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Control Theory Perspective of Effects-Based Thinking and Operations

Modelling "Operations" as a Feedback Control System

Philip S. E. Farrell

Defence R&D Canada – Ottawa

TECHNICAL REPORT
DRDC Ottawa TR 2007-168
November 2007

Canada

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Primary Author

Original signed by Philip S. E. Farrell

Philip S. E. Farrell, Ph.D.

Approved by

Original signed by Paul Labbé

Paul Labbé

Acting-Section Head, CFEC S&T team

Approved for release by

Original signed by Brian Eatock

Brian Eatock, Ph.D.

Acting-Chair, Document Review and Library Committee

Abstract

This paper explores operations that involve effects-based thinking (EBT) using Control Theory techniques in order to highlight the concept's fundamental characteristics in a simple and straightforward manner. It provides some background to EBT, and presents three formal definitions for effects-based approaches to operations (EBAO). This paper shows that Control Theory is a useful framework for studying effects-based concepts.

A specific EBAO concept was modelled using Control Theory techniques. This analysis has exposed key functions for operations and key tenets for effects-based thinking as listed below:

<u>Key Functions for Operations from a Control Theory Perspective</u>

- Planning
- Assessment (feedback)
- Execution (tactical)
- Decision-making
- Analysis
- Organization and Technology structures must be designed to support these functions.

<u>Key Tenets of Effects-Based Thinking from a Control Theory Perspective</u>

- Effects are higher-level states (or changes in state) of the world.
- Effects span the entire range of human endeavours (political, social, etc.).
- Desired effects can be decomposed as a means-end hierarchy.
- Effects are planned for and assessed explicitly.
- Relationships between actions and effects are often complex.
- Control Theory provides both proactive and reactive feedback mechanisms that drive current effects towards their desired values.

Control Theory was used to model EBT concepts and operations, and provide a theoretical basis so that effective system designs can be developed. It is hoped that this new way of looking at EBT operations will provide a framework for continued discussion and investigation of the ideas through mathematical analysis, constructive simulation, and human-in-the-loop experimentation.

Résumé

Ce document traite des opérations qui font intervenir l'application des techniques de la théorie du contrôle à la réflexion basée sur les effets (RBE), l'objectif étant de décrire les caractéristiques fondamentales du concept d'une manière simple et explicite. On y présente des renseignements généraux sur la RBE ainsi que trois définitions d'approches des opérations basées sur les effets (AOBE). Le document montre que la théorie du contrôle fournit un cadre intéressant à l'étude de concepts basés sur les effets.

Un concept spécifique des AOBE a été modélisé à l'aide des techniques de la théorie du contrôle. Cette analyse a dégagé des fonctions clés pour les opérations et des principes clés de la réflexion basée sur les effets, qui sont les suivants :

<u>Fonctions clés pour les opérations du point de vue de la théorie du contrôle</u>

- Planification
- Évaluation (rétroaction)
- Exécution (tactique)
- Prise de décisions
- Analyse
- Structures organisationnelles et technologiques à concevoir pour appuyer ces fonctions

<u>Principes clés de la réflexion basée sur les effets du point de vue de la théorie du contrôle</u>

- Les effets sont des états (ou des changements d'état) du monde d'un niveau élevé.
- Les effets couvrent tout l'éventail des entreprises humaines (entreprises politiques, sociales, etc.).
- Les effets souhaités peuvent être décomposés en fonction d'une hiérarchie de moyens-finalités.
- Les effets sont planifiés et évalués explicitement.
- Les relations entre les actions et les effets sont souvent complexes.
- La théorie du contrôle fournit des mécanismes de rétroaction à la fois proactifs et réactifs qui conduisent les effets actuels à leurs valeurs souhaitées.

La théorie du contrôle a été utilisée pour modéliser des concepts et des opérations faisant appel à la RBE et pour fournir un fondement théorique à la conception de systèmes efficaces. On peut espérer que cette nouvelle façon d'envisager les opérations faisant appel à la RBE fournira un cadre à la poursuite des discussions et à l'exploration d'idées par l'analyse mathématique, la simulation constructive et l'expérimentation à intervention humaine.

Executive summary

This paper explores operations conducted using effects-based thinking (EBT). The operation's main functions are expressed in terms of Control Theory in order to highlight the concept's fundamental characteristics in a simple and straightforward manner. It provides some background to EBT, and presents three formal definitions for effects-based approaches to operations. This paper shows that Control Theory is a useful means for studying effects-based concepts.

Effects-based concepts have become a topic of interest for theorists and practitioners alike since the beginning of the 21st century. In the early 1990's, the evaporation of the Cold War led to the Revolution in Military Affairs and asymmetric threats. In a speech to the Royal Canadian Military Institute in 2005, the Canadian Chief of Defence Staff (CDS) General Rick Hillier described the past security environment as "the Bear" and the current security environment as "the ball of snakes". Western forces need to transform their thinking and their "way of doing business" in order to engage this new type of adversary.

The new approach to operations must do more than produce physical effects with kinetic actions but must include non-physical effects and non-kinetic actions (e.g., both effects and actions may be psychological, social, and economic in nature) in order to achieve the desired outcome. This is the promise of effects-based approaches to operations (EBAO).

A working Canadian definition for effects-based operations is as follows (Grossman-Vermaas, 2004):

"An Effects-based approach consists, in part, of operations designed to influence the long- or short-term state of a system through the achievement of desired physical or psychological effects. Effects are sought to achieve directed policy aims using the integrated application of all applicable instruments of power or influence. Desired effects, and the actions required to achieve them, are concurrently and reactively planned, executed, assessed and re-planned within a complex and adaptive system."

A Control Theory model of EBAO was developed using this definition and other descriptions from the literature. This generic model can be generalized to any operation and, in fact, to any human goal-directed activity (Powers, 1973). The main functions are Planning, Execution, Assessment, Decision-making, and Analysis as a continuous background activity. The main variables were the desired situation, desired effects, desired actions, current actions, current effects, and current situation all organized in a feedback control system.

One might jump to the conclusion that there exists a solution for this type of operational problem using mathematics and Control Theory. However, Control Theory is used here to help understand the problem, and possibly provide conceptual solutions – not to solve a set of mathematical equations.

The Control System Elements section provides a basic, but essential, overview of what is meant by variables, functions, and feedback to help the reader conceptualize effects-based

operations in these mathematical constructs. In this context, the model system variables also include the own force (blue) actions, adversary (red) and neutral (green) action, and forces of nature (the adversary, neutral, and nature actions are grouped together as disturbance variables in the model), as well as world states. As mentioned above, the system functions are Planning, Assessment, Execution, Decision-Making, and Analysis. It is worthy of note that the Decision-Making function has been implicit in effects-based approaches to operations concepts up to this point. A Control Theory perspective of an EBT operation yields key decision points, and therefore system designers would need to develop the appropriate process, organization, and technology structures to support this function, as they would for the other four functions. Also note that the Analysis function does not appear explicitly in the main feedback loop, but it is a continuous background function where information about the operational environment can be pushed or pulled.

The US JFCOM Effects-Based Approach to Multinational Operations, Concept of Operations (CONOPS) was analyzed from a Control Theory perspective. Although the concept developers did not have a control loop in mind when developing the CONOPS, this paper shows that a feedback control system emerges from the CONOPS description. Based on Control Theory, this model was simplified without losing the original essence or intent of the concept. Systematically examining the CONOPS in this manner yields a standard feedback control system model with either parallel or serial feedback.

Process, organization, and technology implications were derived to inform the design of an EBT operation. In terms of the process, the new EBT operations model is clear, simple, and scalable with five basic functions and six basic variable descriptors. Two key implications from a Control Theory perspective were identified:

1) the action loop must be at least twice as fast as the effects loop, which must be at least twice as fast as the situation loop, and

2) the new GAME sub-function makes the model have a *predictive control* structure where various strategies are developed and tried and then one is chosen for actual implementation.

The organizational implications yielded three distinct organizational views:

1) a hierarchical view from the strategic layer through a middle layer down to a tactical layer,
2) a function view – that included planners, assessors, decision-makers, and support staff needed to carry out the operation, and
3) a “variable” view where various variables may be of more or less concern to specific government organizations (e.g., defence, diplomacy, and development) and so each government organization may take the leadership with respect to certain variables.

The organizational structure might look complex, however the EBT operations model provides a simple and logical framework to explore the structures.

The technology implications are that software and hardware aids are required for:

1) the main functions including planning, feedback, and decision-making,
2) “variable” tracking, and
3) human communication and information sharing.

Although a feedback control system model emerges from this analysis as a structural backbone, the human dimension must be considered in the design of this human activity system such as psychology (perception, awareness, intention, cognition, decision-making, information processing), sociology (culture, organizational health, team performance, world view), and system of (human) systems modelling. The human factors implication section alludes to the human dimensions of EBT as well as highlights the need for inter-disciplinary approaches for the analysis and design of EBT operations.

The key conceptual difference between EBT operations and other operations is that the intermediate levels of effects (between strategic objectives and tactical actions) are planned for and assessed explicitly. This analysis has exposed key functions for operations and key tenets for effects-based thinking as listed below:

Key Functions for Operations from a Control Theory Perspective

- Planning
- Assessment (feedback)
- Execution (tactical)
- Decision-making
- Analysis
- Organization and Technology structures must be designed to support these functions.

Key Tenets of Effects-Based Thinking from a Control Theory Perspective

- Effects are higher-level states (or changes in state) of the world.
- Effects span the entire range of human endeavours (political, social, etc.).
- Desired effects can be decomposed as a means-end hierarchy.
- Effects are planned for and assessed explicitly.
- Relationships between actions and effects are often complex.
- Control Theory provides both proactive and reactive feedback mechanisms that drive current effects towards their desired values.

This paper does not claim that Control Theory is the panacea for effects-based thinking. However, it is hoped that this new way of looking at EBT operations will provide an effective framework for continuing discussion and investigation of the ideas through mathematical analysis and constructive simulation, as well as human-in-the-loop experimentation.

Farrell, P.S.E. 2007. Control Theory Perspective of Effects-Based Thinking and Operations: Modelling Operations as a Feedback Control System. DRDC Ottawa TR 2007-168. Defence R&D Canada – Ottawa.

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Sommaire

Ce document porte sur les opérations dans lesquelles on utilise la réflexion basée sur les effets (RBE). Les principales fonctions de l'opération sont exprimées en fonction de la théorie du contrôle, ce qui permet de faire ressortir d'une manière simple et explicite les caractéristiques fondamentales du concept. Le document présente des renseignements généraux sur la RBE ainsi que trois définitions d'approches des opérations basées sur les effets (AOBE). Il montre que la théorie du contrôle fournit un cadre intéressant à l'étude de concepts basés sur les effets.

Les concepts basés sur les effets ont commencé à intéresser les théoriciens et les praticiens il y a quelques années. Au début des années 90, la fin de la guerre froide a conduit à la révolution des affaires militaires et à des menaces asymétriques. Dans un discours qu'il prononçait devant le *Royal Canadian Military Institute* en 2005, le Chef d'état-major de la Défense (CEMD), le Général Rick Hillier, comparait le contexte passé de la sécurité à un « ours » et le contexte actuel de la sécurité à une « poignée de serpents ». Les forces occidentales doivent transformer leur façon de penser et leurs façons de faire pour affronter ce nouveau genre d'adversaire.

La nouvelle approche des opérations ne doit pas seulement déterminer des effets matériels avec des actions cinétiques, elle doit aussi comprendre des effets non matériels et des actions non cinétiques (des effets et des actions psychologiques, sociaux et économiques, p. ex.) pour aboutir au résultat escompté. C'est ce que promettent les approches des opérations basées sur les effets (AOBE).

Au Canada, les opérations basées sur les effets ont été définies comme suit (Grossman-Vernaas, 2004) :

« Une approche basée sur les effets comprend en partie des opérations destinées à influencer à court ou à long terme l'état d'un système par l'obtention d'effets matériels ou psychologiques souhaités. Ces effets doivent atteindre des objectifs stratégiques par l'application intégrée de tous les instruments de pouvoir ou d'influence utiles. Les effets souhaités et les actions requises pour les obtenir sont planifiés, exécutés, évalués et replanifiés simultanément et réactivement, dans un système complexe et adaptatif. »

Un modèle de l'AOBE faisant appel à la théorie du contrôle a été conçu en fonction de cette définition et de descriptions d'autres auteurs. Ce modèle générique peut être étendu à n'importe quelle opération et, en fait, à n'importe quelle activité humaine tendant vers un but (Powers, 1973). Les principales fonctions en jeu – la planification, l'exécution, l'évaluation, la prise de décisions et l'analyse – s'exercent de façon continue, en arrière plan. Les principales variables étaient la situation souhaitée, les effets souhaités, les actions souhaitées, les actions actuelles, les effets actuels et la situation actuelle, toutes étant organisées comme un système d'asservissement.

Il serait facile de conclure que les mathématiques et la théorie du contrôle peuvent offrir une solution à un problème opérationnel de ce genre. En fait, la théorie du contrôle n'est utilisée

ici que pour faciliter la compréhension du problème et peut-être pour fournir des solutions conceptuelles, mais pas pour résoudre un ensemble d'équations mathématiques.

La section consacrée aux éléments du système de contrôle présente un aperçu élémentaire, mais essentiel, de ce que recouvrent les termes « variables », « fonctions » et « rétroaction », l'objectif étant d'aider le lecteur à conceptualiser les opérations basées sur les effets dans ces concepts mathématiques. Dans ce contexte, les variables du système comprennent aussi les actions des forces amies (en bleu), les actions de l'adversaire (en rouge), les actions neutres (en vert), les forces de la nature (les actions de l'ennemi, les actions neutres et les actions de la nature sont réunies et considérées dans le modèle comme des variables perturbatrices), ainsi que les états du monde. Comme on l'a vu ci-dessus, les fonctions du système sont la planification, l'évaluation, l'exécution, la prise de décisions et l'analyse. Il est intéressant de noter que la fonction « prise de décisions » a toujours été considérée comme implicite dans les approches des opérations basées sur les effets. L'application de la théorie du contrôle à une opération faisant appel à la RBE donne des points de décision clés, et les concepteurs de systèmes devraient donc énoncer des structures (processus, organisation et technologie) propres à appuyer cette fonction, comme ils le feraient pour les quatre autres fonctions. Il convient également de souligner que la fonction « analyse » ne figure pas explicitement dans la boucle de rétroaction principale, mais qu'elle est une fonction contextuelle continue dont il est possible d'extraire des renseignements sur le contexte opérationnel ou qui peut être alimentée avec de tels renseignements.

L'approche basée sur les effets du concept des opérations (CONOPS) multinationales du JFCOM des États-Unis a été analysée du point de vue de la théorie du contrôle. Même si les développeurs du concept n'avaient pas de boucle de contrôle à l'esprit quand ils ont énoncé le CONOPS, ce document montre qu'il se dégage un système d'asservissement de la description du CONOPS. Ce modèle a été simplifié en fonction de la théorie du contrôle sans que l'essence ou l'esprit original du concept en souffre. Un examen systématique du CONOPS dans ces termes donne un modèle standard de système d'asservissement à rétroaction parallèle ou sérielle.

