be represented as a simple pulse omitting the nature or precise pattern of reinforcement.

d. Transparency (Clarity) of Assumptions

A client's appreciation of assumptions underlying a model is dependent upon their perception and sophistication as a model user and the simplicity of the model construction. The cause and effect linkages employed in System Dynamics enable the assumptions inherent in the model formulation to become apparent to the system owner.

In the logistics case the nature of the tool was particularly appropriate for modelling ammunition movements enabling easy identification of the storage locations and directions of ammunition movement. Similarly information flow was easily traced to particular sources and sinks enabling policies to be identified.

The battlefield CCIS study employed various modelling techniques which did much to limit the distance of the cognitive horizon, such as restricting the number of variables, aggregating variables with common characteristics or limiting the amount of uncertainty incorporated.

e. Relevance to Problem Solving

The System Dynamics approach is aimed at creating change through understanding. Illumination of the problem area and the facilitation of insight by means of the process of analysis and model construction is more important than attempting to provide definitive answers concerning predicted system behaviour.

For example, during the development of the logistics model the systemic world view of the System Dynamics model clearly highlighted the contradictory goals of operational and logistics personnel and the requirement for policies that balance their needs.

The battlefield CCIS study similarly showed concern for the co-ordination of the disparate battlegroup functions and their interdependencies as an expression of the system-wide impact of the CCIS.

f. Realism

System Dynamics attempts to capture the adaptive information feedback and strategies of organisations. The emphasis is on defining how organisations contribute to their own problems, rather than blaming external influences.

Within both CCIS study streams the variables employed had a direct and apparent real-world counterpart for example ammunition supply rate in the logistics model or attrition rate in the battlefield model. No causal links were included unless they were acknowledged as existing in the real-world organisation.

The realism of the conclusions drawn is dependent upon the perception of the relevant actor, whether client or analyst. Realism is approached by achieving a consensus deriving from the differing viewpoints of all participants in the system.

g. Knowledge Acquisition

System Dynamics models are formulated through iterative interaction with the client. A useful starting point is to provide a rudimentary, unembellished model of the system under investigation which will normally provoke an immediate and positive response from the client. A suitable model may act as a germ which will grow and develop as the concepts and structure underlying the system are exposed. The clarity of these models captures the knowledge of the client more succinctly than mere verbal expression.

This was illustrated in the logistics study when the demonstration model provoked a positive and immediate response and stimulated the logistics system owners to present their requirements in a useful and assimilable form.

h. Interaction and Communication with System Owners

In many systems, the physical processes can be observed by the modeller, but the control policies and mode of information use must usually be obtained by direct interaction with the system owners. In the case of live battle systems, direct observation is unrealistic and the modeller must rely on the system owners to describe the physical processes as well. It is therefore particularly vital that in these applications all the actors have a common medium of expression.

Influence diagrams are easy for a client to understand, and thus provide a sound medium for communication between client and investigator. The client's involvement at every step of model formulation and development increases commitment to the model and encourages a more proactive role. Clearly, influence diagrams are not the only medium of expression and there are situations where other devices work better. But there are few such devices which permit such a closely coupled and immediate relationship between model and user perception.

i. Ability to Create Insight

One of the most powerful aspects of System Dynamics is that it encourages systemic interactions to be considered from a holistic perspective. Participation in the model development process encourages the client to question pre-conceived ideas and to formulate an original approach.

By studying the CCIS integration with current C2 procedures, the method can highlight areas where introducing elements of the CCIS might proved detrimental to the system as a whole. Similarly the method can also be used to experiment with standing procedures in order to make best use of the CCIS.

In both study streams, the essential systems approach compelled the system owners to consider the relationships between the system components and to appreciate the system dependencies.

Assessment of System Dynamics Against Quantitative Criteria

The efficacy and suitability of System Dynamics was appraised by reference to the following quantitative criteria:-

a. Ease of Learning

Quantitative System Dynamics requires the construction of an executable model and the modeller must therefore learn a relevant computer language. The labour involved in translating an influence diagram into a computer executable model may be assuaged by the use of specialist software (such as STELLA or DYSMAP). Such packages automate some of the more routine processes, provide built-in functions and provide debugging aids such as a variable dependency analyser. However, although such tools may appear easy to use, care must be taken that the broader objectives of the technique are understood if misapplication is to be avoided.

The logistics CCIS study stream employed DYSMAP2 run on an IBM PC which employs as source a segment of code consisting of differential equations using time-suffixed variables. DYSMAP2 is a compiler-based package which can slow the turn-around time in performing experiments. The support documentation is relatively inaccessible and some of the provided functions rather clumsy.

The battlefield CCIS study stream employed STELLA on a MacIntosh. By contrast with DYSMAP2, STELLA employs as source an easily constructed influence diagram from which the equations are automatically derived. STELLA thus provides a more interactive and immediate interface with the modeller and enables the modeller to focus on the problem rather than the software.