Des conclusions sur le plan du processus, de l'organisation et de la technologie ont été formulées dans le but d'éclairer la conception d'une opération faisant appel à la RBE. Du point de vue du processus, le nouveau modèle des opérations faisant appel à la RBE est clair et simple et il peut être adapté à cinq fonctions de base et six descripteurs de variables de base. Du point de vue de la théorie du contrôle, deux conclusions clés se détachent :

1) la boucle d'action doit être au moins deux fois plus rapide que la boucle des effets, celle-ci étant au moins deux fois plus rapide que la boucle de la situation;

2) la nouvelle sous-fonction JEU confère au modèle une structure de *contrôle prédictif* dans laquelle diverses stratégies sont développées et mises à l'essai, l'une d'elles étant ensuite retenue pour être mise en œuvre.

Les conclusions sur le plan de l'organisation ont abouti à trois vues distinctes sur le plan de l'organisation :

1) une vue hiérarchique, du niveau stratégique au niveau tactique, en passant par un niveau intermédiaire;

2) une vue des fonctions – qui comprenait les planificateurs, les évaluateurs, les décideurs et le personnel de soutien nécessaire à l'exécution de l'opération;

3) une vue des « variables » dans laquelle des variables peuvent présenter plus ou moins d'intérêt pour des milieux gouvernementaux particuliers (la défense, la diplomatie et le développement, p. ex.), si bien que chacune peut assumer la responsabilité de certaines variables.

Même si la structure organisationnelle peut paraître complexe, le modèle des opérations faisant appel à la RBE fournit un cadre d'étude des structures à la fois simple et logique. Les conclusions sur le plan de la technologie sont qu'il faut des moyens logiciels et matériels pour :

1) les principales fonctions, et notamment la planification, la rétroaction et la prise de décisions;
2) le suivi des « variables »;
3) les communications humaines et les échanges de renseignements.

Même si le modèle du système d'asservissement qui ressort de cette analyse est schématique, il faut tenir compte de la dimension humaine dans la conception d'un système d'activités humaines comme la psychologie (perception, prise de conscience, intention, cognition, prise de décisions, traitement de l'information), la sociologie (culture, santé organisationnelle, rendement de l'équipe, vue du monde) et la modélisation d'un système de systèmes (humains). La section sur les conclusions relatives aux facteurs humains porte notamment sur les dimensions humaines de la RBE et la nécessité de recourir à des approches multidisciplinaires dans l'analyse et la conception des opérations faisant appel à la RBE.

Sur le plan conceptuel, la principale différence entre les opérations faisant appel à la RBE et les autres opérations est que les niveaux intermédiaires d'effets (entre les objectifs stratégiques et les actions tactiques) sont planifiés et évalués explicitement. Cette analyse a dégagé des fonctions clés pour les opérations et des principes clés de la réflexion basée sur les effets, qui sont les suivants :

<u>Fonctions clés pour les opérations du point de vue de la théorie du contrôle</u>

- Planification
- Évaluation (rétroaction)
- Exécution (tactique)
- Prise de décisions
- Analyse
- Structures organisationnelles et technologiques à concevoir pour appuyer ces fonctions

<u>Principes clés de la réflexion basée sur les effets du point de vue de la théorie du contrôle</u>

- Les effets sont des états (ou des changements d'état) du monde d'un niveau élevé.

- Les effets couvrent tout l'éventail des entreprises humaines (entreprises politiques, sociales, etc.).
- Les effets souhaités peuvent être décomposés en fonction d'une hiérarchie de moyens-finalités.
- Les effets sont planifiés et évalués explicitement.
- Les relations entre les actions et les effets sont souvent complexes.
- La théorie du contrôle fournit des mécanismes de rétroaction à la fois proactifs et réactifs qui conduisent les effets actuels à leurs valeurs souhaitées.

L'auteur de ce document ne prétend pas que la théorie du contrôle est la solution à tous les problèmes liés aux problèmes de la réflexion basée sur les effets. Toutefois, on peut espérer que cette nouvelle façon d'envisager les opérations faisant appel à la RBE fournira un cadre intéressant à la poursuite des discussions et à l'exploration d'idées par l'analyse mathématique, la simulation constructive et l'expérimentation à intervention humaine.

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Acknowledgements

I would like to thank the International Programs Coordinator, LCol John Kachuik, at the Canadian Forces Experimentation Centre who is responsible for the Canadian participation in US Joint Forces Command's (US JFCOM) Multinational Experiment series. Because of this participation, the Canadian Forces has become knowledgeable about effects-based thinking and operations.

Also, I would like to acknowledge Robert Grossman-Vermaas, Graham Kessler (US JFCOM), and the multinational concept development team who were instrumental in producing the effects-based approach to multinational operations concept of operations. My gratitude is extended to Mike Whal (US JFCOM) as lead analyst for the event who showed tremendous support and patience for my ideas, and Barbara Reagan (US JFCOM) who obtained the approval to cite certain excerpts from the US JFCOM's effects-based approach to operations concept of operations document.

Finally, this paper's reviewers need to be recognized as also making a contribution to shaping this paper and encouraging me to not forget about the human dimension of effects-based thinking. Thank you very much Rachel Heide, Steven Hughes, Paul Labbé, and Alex Ryan (DSTO) for your scientific and technical review, and France Crochetière for your language and structure review.

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Introduction

This paper explores operations based on effects-based thinking (EBT) using Control Theory techniques in order to highlight the concept's fundamental structures in a simple and straightforward manner. It provides some background to EBT and presents three formal definitions for effects-based approaches to operations. After this introduction to EBT, key elements of Control Theory modelling are introduced and applied to the EBT concept. A specific effects-based approach to operations (EBAO) concept is modelled using Control Theory techniques. Process, organization, technology, as well as human factors implications are derived from the model that, in turn, would inform the design of an EBT operation.

There are multiple views of EBAO: structural (process, organization, technology), psychological, sociological, legal, political, etc. This paper focuses on the structural view and uses analysis techniques typically used for physical systems to conceptually frame and analyse the problem. Although a feedback control system model emerges from this analysis as a structural backbone, the human dimension must be considered in the design of this human activity system such as psychology (perception, awareness, intention, cognition, decision-making, information processing), sociology (culture, organizational health, team performance, world view), and system of (human) systems modelling. The model does allude to the human dimensions of EBT as well as highlights the need for inter-disciplinary approaches for the analysis and design of EBT operations.

EBT operations referred to herein are meant to include the entire gamut of operations from a multinational, whole of government and non-government approach to operations (or the Comprehensive Approach) right through to tactical level Net-Enabled Operations (Net Centric Operations, Net-Centric Warfare, or Net-Enabled Capability are equivalent concepts). These specific operations may be mapped onto the generic EBT operation model developed herein.

The Need for "A New Way of Doing Business"

Effects-based concepts have become a topic of interest for theorists and practitioners alike since the beginning of the 21st century. In the early nineties, the evaporation of the Cold War led to the Revolution in Military Affairs and asymmetric threats. Since then, Force-on-Force engagements (where the adversary could be identified by geographical borders and national values) are no longer the norm. The adversary has adopted trans-national philosophies that are often different from their opponent's foreign policies and core values. The adversary does not have large forces, but still successfully engage their opponents by being small, distributed, and by using unconventional and improvised weapons. Western forces need to transform their thinking and their "way of doing business" in order to engage the new adversary.

In a speech to the Royal Canadian Military Institute in 2005, the Canadian Chief of Defence Staff (CDS) General Rick Hillier described the past security environment as "the Bear" and the current security environment as "the ball of snakes" (Hillier, 2005):

"All that I have to say is that the threat has changed… We have gone from the Warsaw Pact type of state player that threatens us to a ball of snakes. And that ball of snakes is seen differently by many folks of course, and causes some discussion and sometime dissention amongst otherwise friendly and cooperating allies and countries that usually work together. Because the snakes are all different, some are lethal, some make you sick, some change, some grow, some are really chameleons and change based on the circumstances and as such, are seen differently by different groups and different countries. So it is difficult to get a unifying fear such as NATO had that really did unify in the Cold War based on that overwhelming threat from the Warsaw Pact…My point is this. That [*pointing to a Cold War depiction*] was our conventional threat. We structured against that, we equipped against that, we trained against that, we educated against that, we lead against that and we stationed ourselves against that. Now that [*the Cold War*] is the asymmetric threat and that [*pointing to the current security environment depiction*] is the conventional threat, that ball of snakes."

General Hillier's speech implies that the current threat is immune to conventional warfare where "target-based" plans would be produced, kinetic energy would be applied, and battle damage would be assessed in an attempt to achieve a desired outcome. A new approach is needed because the "targets" are often philosophies rather than large physical structures, and the "combatants" are individuals who camouflage themselves amongst a neutral civilian population and are ready to premeditatively sacrifice their lives for their cause.

Thus, "shock and awe" is replaced by "surgical operations." "Force-on-force engagement" becomes the "battle for peace of mind." The adversary wages psychological war sometimes with improvised weapons that produce terror within their opponents' minds. Battle damage is not limited to the number of casualties, but it includes undesired effects such as higher gas prices, political upheaval, and restricted freedoms and privacy. The new approach to operations must do more than produce physical effects with kinetic actions but must include non-physical effects (e.g., psychological, social, and economic) and non-kinetic actions (e.g., psychological, social, and economic) in order to achieve the desired outcome. This is the promise of effects-based thinking and effects-based approaches to operations.

Effects-Based Definitions and Descriptions

Three effects-based approaches to operations definitions are listed as follows:

Canadian working definition

"An Effects-based approach consists, in part, of operations designed to influence the long- or short-term **state** of a system through the achievement of **desired** physical or psychological **effects**. **Effects** are sought to achieve directed policy aims using the integrated application of all applicable instruments of power or influence. **Desired effects**, and the **actions required** to achieve them, are **concurrently and reactively planned, executed, assessed and re-planned** within a complex and adaptive system (Grossman-Vermaas, 2004)."

From US Joint Forces Command EBAO Concept of Operations

"Effects: The physical and/or behavioral **state** of a system that results from a military or non-military **action** or **set of actions**."

"Effects-Based Operations: **Planned, executed, assessed, and adapted actions**, based on a holistic understanding of the operational environment, performed in order to influence system behavior or capabilities, using instruments of power to **achieve directed policy aims**."

"EBAO: The effects-based approach focuses a combination of military and other activities on influencing the overall behavior of other actors – national and transnational, belligerent and benign - in an operational environment. Its application allows the **planning, execution, and assessment** of those operations to be based on a holistic and dynamic understanding of those and other actors in that environment. The resulting benefits are a **set of actions** that are explicitly linked to a set of **strategic goals** (expressed as an "**end state**"), coherently harmonized with those of other governmental organizations, and made truly adaptive within the course of their execution by effective assessment. The treatment of these effects in planning, execution, and assessment is what makes an operation essentially effects-based (JFCOM, 2005)."

A Joint Doctrine Note on the UK Military Effects-Based Approach

"Effects-Based Philosophy. The UK effects-based philosophy recognises that the military instrument needs to **act** in harmony with the diplomatic and economic instruments of national power in taking a long-term view to address both the underlying causes, and the overt symptoms of a crisis. In doing so, it focuses on **planning and delivering** the **end-state** rather than organising military activities. It considers the whole environment, recognising that it is complex, unpredictable and adaptive, requiring constant **iterative Assessment** and **Analysis** to maintain and develop understanding before and during its **Planning** and **Execution**. Through this better understanding, Commanders and their staffs can translate and link the **desired end-state** to activity, ensuring that associated activity addresses not only the physical domain, but also the cognitive (MOD, 2006)."

Both the United States (US) and the United Kingdom (UK) have developed doctrine for effects-based operations. Although Canada does not have such doctrine yet, a Strategic Operating Concept for the Canadian Forces has been drafted with brief mention of the EBAO concept. The Canadian Expeditionary Force Command (CEFCOM) has adopted EBT in their current assessment practices. An effects-based Dashboard has been developed that provides an assessment of effects within CEFCOM's operational environments. The Dashboard is briefed at the highest level of parliament every six months. Slowly but surely, EBT is becoming part of the Canadian Forces culture and ethos.

Effects-based thinking takes into consideration the physical and non-physical effects during all aspects of an operation (e.g., planning, execution, and assessment) [1]. Intermediate layers, called "effects", exist between high-level objectives and physical actions. These layers have always existed, except now they are made explicit in all aspects of an operation.

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[1] EBAO employs the terms: planning, execution, and assessment, while the Comprehensive Approach (i.e., Whole of Government Approach or Integrated Operations) uses the terms: planning, management, evaluation (JFCOM, 2006). These two sets of terms are functionally equivalent.

A team of people, such as an operational level headquarters, analyses and decomposes the desired situation into desired effects (physical and non-physical), links them to desired actions (based on available resources), synchronizes the desired effects and actions, and develops an effects-based plan. The effects-based plan is translated into *operational orders* for execution. As actions are executed, world states are sensed, assessed, and converted into feedback related to the current actions, effects, and situation as they unfold in the theatre of operations. Additional expertise (e.g., psychologists, sociologists, and economists) would be involved with the analysis, planning, execution, and assessment of non-military actions and effects.

The debate continues on whether effects-based thinking is truly a new approach to operations or simply new terminology for old strategies that have been employed over centuries. One might argue that a planning, execution, and assessment cycle is a fundamental harmonic for any type of human or team activity. On the other hand, others have argued that the explicit consideration of non-military effects during an operation makes effects-based thinking novel. This paper does not weigh into the debate, but rather accepts effects-based thinking as another way of describing human team activities such as warfare, and then views the associated process, organization, and technology structures through the lens of Control Theory.

Operations based on effects-based thinking have several labels: Whole of Government, Integrated Operations, Comprehensive Approach, Effects-Based Operations, Effects-Based Approach, Effects-Based Approach(es) to Operations, Net-Centric Operations, Net-Centric Warfare, Net-Enabled Capability, Net-Enabled Operations. The first three labels focus on EBT across governments, non-government agencies, and amongst multiple nations. The next three labels usually would involve a military-led operation, or the military portion of a broader operation. The final four labels are primarily concerned with the computer network technologies that promise to facilitate and optimize networked force that would – under the umbrella of command intent – provide improved information sharing, collaboration, information quality, shared situational awareness, and in particular shared situational awareness, and self-synchronization all together increasing mission effectiveness (Hughes, 2007). Although, each operation has its particular nuances, the basic structure is the same – it involves some form of planning, assessment, execution, decision-making, and analysis.

A Conceptual Control System Model Developed from Effects-Based Definitions

All three definitions of effects-based thinking and operations have recurring themes and notions (in **bold** type) even though they were written from three different perspectives and times. The notions may be divided into three mathematical categories: variables, functions and feedback. In Figure 1, a conceptual Control System model of the operation's variables, functions and feedback is captured schematically in block diagram form. The variables include the desired[2] situation, effects, and actions (R_s, R_e, and R_a), the current actions, disturbances, and states (A, D, and S), and current effects and situation (C_e and C_s). In addition to the three main functions of planning, execution, and assessment, Figure 1 also includes a decision-making function represented by a difference comparator.

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[2] In Control Theory textbooks, the letter "R" refers to Reference variables (equivalent to desired variables) and "D" to Disturbance variables.

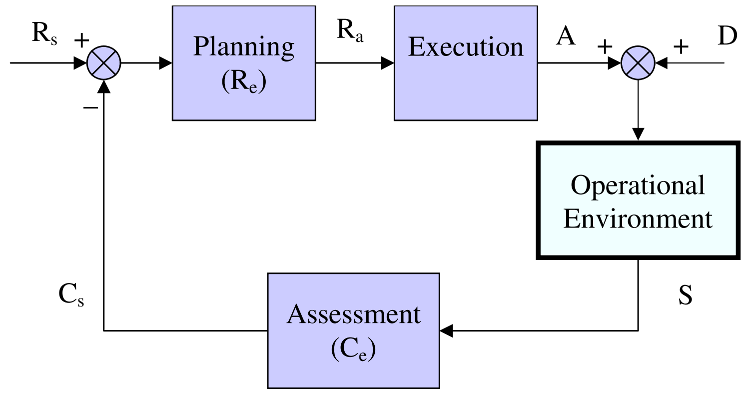

Figure 1. Block diagram of the high-level EBAO functions, variables, and feedback [3]

"Operations" as Feedback Systems in the Literature

Figure 1 is a classical feedback control system. Feedback control systems have been used to describe numerous processes particularly in the engineering domain. One of the earliest examples of a feedback control system is a second century B.C. water clock where a floating valve controlled the water level in a water supply tank using a feedback (Franklin, Powell, & Emami-Naeini, 1991; Miron, 1989). Mead in 1787 invented a governor, and then Boulton and Watt in 1788 used it for a steam engine that regulated the engine speed by changing the position of a valve connected to a flywheel that would speed up or slow down depending on the engine speed.

Another common feedback control system example is the control of the temperature within a house. The thermostat and furnace in a house are specifically engineered such that the current temperature is driven towards the reference temperature as shown in Figure 2. The more that is known about the house dynamics (e.g., the volume, surface area, thermal conductivity, heat producing appliances and occupants, external conditions, etc.), the more precise the design of the controller can be. The temperature control example is conceptually identical to the EBAO process model. Thus, all the analytical power of Control Theory can be brought to bear on the effects-based model.

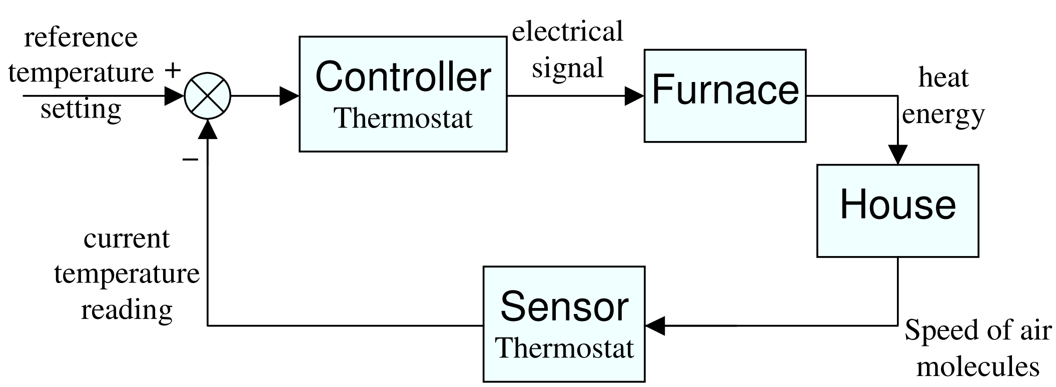

Figure 2: The EBAO process model is conceptually identical to temperature control model

[3] The other comparator represents the summation two vectors.

Several books and papers acknowledge that EBAO can be modelled as a feedback loop. (Alberts, Garstka, Hayes, & Signori, 2001) argue that John Boyd's OODA (Observe, Orient, Decide, and Act) loop does not sufficiently describe Command and Control in this new era of information warfare. They introduce an "adaptive control system" that has "much richer constructs than those in the OODA loop." The constructs are Battlespace Monitoring, Awareness, Understanding, Sensemaking, Command Intent, Battlespace Management and Synchronization. The constructs listed are functions, except for Command Intent and Understanding, which should be considered as variables in this context. This model speaks to human information processes and flows, while the model presented in this paper focuses on the creation and flow of products, presentations, and reports throughout the process. In either case, the variables and functions would be time-varying functions.

Other authors in the CCRP Publication Series share Albert's view of Command and Control. For several chapters in his book entitled "Effects Based Operations", (Smith, 2002) exploits the "Action-Reaction Cycle" that fully describes the interaction between the cognitive, information, and physical domains in terms of a feedback loop. The most explicit reference to a feedback control system for operations can be found in (Alberts & Hayes, 2006). They describe "control" from a classical control engineering perspective. They draw parallels between the command (desired or reference variable) and control (controller and feedback functions) of a room temperature as shown Figure 2 and the command and control (C2) of a military operation. In other words, they model C2 as a classical feedback control system.

In his book on Complexity Theory and Network Centric Warfare, (Moffat, 2003) presents complex mathematical functions and relations that may arise in operations. He provides a set of general differential equations that describe the dynamic behaviour of states within a system. Moffat describes a single differential equation as a function of all state variables including the one for which the differential equation is formulated (i.e., a feedback system), and control variables (i.e., a control system). The book's Appendix contains a control solution for the general system and then provides a unique optimal control solution for a general linear set of differential equations.

Håkon Thuve (unpublished) wrote a draft paper entitled, "State-Space Formulation for Effects-Based Operations." He provided a state-space representation of the operational environment including a random disturbance function, and a conceptual performance index is derived mathematically. The paper yielded a state-space model of Effects Based Operations expressed as a feedback control system.

One might jump to the conclusion that there is a solution for the "Operations" problem using mathematics and Control Theory. Instead, the reader of this literature should be left with two thoughts:

1. Conceptualizing operations as a feedback control system helps in the understanding of the relationships between the operation's functions and variables, and

2. Simplifying assumptions are made in modelling the processes and operational environment in order to make solutions tractable. These solutions still need to be tested within a real environment such as human-in-the-loop experimentation and field trials (Alberts & Hayes, 2002; TTCP JSA AG-12, 2006).

Control System Elements

When modelling a system, the modeller first needs to identify the variables and functions of that system – in the mathematical sense. It may be difficult to imagine that effects-based operations can be described in terms of mathematical equations. However, the goal of this modelling exercise is not to determine the precise differential equations that govern the operation, but to formulate conceptual relationships between known input and output variables. By doing so, a feedback control structure emerges. This section provides a basic, but essential, overview of what is meant by variables, functions, and feedback to help the reader conceptualize effects-based operations using these mathematical constructs.

Variables

A "step" in the US Joint Forces Command (JFCOM) EBAO Concept of Operations (CONOPS) is a low-level function that requires input products before the step's procedures are performed (JFCOM, 2005). It takes time to perform the step's procedures and to complete the output products for that step. The degree to which the output is completed is denoted y(t), which is a function of the dynamics associated with performing the procedures f[·] as well as the degree to which the input product, x(t), has been completed. This input-output relationship is described mathematically (and conceptually) in equation 1.

$$y(t) = f[x(t)] \tag{1}$$

As implied by equation 1, output variables can be expressed as a function of input variables. Also, output variables may become input variables for another function. For example, the output of the Planning function is a document with a set of desired actions, and this output becomes the input into the Execution function as a set of orders for tactical units (see Figure 1). Conceptually, all variables can be expressed mathematically with time as the independent variable.

The variables mentioned in the three definitions given in the introduction include states, desired effects, required actions, actions, set of actions, directed policy aims, strategic goals, end state, and desired end-state. Other terms have been used including strategic objective, desired outcome, effects, unexpected effects, and undesired effects.

The various concept descriptions usually contain an extensive glossary of terms so to minimize the potential confusion. However, once the variables are put in the context of a feedback control model, the meaning of the variables become clear with respect to the inputs and outputs of documented and well-understood functions. For example, terms like aim, goal, end state, objective, or desired outcome should be an input variable to the Planning function, desired actions are inputs for the Execution function, and states become input variables for the Assessment function. Note that the effects variables are not readily identifiable as inputs or outputs of any of the main functions in Figure 1. It will be shown later that the desired and current effects variables are intermediate variables.

In some cases, the variable is scalar or one-dimensional (e.g., desired outcome) while in other cases the variable is multi-dimensional or a vector of variables (set of actions or states). Thus, the variables and functions in Figure 1 are more realistically represented by a vector of variables and a matrix of functions as opposed to a single input variable and a single function that produce a single output variable. There are well known algebraic and Control Theory techniques to describe and analyse these multi-dimensional systems.

The chosen variables for the feedback control system described herein are labelled as desired situation (R_s), desired effects (R_e), desired actions (R_a), then actions (A) and states (S), and finally feedback on states due to current actions (C_a), feedback on current effects as a result of changes in states (C_e), and feedback on the current situation as a result of changes in states and effects (C_s). Note that each desired variable has a corresponding feedback variable.

Functions

Effects-based concepts refer to Processes, Functions, Phases, Tasks, Steps, Activities, and Procedures that are typically organized into a hierarchical “tree” structure. For the purposes of this paper, these descriptors are all “functions” but in a mathematical sense as indicated in equation 1. These functions transform inputs into outputs. For example, input documents are transformed into output documents by following a set of steps and procedures as outlined in the Planning process.

There are five high-level functions for effects-based operations (and arguably for all operations): Planning, Execution, Assessment, Decision-making, and Analysis. The first three functions appear explicitly in Figure 1. A difference comparator represents the Decision-making function. Typically, the Decision-making function is embedded in descriptions of Planning, Execution, and Assessment functions, but the Control Theory model elevates this function to the same level as the other three functions.

Analysis does not appear explicitly on this high-level schematic. However, the UK philosophy refers to a function called Analysis. The Analysis function is described as a function that supports Planning, Execution, and Assessment in the US concept. The Analysis function supports Mission Analysis (JFCOM, 2003) and End State Analysis as part of the Planning function, Identify Issues from the Execution function, and Qualitative Campaign Evaluation within the Assessment Function (JFCOM, 2006). The model developed for this paper does not show the Analysis Function as part of the main feedback loop, but refers to it as an ongoing continuous background function.

The Analysis function involves the analysis of the operational environment and it has been specifically referred to as Operational Net Assessment in Multi-National Limited Objective Experiment 2, System of Systems Analysis in MNE 3, and Continuous Systemic Analysis (CSA) in MNE 4 and MNE 5. During this analysis activity, Subject Matter Experts (SMEs) develop and analyse information about the operational environment that planners, executers, and assessors can then exploit to complete their tasks.

The Analysis function product is a descriptive or information model of the operational environment that is constantly evolving. This information is stored within multiple databases referred to collectively as a Knowledge Base (KB). This model of the operational environment appears later in this paper as the Operational Environment (OE) function, which is embedded in the Planning function. OE is an approximation of the World, which is denoted as W in this model. Thus, the Analysis function's product appears explicitly in the model – not the Analysis function itself.

Feedback

Feedback uses observations of the system error (difference between a desired state and its current value: $R_s - C_s$ as depicted in Figure 1 as the output of the comparator function), and this error is used to make adjustments to improve performance (Van de Vegte, 1990). None of the definitions in the introduction talk explicitly about feedback in the mathematical sense, but they all hint to its existence. The Canadian definition talks about effects and actions being concurrently and reactively planned…and re-planned. The UK philosophy requires constant iteration of the functions. The US CONOPS states "The activity is made adaptive by the iterative or continuous repeating of many of the steps upon the receipt of updated input as indicated… The step-to-step relationships define the flow of the planning process and show where opportunities exist for parallel staff work." Thus, there is the notion that some functions are part of a cycle and revisited in due time while others are done non-sequentially with no precedence restrictions. Both notional structures can be modelled using Control Theory.

There is a natural sequential and cyclical progression to the three main functions: generate a plan, execute the plan, and then assess the consequences. If the assessment results show that the current situation is different from the desired situation then the sequence repeats until the current situation is driven towards the desired situation. This description of a feedback control loop also explains most human activity. (Powers, 1973) exploits this paradigm to describe individual human information processing and (Farrell, 2006) extends this framework for team information processing.

There are also non-sequential elements as part of the overall model. Some of the functions might proceed in parallel, such as the Analysis function, while others have an adaptive influence that estimates uncertain system parameters (p) and uses these approximate values to control the system (Slotine & Li, 1991), such as the Red and Green Teaming activity. Adaptive control takes advantage of system state obervations but it should not be confused with the main feedback process.

$$y(t) = f[p\ x(t)] \text{ where } p = p(t) \qquad [2]$$

Equation 2 is an example of a nonlinear equation that has an uncertain parameter, p(t). "Nonlinear" does not mean "not sequential" as it has been used colloquially in effects-based discussions and in the CONOPS. A mathematical definition for nonlinearity is as follows: nonlinearity exists if and only if there exists times t_1 and t_2 such that $y(t_1+t_2)$ does not equal $y(t_1) + y(t_2)$ (principle of superposition applies to linear functions).

With the understanding of what is meant by variables, functions, and feedback in the mathematical sense, one can read through a concept of operations and begin building a mathematical model of the processes. This is exactly what will be done in the next section.

An EBT Operation Model

A conceptual but detailed feedback control system model is developed from a specific CONOPS entitled Effects-Based Approach to Operations (EBAO) CONOPS (JFCOM, 2005). A similar analysis may be conducted for operations that employ effects-based thinking, if the CONOPS are available. The reverse is true as well. That is, a CONOPS can be designed from a control system model description of an operation.