Inevitably, such tools impose some constraints on the freedom of action of the model developer, occasionally compelling some compromise to be made in model design. They impel the modeller to work within the confines of a shell and, due to memory constraints, usually provide only limited function libraries. These problems are not normally encountered when using free-format high level languages. However the quality of support software is constantly improving and whilst the employment of a general purpose language may overcome these constraints, its use greatly reduces modeller productivity and increases model development time.

b. Data Requirements

In both the study streams the "real-world" nature of the models meant that most data requirements could be defined in precise and meaningful terms.

A typical System Dynamics model includes relationships and flows for which data is not available. This may be considered a weakness. However, System Dynamics is not concerned with accurate prediction and so does not require high quality data in order to yield executable models; rather it seeks to capture the broad behavioural dynamics of the relevant functions. The System

Dynamics paradigm attempts to include all relevant interdependencies, even if performed imperfectly, rather then exclude some from consideration. By contrast, the hard systems paradigm encourages the incorporation of only those relationships for which data is known to be available or can be acquired.

When a study attempts to produce definitive answers, there is often an unjustified degree of precision implied in the values contained in the output. There is a natural temptation for the client to place more faith in precise numerical output. System Dynamics provides output in the form of graphical traces of the broad behavioural dynamics existent within the model under investigation. It is far easier for both investigator and client to comprehend trends and modes of behaviour than it to attempt to interpret a set of numerical values, with no understanding of how these values were derived or their fallibility.

c. Ease of Validation

The validation of the CCIS effectiveness in both study streams requires the following to be established:

Does the stage 1 model exhibit the same behaviour as the real-world system?

Does the stage 2 model accurately reflect the behaviour of the system after installation of the CCIS?

Validation in the case of CCIS is therefore difficult. The real world only exists in time of war and, in any case, no tangible form of the CCIS exists. Therefore model validity is assessed relative to purpose, the level of client confidence in the model and the satisfactory explanation of observed systemic behaviour.

The rational-empiricist epistemology of hard systems thinking applies a reductionist approach to the modelling of systemic phenomena. System Dynamics instead strives for an understanding of the structure and broad behavioural dynamics of complex systems. Attitudes towards data, validation, accuracy and model use are influenced by these differences and it is unrealistic to expect such models to give accurate predictions of future states.

Definition of Performance and Effectiveness Measures

These study streams have assessed the effectiveness of the CCIS in terms of its impact on its host environment. System Dynamics attempts to incorporate subjective measures of intangible concepts. The sensitivity of these variables to changes in CCIS characteristics can be rapidly assessed by means of experimentation encouraging the development of effective performance measures.

For example the ammunition profile concept in the logistics CCIS model arose directly from the analysis of model behaviour. Similarly the "overkill space" concept in the battlefield CCIS model arose from experimentation with the model.

e. Depth of Analysis Achievable

The depth of the analysis can be extended by focussing the study on particular sub-systems and expanding the corresponding sub-model. The breadth of analysis can be similarly extended to encompass areas previously outside the study boundary with co-incident expansion of the model's scope. The ability of System Dynamics to conveniently aggregate and disaggregate functions and variables eases this process while maintaining a firmly orchestrated approach to the study objectives.

In general the depth of analysis achieved depends on the hardness of the system and the ability of the analyst. In a harder system, the depth of analysis can be extended to encompass the use of sophisticated control theory and optimisation methods. In the case of the CCIS models, such a deepening could be applied to any of the component functions although in some cases with dubious utility.

f. Ability to Create Insights

System Dynamics models cover a greater scope and manipulate more variables than is possible within normal human cognitive limits. Understanding and insight comes from interpretation of results in terms of the feedback loop structures of models. Observed model behaviour can often surprise and even be counter-intuitive inciting a closer analysis of the system structures which is in turn rewarded by additional insight.

g. Ease of Model Development and Analysis

The iterative nature of System Dynamics analysis imposes an incremental approach to model development. As the understanding of the system improves, additional areas of importance become apparent. Consequently, System Dynamics models tend to lead their own development. The limits to this process are provided, in breadth, by the problem boundaries and, in depth, by the level of resolution required.

The success of an System Dynamics model leans rather less upon the availability of empirical data than do other methods. This serves to improve model flexibility and adaptability and to ease development in intangible areas.

The development of executable models is considerably eased by the provision of support tools and functions, such as dimension validation routines and the provision of devices to support sensible structuring of the code segments. The latter point is particularly relevant in DYSMAP2 where no structure is imposed on the order of equations.

STELLA has the weakness that no automated dimension checking facilities are provided. This omission can give rise to dimensional imbalance in development models.

h. Degree of Implementation Achievable

This is high. Ultimately the enhanced understanding achieved perpetuates the problem solving capability of system owners.

The ease with which System Dynamics models can be constructed, executed and modified (particularly when using interactive packages) means that ideas and suggestions from both the analyst and the client can be implemented rapidly. However, all software packages have limitations which impel some compromise in representation of real-world features.