The EBAO CONOPS is decomposed in four levels: Functions[4] or Processes, Activities, Steps, and Procedures. The highest-level function is labelled as Level 1 in Figure 3. Level 1 functions are decomposed into Level 2 functions, Level 3 functions, and so on. The functions at every level have Inputs and Outputs (could be documents, presentations, awareness, decisions, actions, measured indicators, assessments, reports, etc.), and they are specified within each Step. The following is a sample of a typical Step description found in the CONOPS:

Decomposition Levels

Level 1	**CONOPS:** EBAO
Level 2	**Process:** EBP
Level 3	**Activity:** End State Analysis (ESA)
Level 3	**Activity:** Effects Development (ED)
Level 4	**Step:** ED1. Develop desired effects
Level 4	**Step:** ED2. Develop Commander's Approved Effects List (CAEL)
Level 4	**Step:** ED3. Sequencing the CAEL and develop Cdr's Guidance
	Purpose: To determine (and review/revise as necessary) the temporal relationships and dependencies between desired effects…
	Input: CAEL from step ED2 [*likely a word processing document*]
	Procedures:
Level 5	• Brainstorm ideas to determine when each desired effect needs to be created....
Level 5	• Create the first draft sequencing matrix, relating effects to time.
Level 5	• Develop the Commander's Guidance, which must include:
	- Relevant excerpts from the Coalition Coordinated Strategy
	- The revised operational level military end state
	- …
	- The CAEL with associated MOE [*measures of effectiveness*]
	- The first draft desired effects sequencing matrix
	Output: Commander's Guidance …[*likely in presentation form*]
	Staff Participation:
	• Planning Staff
	• *Command Group*
Level 3	**Activity:** Red and Green Teaming (RG)
Level 3	**Activity:** Action Development and Resource Matching (ADRM)
Level 3	**Activity:** Effects-Based Assessment Planning (EBAP)
Level 3	**Activity:** Synchronization and Plan Refinement (SPR)
Level 2	**Process:** EBE
Level 2	**Process:** EBA

Figure 3. A sample of the EBAO CONOPS decomposition

[4] The CONOPs use the word "Functions" in the sense of a high level task within the EBAO system, rather than in the mathematical sense. Note that this word is capitalized.

The third level functions (Activities) are extracted from the CONOPS and schematically depicted as a feedback control system in Figure 4. The boxes represent the Activities' dynamics that represent the time it takes to transform an Activity's Inputs to its Outputs. The arrows represent the Inputs and Outputs that flow in and out of each Activity. The Activities' Outputs (as indicated in the CONOPs) dictate the connections between functions. That is, an Activity would not even begin unless the Input products are completed (to some given extent) from the previous Activity. For example, the Effects Development (ED) Activity produces the Commander's Guidance (see Figure 3) and Commander's Guidance is needed to initiate Action Development and Resource Matching (ADRM) according to the CONOPs. Therefore the ED output becomes one of the ADRM inputs. This logic is repeated for the entire CONOPS resulting in Figure 4. The following sections provide brief explanations for each function in Figure 4.

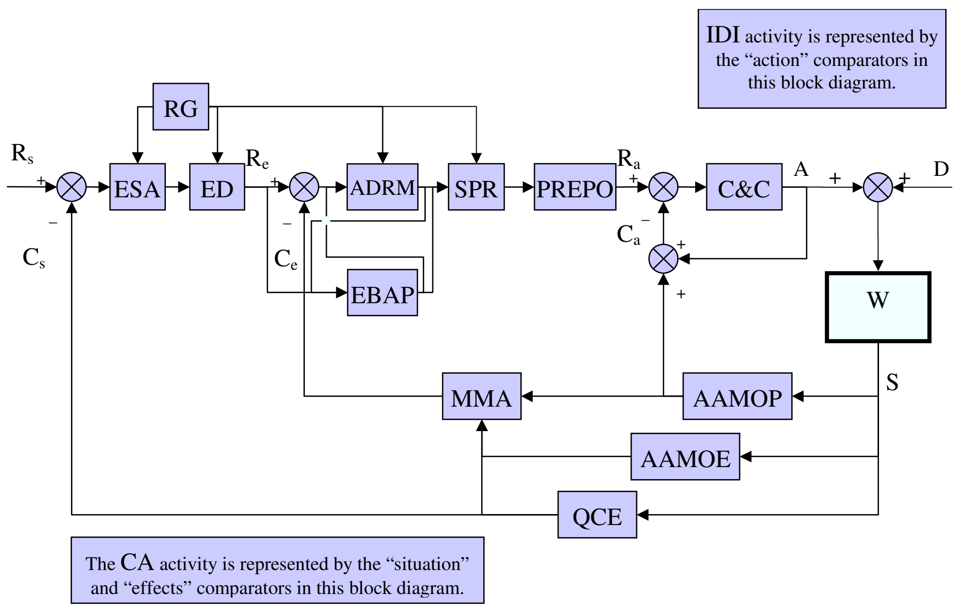

Figure 4: Feedback control system model based on EBAO CONOPS v0.9 decomposed down to the Activity level.

Effects-Based Planning

The Effects-Based Planning (EBP) function consists of six Activities:

1. End State Analysis (ESA)
2. Effects Development (ED)
3. Red and Green Teaming (RG)
4. Action Development and Resource Matching (ADRM)
5. Effects-Based Assessment Planning (EBAP) [appears in CONOPs version 0.9]
6. Synchronization and Plan Refinement (SPR)

EBP is the most mature of the functions and was fully explored in MNE 3 (J9, 2004) and refined for play in MNE 4. EBP requires an understanding of the desired situation or the End State in order to develop desired effects and desired actions that are planned to achieve the End State. Once the ESA is completed, the planners engage in ED. The RG Activity is a form of wargaming (or gaming) where team members verify that the desired effects and desired actions are robust in lieu of adversarial and neutral reactions. Once the Commander is satisfied with the desired effects, then the planners link actions and resources to the effects during ADRM. Concurrently, the EBAP starts. Finally, the effects, actions, and resources are synchronized during the SPR Activity.

Effects-Based Execution

The Effects-Based Execution (EBE) function consists of three Activities:

1. Prepare Orders (PREPO)
2. Control and Coordinate Operations (C&C)
3. Identify Issues (IDI)

Although EBE is the newest and least mature of the four functions, it is fairly straightforward because this function is familiar to militaries – they execute plans. Fundamentally, the EBE function involves converting the Plan into Orders for the tactical level (PREPO), controlling and coordinating the actions and resources outlined in the Orders (C&C), identifying issues associated with the actions and correcting the actions by generating new Orders as necessary (IDI). This cycle may repeat itself until the desired actions are achieved (i.e., a feedback loop within a feedback loop).

Effects-Based Assessment

The Effects-Based Assessment (EBA) function consists of five major Activities:

1. Qualitative Campaign Evaluation (QCE)
2. Effects Analysis by use of Measures of Effectiveness (EAMOE)
3. Actions Analysis by use of Measures of Performance (AAMOP)
4. Measures of Effectiveness – Measures of Performance Analysis (MMA)
5. Campaign Assessment (CA)

Simply put, EBA provides feedback for three primary variables: situation (QCE), effects (EAMOE), and states due to actions (AAMOP). If the current situation and effects are progressing towards the desired situation and desired effects then the EBP and EBE staffs may continue to follow the plan and operations order. However, if these variables begin to significantly diverge from their desired values, then this would initiate a re-execution, re-planning, or even a re-evaluation of the strategic context and the desired outcome (CA: represented by the effects and situation comparators in Figure 4). The terms, Measure of Performance and Measure of Effectiveness, refer to action and effects analyses, respectively, which causes confusion with the engineering use of the terms[5]. To avoid this confusion, these names could be shortened to Effects Assessment (EA), Action Assessment (AA), and Situation Assessment (SA).

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[5] Normally, MOP is the measurement of a variable (e.g., a car speed was measured at 100 km) while MOE is the measurement of the extent to which a variable matches its desired value (e.g., a car was measured to be 90% effective when travelling at 45 km on a dirt road while its desired speed was 50 km).

Operational Environment

Figure 4 includes a function that represents the real operational environment (W). It is taken for granted that W cannot be fully replicated using partial differential equations, however, conceptually it is beneficial and insightful to think of the world as a function that has inputs and outputs. There are two major inputs to W: actions that are produced by tactical-level organizations, and other actions caused by the adversary, neutral entities in the operational environment, as well as natural phenomena. A disturbance vector is the representation of the latter three actions. The outputs of the world function are physical states such as changes in energy (fluctuations of light, sound, and pressure) such that these states can be experienced (seen, heard, and felt). Certain changes in physical states can cause shifts in psychological and societal states (the World Trade Centre's physical destruction on September 11, 2001 caused changes in perception, belief, and societal norms).

The Operational Environment (OE) model is a representation of W. OE is a product of the Analysis function, currently called Knowledge Development (KD) [6]. In MNE 4, OE took the form of a descriptive, static model of the operational environment – that is, information organized and viewed along the six dimensions: political, military, economic, social, information, and infrastructure. Also, inference diagrams were used to display the information and their interrelationships.

A dynamic OE model could be developed from the information within the static model, given that time estimates are available for certain events. The dynamic OE model has the potential to be (mathematically) complex with feedback, adaptive functions, nonlinear differential equations, inference networks, and so on, depending on the level of fidelity required. The world is constantly changing, and so theoretically the OE model should be updated at the same rate. Practically, time and cost will constrain the number of OE model updates.

In the most recent version of the CONOPS (JFCOM, 2006), the previous three KBD activities have been reduced to a single KD activity called Continuous Systemic Analysis. This activity has been decomposed into four main steps:

a. Examine the operational environment (CSA 1)
b. Model the operational environment (CSA 2)
c. Examine and simulate possible future system behaviour (CSA 3)
d. Provide systemic analysis updates for the Commander and staff (CSA 4)

KD remains a continuous process that occurs outside the main EBAO loop, with its products inserted deliberately during certain activities. For example, there is an overlap of CSA 1 with ESA. Both the Planning and Analysis staffs would likely work together in accomplishing these tasks. It will be shown later in this paper that the OE model produced during CSA 2 will be used during a combined ADRM and SPR function called GAME.

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[6] Knowledge Development (KD) was originally Knowledge Base Development (KBD) where a relational database was built between many pieces of information. This function should be properly called OE Model Development because the resultant database is an external representation of the operational environment. Individuals can develop their own knowledge about the operational environment by exploring the database.

Key Decisions and Additional Inputs

The comparator functions (denoted "⊗" in the control system figures) have inputs and outputs like other functions, and they complete the feedback loop. The difference comparators (comparators with plus and minus signs) represent decision-making functions that depend on context of a large body of experience, tacit knowledge, social and cultural norms, and therefore they are not often as simple as an arithmetic difference function. The comparator function may be time-varying logic or fuzzy logic operators (e.g., AND or OR, UNION or INTERSECTION, etc.) on the inputs to produce an output. The difference comparator denotes a key decision that is being made to 1) determine the extent to which the difference between the two inputs (or two input vectors) is significant, and 2) choose actions (or communications) that eventually would minimize the difference. In the case where the comparator denotes a summation function (two plus signs), inputs from other sources are added together – or more generally convoluted – forming an overall output vector.

Figure 4 shows summation and difference comparators for the inner action loop. For the difference comparator, the IDI procedure presents a choice: "decide whether to continue to consider the issue, or simply continue with solution(s) developed during planning (JFCOM, 2006)." In other words, "either change the desired action variable, or continue executing the plan in an attempt to match the desired and the current action variables (i.e., minimize their difference) (JFCOM, 2006)." A decision matrix, like in Table 1, can be generated that represents the logic within the difference comparator in a straightforward and simple manner. The matrix has two dimensions: the degree to which the action is complete and the degree to which the immediate state due to that action is realised: for example, an action might be to drop a bomb on a bridge and the immediate state may be that a) the bomb missed and the bridge is still intact, b) only partial damage was observed, or c) the bomb did enough damage to the bridge to make it impassable.

TABLE 1. A DECISION MATRIX FOR THE ACTION FEEDBACK LOOP

		Action complete?		
		No	*Partially*	*Yes*
State realised?	*No*	**Start**	Execute	Change
	Partially	Assess	**Execute**	Assess
	Yes	End	End	**End**

Normally, the decision would begin in the upper left corner of the table where the action would **start**, then the decisions would traverse along the diagonal where the same action would **continue** until the state is fully realised, at which point the control and coordination loop would **end**.

If, for some reason, there is no action but the state is partially or fully realised then the decision would be to continue assessing the state or end the loop. If the action is partially complete then continue executing the action until the state is fully realised. If the action is fully complete but the change in state is not realised then one might change the desired action. Finally, if the action is fully complete and the state is partially realised then one would continue assessing the state. Thus, the decision-making matrix has both the expected decision-making path as well as contingencies represented by the off-diagonal entries.

Similar to IDI, the CA function describes a series of decisions to be made. In fact, the CONOPS provides a decision matrix for CA (see Table 2). Four decisions are proposed that depend on a combination of the effects and the desired situation (end state) variables. There seems to be no systematic means for organizing these decisions. However, a much simpler decision matrix could be developed for the effects comparison, similar to Table 1.

TABLE 2: EFFECTS TO END-STATE COMPARISON[7]

<table>
<tr><td></td><td></td><td colspan="2">End State Progress?</td><td></td></tr>
<tr><td></td><td></td><td>**YES**</td><td>**NO**</td><td></td></tr>
<tr><td rowspan="2">Effects Creation?</td><td>**YES**</td><td>**Case 1**
“Proceeding as planned”</td><td>**Case 3**
“Requires immediate attention”</td><td></td></tr>
<tr><td>**NO**</td><td>**Case 2**
“Requires moderate attention”</td><td>**Case 4**
“Highest importance” (except early in the campaign)</td><td>Possible campaign modifications:
Action execution
CAEL
Individual MOEs</td></tr>
<tr><td></td><td></td><td></td><td>Possible campaign modifications:
New / partial EBP iteration
Statement of desired end state
CAEL
Individual MOEs</td><td></td></tr>
</table>

Currently, descriptions of the key decisions (difference comparator functions) are embedded in the step level of various CONOPS activities. However, this paper argues that in a future version of a CONOPS, these decisions must be brought to the same level as the Planning, Execution, Assessment, and Analysis functions. Therefore, the future CONOPS would have a separate section in which the decision steps and procedures (or decision matrix) would be clearly articulated, and the steps’ Inputs and Outputs would be clearly identified similar to the other sections. The Decision-Making section should also take into consideration the cognitive and social impacts of decision-making.

There are two summation comparators in Figure 4. The first one, in the forward loop, does not appear explicitly in the CONOPS but was added to the model to represent the addition of disturbances (D) within the operational environment. The disturbance represents the actions of the adversary and neutral organizations, as well as forces due to nature. The second summation comparator next to C_a is part of the action loop, and represents the combination of the status of the action and the immediate states due to the action. This combination is not clear in the CONOPS, and so an alternative description will be provided based on a simplification of the action loop model.

In summary, Figure 4 represents a sequence of activities proposed for an effects-based operation. Interestingly, the concept developers did not have in mind a feedback control system when they wrote the CONOPS, yet the underlining structure is a feedback control system, which has tremendous implications for analysis and simulation of the concept as well as implications for re-stating the concept so that it is clear, simple, and scalable. The next

[7]Figure 28 is an excerpt from (JFCOM, 2006) as approved by JFCOM.

section examines ways to simplify the operation model in Figure 4 without losing or diluting any essential features of the concept.

Simplifications

The first simplification of the Operations model was done in version 1.0 of the EBAO CONOPS (JFCOM, 2006), again without the concept developers being conscious of the Control Theory implications. That is, the EBAP function was absorbed into the ED and ADRM functions, thereby eliminating a complex relationship and simplifying the overall model. The following sections simplify (or make clear) the rest of the model in Figure 5 by introducing adaptive inputs, re-organizing the connections in a logical and systematic way, and combining activities where it makes sense to do so.

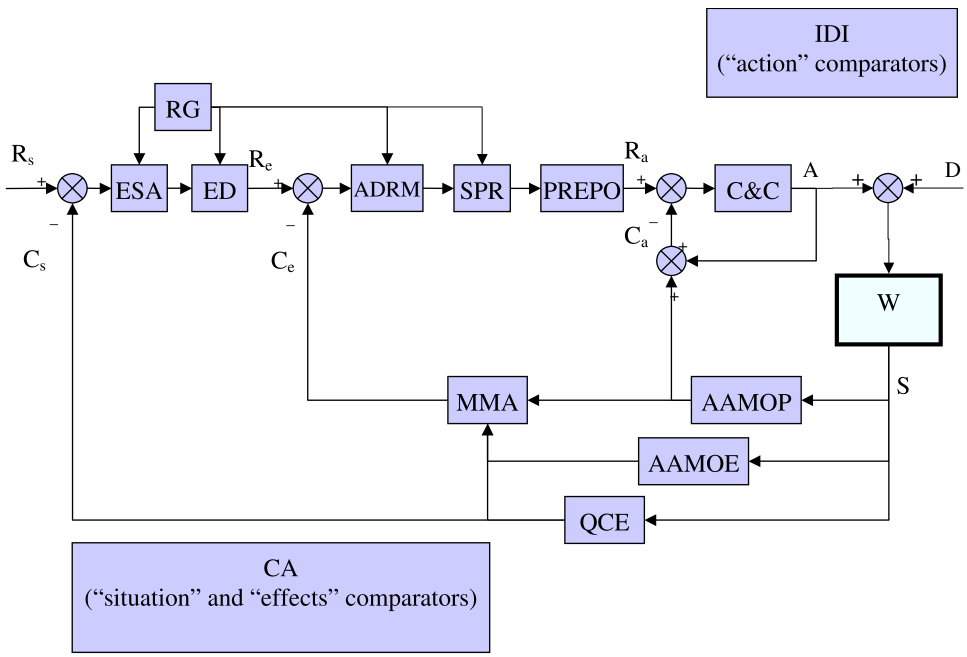

Figure 5: Feedback Control System model based on EBAO CONOPS v1.0.

EBP Simplification

The RG Activity[8] generates the adversary (red) and neutral's (green) desired situation, effects, and actions. The RG Activity and its feed-forward configuration can be simplified by recognizing that RG generates information for other Activities. RG provides inputs to ESA, ED, ADRM, and SPR but does not receive any inputs from other functions (according to the CONOPS). From a Control Theory perspective, RG generates inputs that come from outside of the main EBAO loop (similar to R_s and D).

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[8] The RG Activity is in fact blue's (own team) perspective of red (adversary) and green (neutral entities). One must keep in mind that the RG Activity may not produce the exact same product that would be produced by real world adversaries and neutral entities. This is a key reason for having a feedback control system as the main structure of the operation – to react to unexpected effects.

Red and green's desired situations (Rr_s and Rg_s, respectively, in Figure 6) are compared to the i^{th} iteration of blue's desired situation ($R_{s\,[i]}$) in the ESA activity. This comparison yields a decision to accept R_s and continue planning, or to significantly re-define $R_{s\,[i]}$ yielding $R_{s\,[i+1]}$. For example, the desired situation for both blue and red may be to realize economic growth in the region, but each side may interpret it differently. Blue may want to see economic growth benefit the entire population under the control of a stable government so that one could engage in foreign trade, while red may want to see economic growth only for each tribe and under the control of each tribal leader.

The input from the RG function is not added linearly to the other functions, as would be the case with a summation comparator. Rather, the RG input arrows shown in Figure 6 have different arrowheads, which is meant to suggest that the RG inputs modify or 'adapt' the function in a nonlinear fashion. The conceptual mathematical relationship may be described as follows:

$$R_{s\,[i+1]} = f_s\,(Rr_s, Rg_s)\,R_{s\,[i]} \qquad [3]$$

The function, f_s, is a nonlinear function of red and green's desired situations that modify blue's desired situation (as described in the CONOPS).

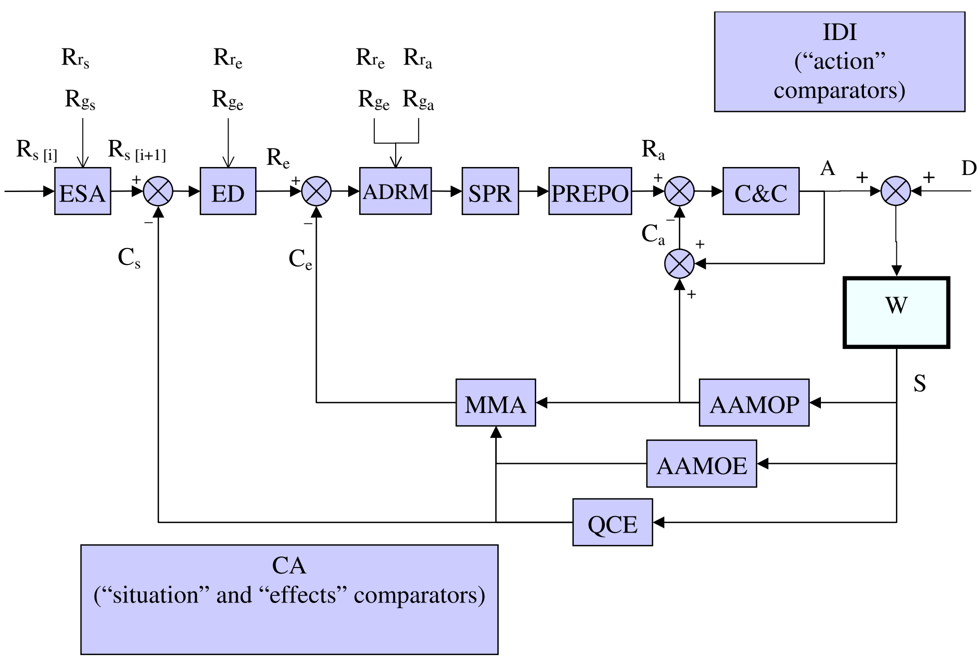

Figure 6: Feedback Control System model with RG Inputs shown as nonlinear inputs

Note that the comparator that examines the desired and current situation variables is shifted to the right in Figure 6 compared to its position in Figure 5. That is, while the operation is proceeding, the current situation (C_s) would be compared to the most recent refined desired situation ($R_{s\,[i+1]}$). If the current situation were not converging onto the desired situation (i.e., EBAO control system is not stable) then this would trigger a re-examination of the strategic context and the initial desired situation.

The Effects Development (ED) activity has three main steps or sub-functions: development of an effects list, conflict resolution and refinement of desired effects using red and green desired effects (Rr_e and Rg_e), and identification of world states related to desired effects. The first sub-function assumes that the refined desired situation can be decomposed into a vector of effects, sub-effects, and so on[9]. Conceptually, the mathematical expression is as follows:

$$R_s = G_{se}R_e \qquad [4]$$

G_{se} is a transformation matrix that transforms effects into a situation and G_{es} is the inverse transformation. Therefore:

$$R_{e\,[i]} = G_{es}\,(R_s - C_s) \qquad [5]$$

Similar to the ESA process, the second ED sub-function is designed to resolve any conflicts between blue's desired effects and red and green's desired effects; it filters out unachievable desired effects and ultimately leads to an approved list of desired effects for blue called the Commander's Approved Effects List (CAEL). The conceptual relationship is as follows:

$$R_{e\,[i+1]} = f_e(Rr_e, Rg_e)\, R_{e\,[i]} \qquad [6]$$

The third ED sub-function is related to the identification of states that produce the effect, and how one can measure those states (formerly the EBAP activity). This sub-function produces a version of the "measure of effectiveness (MOE)", or more appropriately termed "feedback on effects" based on an examination of current states. This can be expressed mathematically as:

$$C_e = H_{e_\sigma} S \qquad [7]$$

S is the set of current world states, and H_{e_σ} is a feedback matrix that transforms current states into current effects (C_e) that are related to the desired effects (R_e).

Moving on, both ADRM and SPR activities involve "war-gaming" or simulating the interaction between blue, red, and green but for two separate reasons. ADRM1 identifies a list of desired actions required to achieve the desired effects, and ADRM2 involves an action-reaction-counteraction cycle in order to refine the list in lieu of red and green actions. SPR2 involves an action-reaction-counteraction to determine a temporal order of actions to be performed that would yield the desired temporal order of effects (i.e., synchronization of effects and actions). The action-reaction-counteraction could be modelled as a "turn-taking" or "free-play" game. While the original intention was to take turns, a free-play game is a closer representation to what might happen in real operations. In effect, ADRM and SPR may be combined into one function called "GAME."

The block diagram in Figure 7 is a model of a three-player interaction. The model may represent turn-taking, free-play, or any combination of the two by applying certain game rules. The three players have their own desired effects and desired actions, and they perform

[9]It is more art than science to determine the number of decomposition levels. A guideline is to decompose down to a level of real world states that can be directly influenced by coalition actions. Note that "states" is a synonym for "effects" and "sub-effects" in this discussion.

simulated actions that influence the states of the operational environment function (OE). Note that the model structure for each player mimics the structure for real operations.

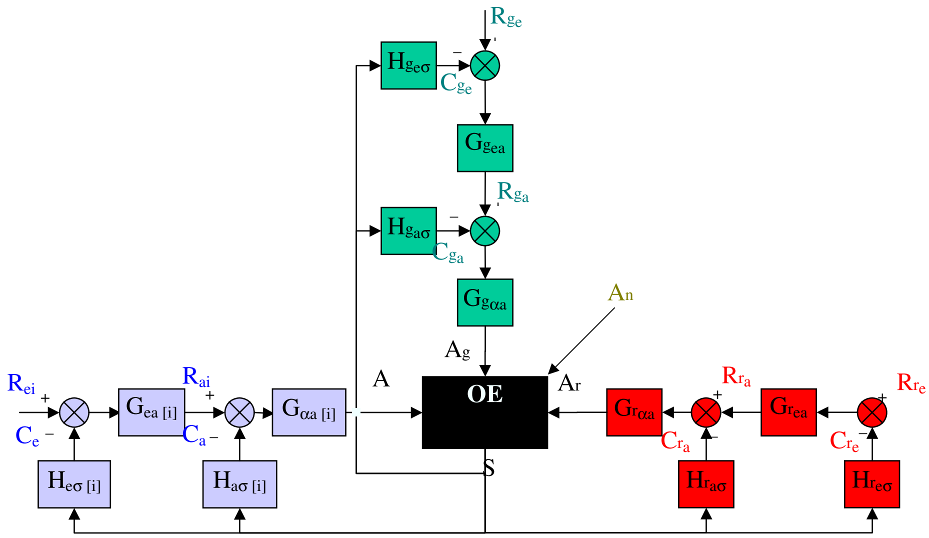

Figure 7: Blue, Red, and Green gaming model

With the inclusion of the GAME function, the complete feedback control system model would be said to exhibit a *predictive model structure*. There are two key reasons to adopt this iterative approach to the development and refinement of the matrices. First, the objective of this game is not to win, but to propose and trial blue functions and desired vectors that stabilize the system[10]. It is likely that there are several options that would yield a stable system and all of them can be trialed during this activity. Second, after an ideal option is found, other constraints must be taken into consideration (e.g., resources, rules of engagement, costs, etc.), and these can be applied safely in this synthetic environment. Several iterations of the game should yield a workable solution for blue's matrices and the desired effects vectors. However, the current CONOPS calls for a single iteration of the ADRM and SPR steps. The matrices and vectors that result from the game are readily translated into prose (e.g., procedures) and products (e.g., desired effects list), respectively.

According to the CONOPS, $G_{ae\,[i]}$ is the transformation from desired effects to desired actions and would be produced during the ADRM activity such that:

$$R_a = G_{ae\,[i]}\, R_e \qquad [8]$$

Similarly, $G_{\alpha a\,[i]}$ is the transformation from desired actions to actual actions representing the Command and Coordination (C&C) and Identify Issues (IDI) Activities within the EBE function. The input-output relationship is expressed as follows:

$$A = G_{\alpha a\,[i]}\,(R_a - C_a) \qquad [9]$$

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[10] Stability, in this case, means that at least blue reference values are achieved or modified to minimize the difference between the reference and current values. If, in addition, green and red reference values are achieved or modified during the course of the game, then the system becomes optimal.

$H_{a_\sigma [i]}$ is the feedback on the change in states due to the current actions (C_a). This feedback matrix would be developed initially during the game. The input-output relationship is expressed as follows:

$$C_a = H_{a_\sigma [i]} S \qquad [10]$$

Similarly, $H_{e_\sigma [i]}$ is the feedback on the effects due to the changes in states (equation 7). This feedback matrix was first formulated in ED, but could be refined during the game.

$$C_e = H_{e_\sigma [i]} S \qquad [11]$$

The GAME activity is a combination of the ADRM and SPR activities, and the results of the game include descriptions of variables and functions for other parts of the loop:

$R_{e [n]}$ – Refined Commander's Approved Effects List
$R_{a [n]}$ – Commander's preferred course of action (with associated resources)
$G_{ea [n]}$ and $G_{\alpha a [n]}$ – Synchronization matrices
$H_{e_\sigma [n]}$ and $H_{a_\sigma [n]}$ – Effects and action assessment plan

These descriptions are used to compile the Effects-Based Plan (EB Plan).