For example DYSMAP2 has some limitations with representing variable transfer times. There is a dearth of variety in the probability distributions provided. Most important of all the DYSMAP2 restricts user control over the random number streams provided which can create problems with comparative assessments of similar runs.

i. Ability to Deal with Uncertainty

System Dynamics is essentially deterministic normally producing the same output for every run given the same set of inputs. However, stochastic elements can be represented within a model, using facilities provided in both DYSMAP2 and STELLA, enabling variability and uncertainty to be incorporated.

j. The Value Added to Understanding per Unit of Effort

The method is very productive in modelling terms, since a small input of time and effort can lead to meaningful insights. For example, at an early point in the development of the logistics model, the problems resulting from resource capacity constraints such as transport were confronted

The method also enables models to be constructed in a short time (particularly if the modelling software semi-automates some of the model building procedures) and for little cost. With regard to the particular application to CCIS assessment, the technical and theoretical base for the methodology has been established and, given that a formal set of guidelines can be produced, model development time will be further reduced.

k. Contribution to Training

Most System Dynamics models can be converted to gaming situations and used as direct training tools. This is particularly useful when attempting to analyse the impact of strategy decisions on future outcomes, where the method can feed back an immediate result. This could be useful in training CCIS managers and designers and in demonstrating the consequences of their actions. However the training aspects were not overtly considered in this study.

Weaknesses and Strengths

System Dynamics is based on principles of control theory, modelling cause and effect in terms of feedback loops. This imposes particular structures on a formulation of the problem area. The resulting viewpoint is adaptable and incisive but it is not the only view. Many aspects of the CCIS assessment problem will benefit from an alternative approach to its solution performed in parallel. Indeed some aspects will require an alternative method of solution:- those which involve the assessment of specific detailed features; those embodying detailed technical aspects; those where each entity involves explicit representation of a large number of attributes within one entity.

The strengths of the method are considerable. It is flexible and adaptable and able to grapple with complexity. It is a rapid modelling technique which involves the client fully and which serves as a medium for the expression of requirements. It is capable of capturing the essence of an organisation's structure and function for relatively little cost or effort. When supplemented by other methods for the study of particular detailed areas, the technique can make a valuable contribution to CCIS assessment.

The CCIS Life-cycle

The life-cycle associated with the procurement of CCIS will traditionally proceed through several phases - from feasibility through analysis to design (both logical and physical) and eventually to specification, development and implementation. The continued justification of any project depends on a parallel process of benefit/cost assessment at each phase. This process will also feed back enhancements or amendments to earlier phases for re-evaluation. This feedback process is illustrated in Fig. 1 below.

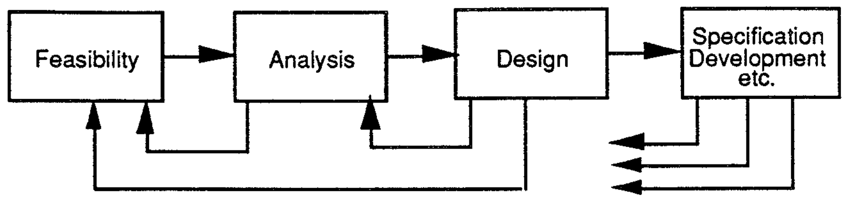

Fig. 1 The traditional structured evolution of a CCIS

However, no modelling method can be regarded as having a definitive role to play in this process. Commonly employed methods tend to focus on specific benefits relating to the CCIS itself and neglect the context of the underlying application. The weakness of this approach is especially apparent during the earliest phases of the software life-cycle

. The two streams of study indicate that use of this methodology in parallel with the development process can contribute throughout the earliest phases of the CCIS life-cycle. In particular, by focussing on the formative phases of the life-cycle, the ultimate CCIS specification is improved, thereby improving anticipation of latent or potential problems and lessening the risk of an expensive retrofit at a later point.

Requirements capture is an ill-structured task which can often result in a narrowing of perspective because of difficulties in expression. Recently, the prototyping paradigm has evolved whereby the main analysis and design principles are applied and a scale model constructed for client assessment. The System Dynamics modelling approach parallels this process, constructing a model of the real-world system and incorporating the main features of the CCIS design for client assessment. The System Dynamics model itself becomes a component of the requirement.

The study has concentrated on System Dynamics as a means of assessing the benefits arising from any improvement of operational effectiveness in the target application area. It has also indicated the potential of the method in contributing directly to the various phases of the CCIS life cycle itself. In particular, the battlefield CCIS study stream has shown the benefits of System Dynamics as a qualitative, participative method, well suited to the ill-structured problems and ephemeral issues associated with the feasibility or pre-feasibility phases of system investigation. The logistics CCIS study stream has demonstrated the utility of capturing the essence of an organisation's management structure and, by revealing its dynamic behaviour under various assumptions, assessing the benefits of particular designs.

Conclusions

Though all CCIS systems have some degree of similarity, every CCIS system is different in some way and each possesses unique features. Consequently CCIS assessment is a complex, multi-faceted and costly process. The decision support capability required for CCIS assessment must similarly be capable of complex analysis, have an ability to deal with radically different types of problem (technical, financial, behavioural, etc.) and be cost-effective in itself. This implies that ultimately each CCIS assessment exercise requires a selection of decision support tools to be applied as required. This study has indicated that System Dynamics provides a valuable addition to the armoury of weapons available to the decision support analyst.

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