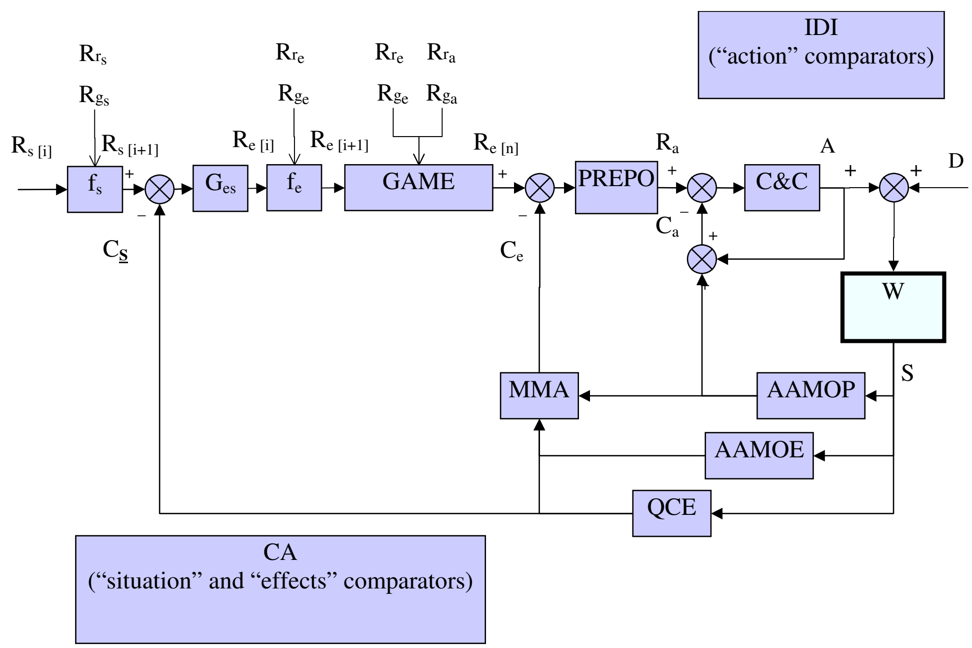

Figure 8: Combining ADRM and SPR activities into a single GAME activity

In summary, Figure 8 shows the system model with the EBP simplifications as described above. Essentially, there are three main planning activities. The first activity is to perform an End State Analysis and produce the desired situation while taking into consideration red and green desired situations. The next activity is to decompose the desired situation into effects (Effects Development) while taking into consideration the red and green desired effects. The third activity is to play a game in order to refine the effects, develop actions, link resources to actions, and synchronize the actions so that the effects are produced in a specific order. All the GAME products listed above are included in the original CONOPS. While all the original activities still exist in this model, they have been re-organized in more systematic manner. Note that the "effects" comparator has moved to the right compared to Figure 6.

EBE Simplification

The EBE function involves PREPO, C&C, and IDI. Whereas the EB Plan (specifically $G_{ae\,[n]}$) indicates the desired actions needed to be executed to generate the desired effects, the Operations Order (OPORD) rephrases the EB Plan into orders for tactical-level teams. The input and output for PREPO are $R_e = R_{e\,[n]}$ and $R_a = R_{a\,[n]}$, respectively: that is, the desired effects and desired actions for the last iteration, n, of the game. Thus, the PREPO function is defined as $G_{ae} = G_{ae\,[n]}$ and therefore equation 11 is identical to equation 8 from the game:

$$R_a = G_{ae} R_e \qquad [11]$$

C&C involves the coordination of orders with other agencies and the control of their own actions. The result of this activity is actual actions that influence and change the world states. The CONOPS only describes the coordination and control activities, but the transformation of desired actions to current actions is implied as the responsibility of tactical-level teams. The control portion of C&C implies feedback on current actions. Thus, the simplification stages of the action loop are shown in Figure 9.

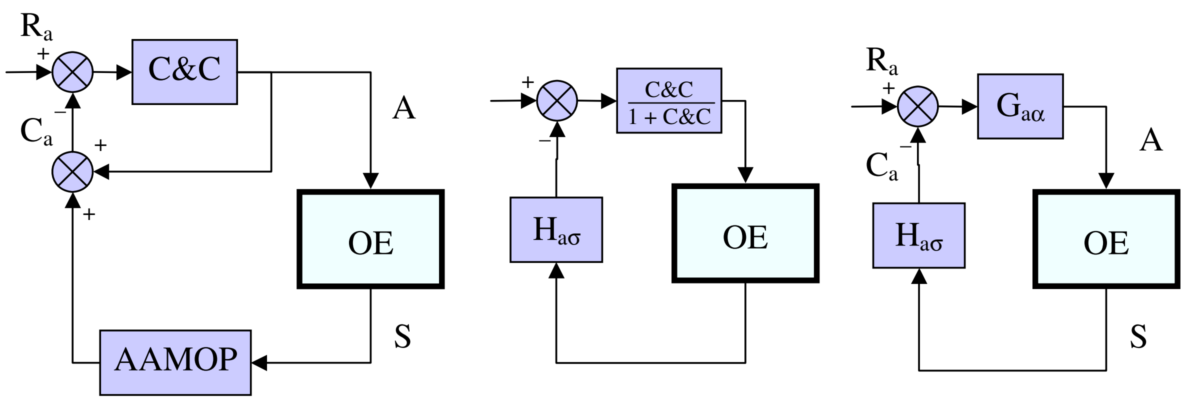

Figure 9: Simplifying the Action Loop

The implication of this simplification is that C&C, IDI, and AAMOP involve two primary sub-functions:

G_{a_α} – generates actions based on any differences between desired actions and measured states (C&C activity primarily).

H_{a_σ} – generates feedback on current actions as well as states that vary directly due to those actions (IDI and AAMOP activities).

EBA Simplification

The EBA function shown in Figure 8 is not straightforward for several reasons. First, the terminology is confusing as mentioned earlier. Second, the input-output relationships are awkward. Third, assessing actions, states, effects, and the overall situation is likely the most difficult aspect of EBAO. The Control Theory view simplifies the terminology, provides simple options for input-output relationships, and provides some guidelines for assessment.

Current EBA descriptions include measures of performance, measures of effectiveness, quality campaign evaluation, action analysis, effects analysis, and campaign assessment[11]. After reading the EBA description in detail, it can be concluded that EBA is about sensing the operational environment to generate feedback on the status of actions, effects, and the overall situation. Therefore, simple and clear alternatives for EBA descriptions are feedback on status of current actions (action status), feedback on current effects (current effects), and feedback on current situation (current situation). It is this feedback that is required to close the loop and stabilize the system.

The assessment structure in Figure 8 is a mixture of serial and parallel feedback. For example, CA needs information from MMA, and MMA needs information from AAMOP and AAMOE (serial). Meanwhile, QCE, AAMOP, and AAMOE seem to draw information directly from the operational environment (parallel).

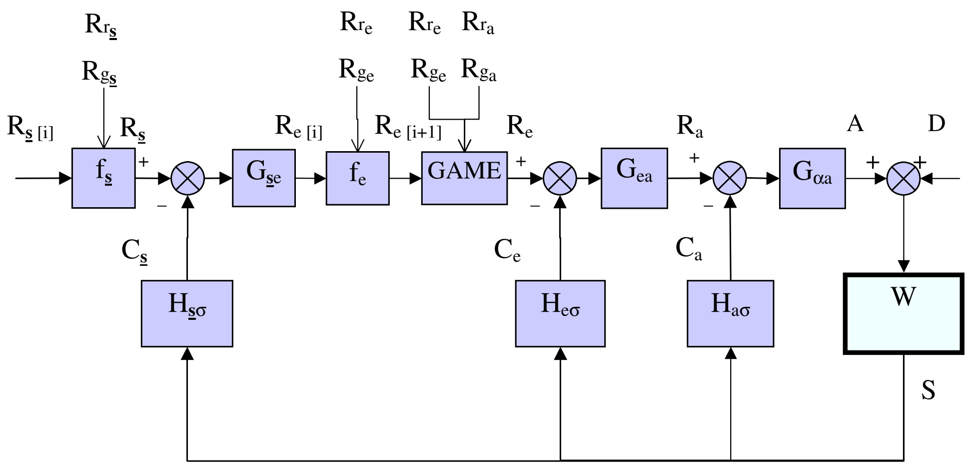

Figure 10: Simplified feedback control system model with parallel feedback

Two feedback structures – serial (Figure 10) or parallel (Figure 11) – are proposed; neither of which has a clear advantage over the other. The serial structure has one-to-one relationships between the states and action status, action status and current effects, current effects and the current situation, but the order in which the feedback is collected is critical. The parallel structure produces mathematically complicated transformations between the states and action status, current effects, and the current situation, but feedback on these variables may happen simultaneously. Although the two structures are mathematically identical, it is likely that the

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[11] Evaluation, analysis, and assessment have the same meaning in this context.

serial structure is more useful since it is likely that actions evolve first, then effects, and finally the situation (i.e., order matters).

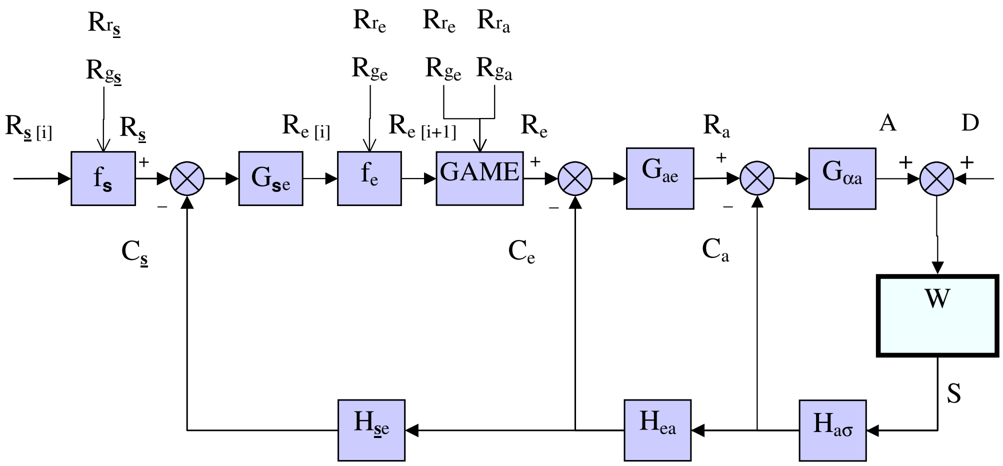

Figure 11: Simplified feedback control system model with serial feedback

The first estimate of the feedback matrices (H) is the inverse of the feedforward matrices (G). In other words, if G is the transformation function between variable x and y then H is the transformation function between y and x. For example, if G_{ae} is the function that transforms desired effects into desired actions, then H_{ea} is the function that transforms action status into current effects (i.e., $H_{ea} = G_{ae}^{-1}$). This inverse relationship appears in CONOPS v0.9 within the EBAP activity.

Although the parallel and serial feedback models do not appear to resemble the original EBA process, all the EBA functionality is preserved in the new models. The models simplify and clarify the EBA terminology and structure. Furthermore, the model provides guidance on generating the first estimate of the feedback matrices. These ideas are to be pursued in subsequent studies.

Implications

This section summarizes the implications for operations that involve EBT from a Control Theory perspective in terms of process, organization, technology structures as well as human factors. Although the model was built using, specifically, the EBAO CONOPS v1.0, the basic feedback control structure can be generalized to any operation.

Process Implications

The Control Theory view of EBAO allows one to develop concept descriptions and labels that are clear, simple, and scalable. There are three feedback loops that involve three key variables: situation, effects, and actions. The situation is a high-level state of the world and effects are lower-level states of the world. Actions are not states of the world, but actions influence or change the states of the world. Regardless of the labels for the variables, the essential feature of EBAO from a Control Theory perspective is to take a high-level description of a desired state of the world and explicitly decompose it to a level where specific actions can be identified that influence the lower-level states. The lower-level states are sensed and reconstituted to determine the status of successively higher-level states.

The underlying control system structure of the EBT operation is simple. From a structural point of view, EBT operations are no different than any other operation or any other human activity. Given a high-level desired End State and information about the world (Strategic Objective and Analysis function), the person or team plans to accomplish the desired situation (Planning function), executes the actions that were planned to change the world states (Execution function), and collects feedback on the world states that are related to the desired variable (Assessment function). The desired and current variables are compared to each other and decisions are made to change the desired variable, to continue with the planning, execution, and assessment cycle, or to end the operation (Decision-making function).

The control system structure is the same for the situation, effect, and action variables, and therefore it is scalable to any number of intermediate variables. That is, if there is a need to decompose the situation into more than one level, then the structure would repeat itself for each level in the hierarchy of world states with the action variable at the lowest level.

Sampling Theory (Van de Vegte, 1990) would indicate that the inner loop (actions) should be, as a minimum, twice[12] as fast as the middle loop (effects) and therefore four times as fast as the outer loop (situation) to achieving stability. This means that if the desired situation is expected to change in four weeks, then changes to the desired effects should happen every two weeks and actions should be completed each week. More realistically, a major military offensive may take a month to complete, ten months before the desired effects are realized, and many years before the desired situation is achieved. More often than not, political will does not outlast the time it takes to stabilize the situation loop, a new government is formed, and troops are recalled. This phenomenon is to be explored in follow-on studies.

[12] The rule of thumb is ten times depending on the accuracy requirements and energy costs.

The process structure is formally called a *predictive control structure* because of the GAME activity that emerged by combining ADRM and SPR. This is a powerful technique for ensuring the stability and optimizing the performance of the system. In addition to the predictive control structure, other control methods will be explored in subsequent studies including proportional-integral-derivative (PID) control, variable structure, fuzzy logic, case-based reasoning, and genetic algorithms. The primary purpose of exploring these algorithms is not to necessarily generate insight into decision-making processes during effects-based operations, but to mimic various decision-making strategies so that one can begin to build a simulation of the feedback control system model.

Organization Implications

There are many ways to develop an organizational structure that would conduct an operation based on EBT. However, the control system description of the operation provides some clues for defining and designing a generic organizational structure based on the structure, functions, and variables of the control system model.

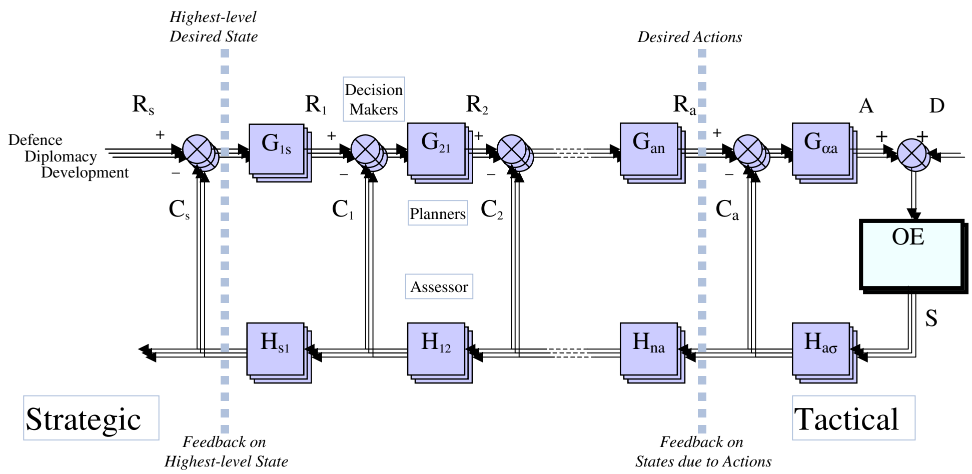

Figure 12. Organizational structures superimposed on the EBAO control system model

First, based on the structure, there are natural divisions of the model: strategic, tactical, and a middle layer. Most government and non-government organizations have strategic and tactical layers, but not all organizations have a middle layer (the "operational" layer in the military). Nevertheless, the structure lends itself to these three organizational layers. The responsibility of the strategic layer would be to generate the highest-level desired state or the strategic objective. The responsibility of the tactical layer would be to execute and realize the desired actions. The responsibility of the middle layer would be to:

1. Decompose the high-level desired state into detailed descriptions of lower-level desired states to a level where desired actions can be identified that is expected to influence the related desired state.
2. Collect feedback on action status, current effects, and the current situation that are associated with their desired counterparts.
3. Make decisions, based on the desired and current variables, to maintain status quo, re-plan, or end the activity for that particular level of states.

4. Model the operational environment to the greatest extent possible: the higher the fidelity of the model with the most recent and accurate information, the more confidence one will have in the GAME activity products. This continuous function is not shown in Figure 12.

Second, upon closer examination, the middle layer suggests that Planners, Assessors, Decision-makers, and Analysts are needed to perform the functions. Note that Execution staffs are not excluded from this model but they actually perform actions – they are the "soldiers and diplomats on the ground." The following paragraph will hint that EBE in the tactical layer will be just as involved as if it were to remain in the middle layer.

Like any other organization, there would be support staff including an RG staff, and OE Modelling and Simulation (i.e., GAME) staffs. The GAME staff would be responsible for taking information from the Planners, Analysts, and RG staff, setting up the game, running the game, and feeding the game results back to the Planners and Assessors so that they can update the desired states and desired actions, and propose methods to measure the states and convert them into feedback for higher-level states. The GAME may become a rehearsal for the actual operation, and could involve tactical-level teams towards the latter iterations in order to increase the level of fidelity.

Third, the variables in the model are multi-dimensional. For example, in the Canadian context, we talk about the 3D approach to operations: Defence, Diplomacy, and Development. Figure 12 depicts three layered feedback control systems corresponding to the three instruments of national power. The depiction falls short in that there are not three separate and distinct systems, but the systems are linked to each other – particularly within the middle layer. One might argue that Diplomacy may take the strategic lead, and that at the tactical layer, each government organization will be given orders through their separate chain of commands, but because the system states themselves are highly dependent on each other (e.g., destroying a building could have political and economic consequences) it would be prudent that the middle layer staffs have representatives from all instruments of national power.

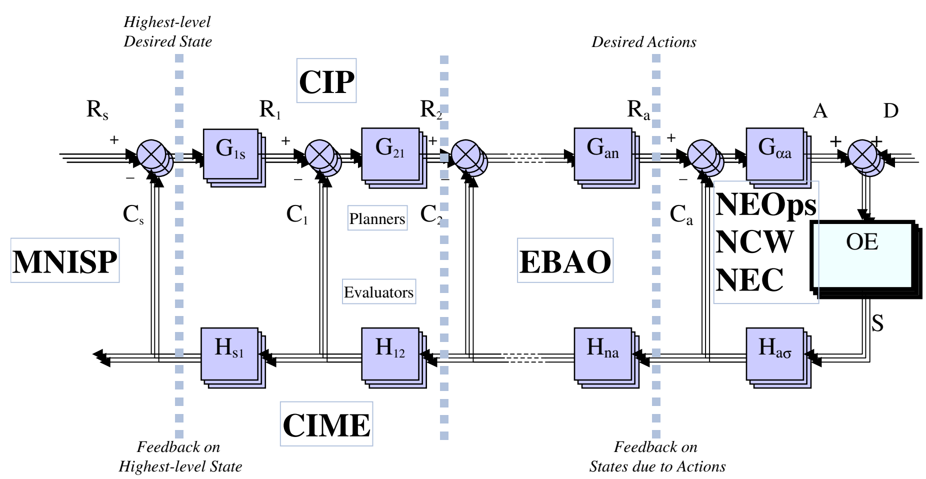

Figure 13. Mapping MNISP, CIP, CIME, and EBAO onto the EBT Operation model.

One can also imagine a multinational operation where Figure 13 is repeated for each nation involved in the coalition. In MNE 3 and 4, the Multinational Interagency Group embodied this idea, in that it had representatives from other government agencies, however, they acted in an advisory capacity only. This model builds on this concept and suggests that Defence, Diplomacy, and Development Planners, Assessors, and Decision-makers from multiple nations work together as one staff and for one purpose: the achievement of the strategic objective. Real world policy, resources, and constraints may cause this ideal situation is replaced by something more workable.

One final comment about organizational implications deals with the ability to conceptually place any of the wide range of EBT operations within the model. That is, Multinational Interagency Strategic Planning (MNISP), Collaborative Implementation Planning (CIP), the Collaborative Implementation Management and Evaluation (CIME), EBAO, NEOps, NCW, NEC concepts can be mapped one for one onto the organizational view as shown in Figure 13. Thus, the model is completely scalable for any EBT operation.

Technology Implications

Technology implications and requirements are derived from the model in a similar fashion to process and organization implications. Technology is required to guide the staff through the process, to facilitate human communication and information sharing, and to manage the system variables, which would likely include a way of visualizing the variables.

Technology Requirements for Key Functions

Recall that the Analysis function produces information models of the operational environment. This information needs to be created, organized, formalized, distributed, applied, and evolved (Nissen, 2002), or acquired, administered, and exploited (MNE 5 information management taxonomy). Software applications may be used to assist the user to acquire, administer, and exploit the information. For example, the information gathered during the Analysis function would be exploited in the GAME activity simulation. Thus, the GAME activity and other activities would drive the technology requirements that would support the Analysis function.

The Planning, Assessment, and Decision-Making functions can also benefit from technology. Planning aid tools might include a software application like EB TOPFAS (a customized effects-based planning tool developed by NATO NC3A) or CoplanS (a customized planning tool originally for the Operational Planning Process (OPP) developed by DRDC Valcartier) that helps planners navigate through the functions, activities, steps, and procedures of the operation. Such a tool, for example, could be a series of web pages where each web page might represent a specific step with appropriate links to expected input and output documents for that step, links to expected people who would be involved in that step, and links to other applications and computer aids that would be useful during that step. Figure 14 is a snap shot of what such a web page might look like. It is based on a series of human-computer interface designs that were generated (but not used) for MNE 4. These pages would not be limited to Planning, but could be generated for all three functions.

During the Assessment function, certain states of the world need to be measured and sensed. Certain sensors (human and/or machine) can collect information on those states, and others may not. There may be an engineering solution for sensing and collecting that data, but not in all cases. In some cases, one may need to depend on human judgment and intuition.

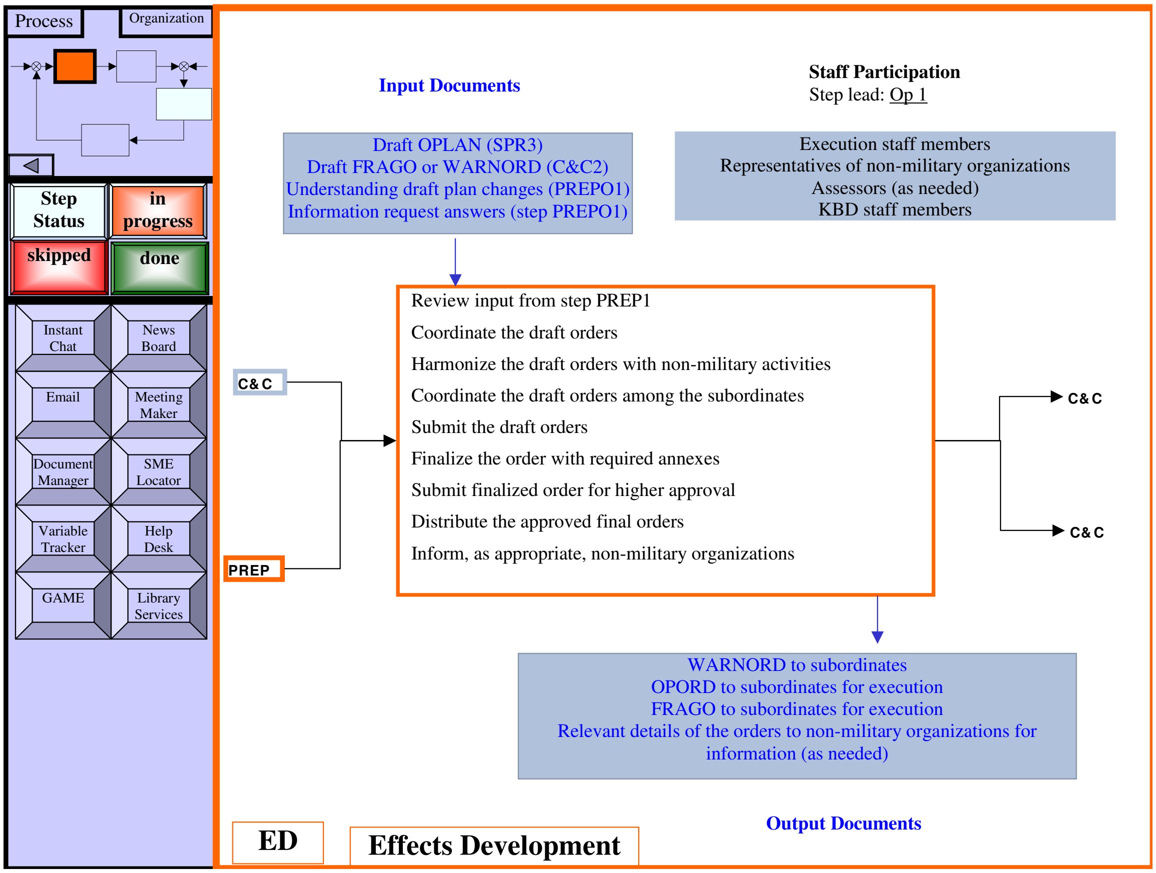

Figure 14: A Human-computer Interface Design Sample for ED Activity

Also, the Assessment function assumes that information arrives primarily in terms of reports, particularly at higher levels of abstraction, rather than raw sensor information (which would be the case at the tactical level). Thus, the Assessment function would likely use the same information technologies that the Planning function would use, and take advantage of the wealth of information accumulated during the Analysis function.

The Decision-making function first requires knowledge of the desired and current variables, and then the decision-maker compares the variable pairs and makes a decision based on their difference. Technology can be used to display the variables in a hierarchical fashion particularly if there are a large number of variables at many levels of abstraction. A simple spreadsheet or relational database would help the decision-maker maintain visibility onto the variables for which they are responsible. The planners and assessors would need to be diligent in maintaining the currency of variables in their own databases. The decision-makers' database could be linked to the planners and assessors' databases so that the information about the variables is automatically updated. The decision-maker may also have a decision aid that lists the possible decisions to be made (similar to Table 1); depending on how 'close' the desired and current variables are to each other.

The Execution function is not omitted from this discussion, but conceptually, it falls in the tactical realm where actions are actually performed and world states are changed. It is within this function that technological requirements associated with Net-Enabled Operations, integrated rapid response, and joint fires would come to the forefront. The ability to do real-time human interaction, machine interaction, human-machine interaction, intent sharing, decision-making, coordinated action amongst various tactical groups, and situation awareness will require wired and wireless Internet-like networks, applications, and computer technologies and solutions.

Technology Requirements for Tracking Variables

The previous section highlights technology requirements that support the model's functions. This section proposes requirements for the model's variables. It is assumed that both desired variables and current variables may be modified or may change over time. There needs to be a way of tracking these modifications and showing the variable status. One simple technology solution is a dynamic relational database that stores the variables' word descriptions.

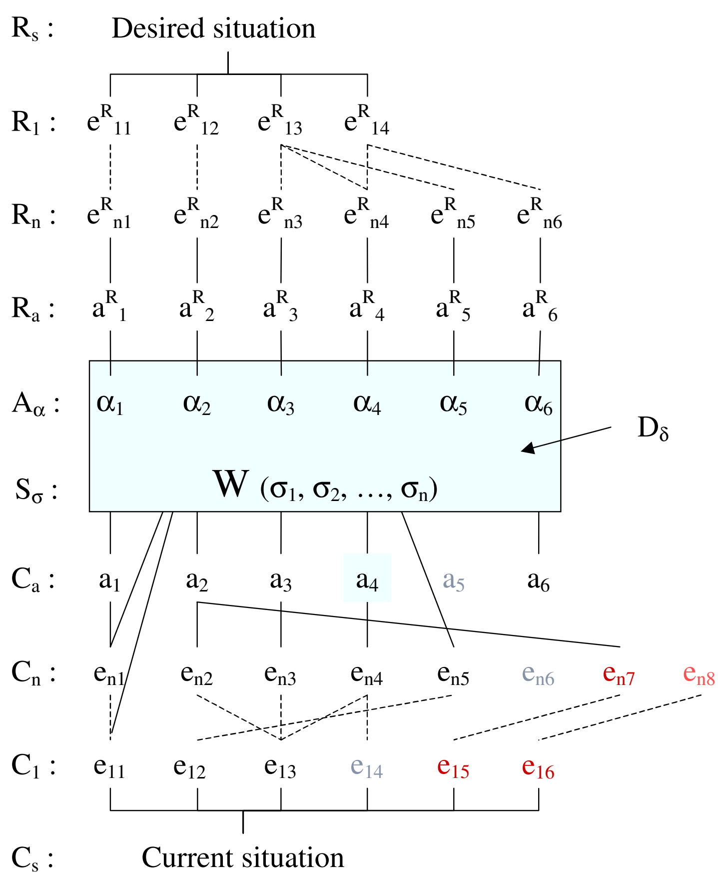

Figure 15. Elements contained in a relational database for EBAO.

Figure 15 is a schematic depiction of effects-based variables in a relational database. At the top level, the database would contain a hierarchical decomposition of the desired situation into desired effects. The dashed lines between level R_1 and R_n represent a number of decomposition levels. Typically in mission decomposition exercises, three abstraction levels seem to be the norm. The next level after the desired effects decomposition is the desired action level. At this point desired actions are chosen that have the potential to achieve the associated desired effects. A one-to-one correspondence between the n^{th}-level desired effect and the desired action would be ideal. In a relational database, one can attach attributes to the elements. For example, resources can be related to the desired actions, and the name of a decision-maker that has the responsibility for a particular abstraction level could also be attached as an attribute.

The bottom half of Figure 15 is not as straightforward as the hierarchical means-end decomposition of the desired effects. Note that, for illustrative purposes, a_5 is "greyed-out" indicating that the action was not completed and did not influence its corresponding effect. However, e_{n5} is measured directly from the world states but does not have a link to any known action. e_{n2}, e_{n3}, and e_{n4} are current effects that are inferred only from feedback on a_2, a_3, and a_4. On the other hand, e_{n6} is an effect that was planned for but it is "greyed-out" indicating it has not been completed or perhaps not observable. e_{n7} is an unexpected effect caused by α_2, and it is red indicating that it is undesirable as well. e_{n8} is not only unexpected and undesirable, but also "greyed-out" indicating that there is no known cause for it – it simply appears. Needless to say, the bottom half of Figure 15 has the potential to be complex.

Nevertheless, a Graphical User Interface (GUI) of the relational database similar to Figure 15 is needed to keep track of the variables and their links. A user should be able to perform the expected interface tasks such as add abstraction levels, add and delete variables, display the variable descriptions, and change the description at that abstraction level by perhaps double-clicking on a variable icon. Selecting any two variables should be the first step in creating a link between variables. Double-clicking a link should allow the user to delete the relationship and re-connect to other variables. Needless to say, there is the potential for many users needing access to the relational database. Care must be taken in managing the database and who has read-only versus read-write permissions since multiple individuals would want access to the database. Other intelligent features of the interface may be included, such as a change of colour of the current variable depending on how different they are from the corresponding desired variable.

Technology Requirements for Human Interaction and Communication

Given that the organization implications require human interaction across at least three domains – 1) from strategic to tactical (executors), 2) between planners, assessors, decision-makers, analysts, and support staff, and 3) across government and non-government organizations – technology can be exploited to facilitate communication and information sharing. It is assumed that people will have access to a computer or computer technology such as a Personal Device Assistant (PDA). A computer network would need to be established amongst these devices. A minimum application requirement would be a chat capability, a document management system, and an MS Office –like suite of tools.

The computer technology hardware with applications and a network becomes the basis for Net-Enabled Operation (NEOps), as it is called in Canada. The basic idea is the use of computer technologies, applications, and networks to facilitate human interaction, information sharing, and coordinated action at the tactical layer.

Human Factors Implications

There are a number of implications alluded to in this paper that are related to the human dimension or ‘soft’ systems. This section does not provide an exhaustive list or pursue them in any depth but highlights the human factors implications for future investigations.

The section entitled, “Key Decisions and Additional Inputs” alludes to the issue of decision-making in an effects-based thinking environment. The decision matrices presented in this section represent a fairly simple strategy for making decisions at the action and state level. The research question that emerges is, “does the nature of decision-making change when making decisions about effects and outcomes?” Making a decision on whether the desired effect has been reached may be a judgement call rather than a logical or deductive conclusion based on the available evidence. There are a number of factors that will influence the decision-maker’s judgement, which includes sensemaking, awareness, team characteristics, intent, etc. (SAS-050, 2006). The NATO RTO SAS panel continues investigating robust models for decision-making, particularly for network enabled and whole-of-government approaches to operations.

Situation awareness (SA) is another key psychological consideration during EBAO. Observability is related to SA in the sense that if a particular state or effect can not be observed, it will degrade one’s awareness of the situation. The bottom half of Figure 15 may be a useful starting point in investigating either an individual’s SA, shared SA, or an organization awareness. It might represent the first and second aspects of Endsley’s SA model: perception and comprehension (Endsley, 1995). Perhaps the variables, once populated with descriptions of world states, are an external representation of the organization’s awareness of the situation.

McCann and Pigeau assert that Common Intent is a critical aspect for teams (Pigeau & McCann, 2000). They decompose Common Intent into two parts: Explicit Intent and Implicit Intent. The top part of Figure 15 could be viewed as an external representation (explicit intent) of the organization’s intent or system’s mission. Implicit Intent involves the interpretation of the Explicit Intent with respect to one’s own expectations, training, experience, and values. Clearly, the understanding of intent from the individual’s perspective as well as the team’s perspective is important in this interagency and multinational environment.

Other psychological considerations include information processing and information flows. The decomposition of the desired situation has the potential to explode exponentially and cause information overload. Careful thought must be taken in terms of scoping the desired goals and objectives, and limiting the number of hierarchical levels. On the other hand, there may be critical information that flows into the system that was unexpected, and information management systems cannot be so restrictive that this information goes undetected. An

Information Needs analysis would be beneficial for humans and computer agents alike as they wade through the potentially high volumes of information during these processes.

Decision-making, SA, Common Intent, and information processing are psychological processes that overlap in the social domain. For example, leadership and leadership style has a significant impact on decision-making – both for the leader and followers making decisions. The notion of shared SA is still a hotly contested topic in SA research circles, where the key question is "to what extent must the awareness of the situation be shared?" Common Intent starts as an individual construct but quickly becomes a social or team construct, and is linked to the notion of competencies, authorities, and responsibilities (CAR) within the team or organization. Information processing becomes important when dealing with networked but geographically distributed communications where the communicating partners may potentially have very different work and national cultures.

The nature of the variables forces the analyst and designer of effects-based systems to consider the social dynamics of teams experts related to the effects and other ad hoc groups of people coming together for a common purpose (as depicted in Figures 12 and 13). Watkins proposes a multimethodological approach to 'soft' system design as well as provides an excellent review of other 'soft' system design techniques in the appendices (Watkins, 2003). This thesis includes reviews of Churchman's book on Social Systems Design (Churchman, 1983) and Checkland's book on Systems Thinking (Checkland, 1989), to name a few, that suggest traditional engineering techniques are appropriate for physical or 'hard' systems, but new techniques are required for the design of human activity or 'soft' systems. Similar to the human systems and human engineering literature, Watkins argue for a broader analysis and design approach that considers the unique characteristics of humans such as the ability to have different worldviews that are context and time sensitive.

For example, the JFCOM EBAO CONOPS assumes a single (although comprehensive) view of the world would be captured in the OE model. However, decision-making may be enhanced if the decision-maker had access to multiple opinions and perspectives of the OE model. The EBAO CONOPS does this, in part, with the RG activity, however, from Watkin's perspective, the EBAO staff would not need to be restricted to a single view of desired effects and a single course of actions, but could have multiple desired effect hierarchies, multiple courses of actions, and even multiple interpretations for the assessment function so that the decision-maker has a much richer supply of information to make an informed decision. This idea would need to be balanced with time and resources.

Thus, Control Theory does not claim to be a panacea for the analysis and design of EBT systems, but it does provide a sound theoretical foundation from which one can explore the structural (process, organization, and technology), psychological, social, and system of (human) systems issues that are associated with effects-based thinking.

Conclusions

This paper has shown how operations that involve effects-based thinking can be modelled as a feedback control system. The introduction presented a justification for “a new way of doing business” and implied that effects-based thinking and concepts are viable alternatives for conducting operations. A conceptual control system model emerged from exploring the effects-based definitions. Moreover, there is some evidence in the literature that Control Theory has been used to describe operations. Thus, the notion of describing human and team operations as a feedback loop is not new. The key difference between EBT operations and other operations is that the intermediate levels of effects (between strategic objectives and tactical actions) are planned for, assessed, decided upon, and analyzed explicitly. Actions are executed – not effects. Thus the Execution function should be relegated to the tactical layer.

The EBT process model was developed based on the MNE 4 EBAO CONOPS (JFCOM, 2006). The underlying structure of the CONOPS has been shown to be a feedback control system, even though there was no indication that the CONOPS authors drafted the document with Control Theory in mind. The main functions were Planning, Execution, Assessment (Feedback), and Decision-making. The Analysis function is a continuous, background function whose products are used at certain points of the model. The model variables were the desired situation, desired effects, desired actions, current actions, current effects, and current situation all organized in a feedback control system.

It was noted that, with the EBAO CONOPS in this form, all the analytical power of Control Theory could be brought to bear on the model. Knowledge of Control Theory was used to simplify the model, without losing the essence of the EBT concept.

Process, organization, and technology implications of the simplified EBT operation model were derived in the final section. In terms of the process, the new model was clear, simple, and scalable with five basic functions and six basic variable descriptors. Two key implications were derived from a Control Theory perspective: 1) the inner loop must be at least twice as fast as the next middle loop, and so on, up to the highest loop, and 2) the GAME sub-function makes the model have a predictive control structure where a number of options are developed and tried and then one is chosen for actual implementation.

The organizational implications yielded three distinct organizational views: 1) a hierarchical view from the strategic layer through a middle layer down to a tactical layer, 2) a function view – that is planners, assessors, decision-makers, and support staff are needed to carry out the operation, and 3) a “variable” view where various variables may be of more or less concern to specific government organizations (e.g., defence, diplomacy, and development) and so these government organizations may take the leadership with respect to certain variables. The EBT operation model provides a point of reference for concept developers and organization designers to explore a number of organizational designs that support the main functions.

The technology implications are also threefold. That is technology aids are required for: 1) the main functions 2) variable-tracking, and 3) human communication and information sharing.

The subsection on human factors implications highlighted the fact that there are psychological, sociological and system of (human) systems perspectives of effects-based thinking that need to be considered in addition to the structural aspects. Nevertheless, this analysis has exposed key functions for operations and key tenets for effects-based thinking as listed below:

<u>Key Functions for Operations from a Control Theory Perspective</u>

- Planning
- Assessment (feedback)
- Execution (tactical)
- Decision-making
- Analysis
- Organization and Technology structures must be designed to support these functions.

<u>Key Tenets of Effects-Based Thinking from a Control Theory Perspective</u>

- Effects are higher-level states (or changes in state) of the world.
- Effects span the entire range of human endeavours (political, social, etc.).
- Desired effects can be decomposed as a means-end hierarchy.
- Effects are planned for and assessed explicitly.
- Relationships between actions and effects are often complex.
- Control Theory provides both proactive and reactive feedback mechanisms that drive current effects towards their desired values.

Future work will involve, first, Control Theory controllability, stabilizability, and observability analyses applied to the EBT feedback control system model. These analyses should yield the stability and controllability conditions for the effect variables. Second, the Control Theory perspective of EBT and operations must be promulgated, debated, and refined. CFEC has started a three-year project that will produce an EBAO detailed concept description with scientific evidence that supports the key tenets. The evidence will come from the project's refinement activities including a comprehensive literature review, fora to debate the tenets and determine the concept issues and challenges, constructive simulation to resolve the issues and demonstrate the tenets, and human-in-the-loop experimentation to validate the simulation, evaluate any outstanding issues, and demonstrate the concept. The detailed concept description will become the basis for CF EBAO doctrine and training/ education curriculum.

Finally, this paper does not claim that Control Theory is the panacea for studying effects-based thinking. Rather, Control Theory was used in a novel way to model EBT concepts and operations, and gives the concept some structure so that effective system designs can be produced. This new way of looking at EBT operations should provide an effective framework for continuing discussion and investigation of the ideas through mathematical analysis, constructive simulation, and experimentation.

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List of Symbols

A	Actions variable
ADRM	Action development and Resource Matching
AAMOP	Actions Analysis by use of Measures of Performance
C2	Command and Control
C_a	States due to current actions variable
C_e	Current effects variable
C_s	Current situation variable
C&C	Control and Coordinate Operations
CA	Campaign Assessment
CA	Canada
CF	Canadian Forces
CG	Command Group
CFEC	Canadian Forces Experimentation Centre
CIDA	Canadian International Development Agency
CONOPS	Concept of Operations
COP	Common Operating Picture
COS	Chief of Staff
D	Disturbance variable
DFAIT	Department of Foreign Affairs and International Trade
DIME	Diplomacy, Information, Military, Economic
DND	Department of National Defence
EAMOP	Effects Analysis by use of Measures of Effectiveness
EBA	Effects Based Assessment
EBAP	Effects Based Assessment Planning
EBAO	Effects Based Approaches to Operations
EBE	Effects Based Execution
EBO	Effects Based Operations
EBP	Effects Based Planning
EBT	Effects Based Thinking
ED	Effects Development

ESA	End State Analysis
GRA	Guidance and Requirements Analysis
IDI	Identify Issues
JFCOM	Joint Forces Command
KB	Knowledge Base
KBD	Knowledge Base Development
KD	Knowledge Development
KM	Knolwedge Management
KP	Knowledge Processing
KR	Knowledge Request
KS	Knowledge Support
M&S	Modelling and Simulation
MMA	Measures of Effectiveness – Measures of Performance Analysis
MNE	Multinational Experiment
MNIG	Multinational Interagency Group
MNIS	Multinational Information Sharing
NATO	North Atlantic Treaty Organization
NDHQ	National Defence Headquarters
NGA	Non-government Agencies
OGD	Other Government Departments
OODA	Observe, Orient, Decide, and Act
PMESII	Political, Military, Economic, Social, Information, and Infrastructure
POT	Process, Organization, and Technology
R_a	Required actions variable
R_e	Required effects variable
R_s	Required situation variable
RG	Red and Green Teaming
S	States variable
SA	Situation Assessment
SA	Situational Awareness
SJFHQ	Standing Joint Force Headquarters
SME	Subject Matter Expert

SoSA	System of Systems Analysts
SPR	Synchronization and Plan Refinement
UK	United Kingdom
US	United States of America
W	World Model

Glossary

Action	An action is a physical force that influence and change physical states of the world.
Control Theory	Control Theory is a field of engineering and mathematics that provides a set of mathematical laws and principles so that a measured variable is driven towards its corresponding desired variable.
Effect	An effect is a state of the world expressed at higher levels of abstraction. Effects can be psychological as well as physical.
effects-based thinking	Effects-based thinking is an alternative way of thinking about an operation that focuses on seeing a particular world state appear rather than targeting certain enemy assets.
Operation	An operation is a human activity that involves goal setting, planning, executing the plan, assessing the outcome, making decisions to act or not to act, all based on the analysis of available information about the world.

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.)

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2. SECURITY CLASSIFICATION (overall security classification of the document, including special warning terms if applicable)

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3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

   Control Theory Perspective of Effects-Based Thinking and Operations: Modelling "Operations" as a Feedback Control System (U)

4. AUTHORS (Last name, first name, middle initial)

   Philip S. E. Farrell

5. DATE OF PUBLICATION (month and year of publication of document)

   Novewmber 2007

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

   60

6b. NO. OF REFS (total cited in document)

   28

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

   Technical Report

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

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9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

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10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

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This paper explores operations that involve effects-based thinking (EBT) using Control Theory techniques in order to highlight the concept's fundamental characteristics in a simple and straightforward manner. It provides some background to EBT, and presents three formal definitions for effects-based approaches to operations (EBAO). This paper shows that Control Theory is a useful framework for studying effects-based concepts. A specific EBAO concept was modelled using Control Theory techniques. This analysis has exposed key functions for operations and key tenets for effects-based thinking as listed below:

Key Functions for Operations from a Control Theory Perspective: Planning, Assessment, Execution, Decision-making, and Analysis. Organization and Technology structures must be designed to support these functions.

Key Tenets of Effects-Based Thinking from a Control Theory Perspective:

- Effects are higher-level states (or changes in state) of the world.
- Effects span the entire range of human endeavours (political, social, etc.).
- Desired effects can be decomposed as a means-end hierarchy.
- Effects are planned for and assessed explicitly.
- Relationships between actions and effects are often complex.
- Control Theory provides both proactive and reactive feedback mechanisms that drive current effects towards their desired values.

Control Theory was used to model EBT concepts and operations, and provide a theoretical basis so that effective system designs can be developed. It is hoped that this new way of looking at EBT operations will provide a framework for continued discussion and investigation of the ideas through mathematical analysis, constructive simulation, and human-in-the-loop experimentation.

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