Aalto University
School of Science
Master's Programme in Mathematics and Operations Research

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Moving decision horizon multi-criteria approach to planning of air combat tactics, techniques and procedures

Master's Thesis
Espoo, November 13, 2023

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ABSTRACT OF MASTER'S THESIS

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Title:	Moving decision horizon multi-criteria approach to planning of air combat tactics, techniques and procedures		
Date:	November 13, 2023	**Pages:**	106
Major:	Systems and Operations Research	**Code:**	SCI3055
Supervisors:	Professor Kai Virtanen		
Advisor:	Professor Kai Virtanen		

Tactics, techniques and procedures (TTPs) guide the decisions of pilots in air combat. Traditionally developed TTPs try to address a predefined threat and do not respond to its unexpected behavior. Hence, there exists a need for TTPs that address the prevailing air combat state, i.e., that are state-dependent. In addition, TTPs need to be chained, i.e., decisions made earlier affect later decisions. In this thesis, a TTP planning problem is formulated to describe the components of the TTP development for a one versus one air combat scenario. The formulation includes decisions which are made to proceed towards objectives.

This thesis introduces a novel moving decision horizon multi-criteria approach (MDH approach) for supporting the solution of the TTP planning problem. The approach includes a dynamic multi-criteria decision analysis model (DMCDA) and its solution procedure which is operated by the decision maker (DM) via a graphical user interface. The DMCDA model includes the decisions of the friendly Blue as well as the fixed threat presentation of Red, and it describes the air combat scenario with an air combat state. The progress of the air combat scenario is represented by the kill and live chains. The kill chain describes the taskwork of Blue. The live chain illustrates how Blue is able to deny the taskwork of Red. Both chains contain three successive phases, i.e., search, target and engage. The solution procedure provides decision suggestions to the DM. They are generated by predicting future air combat states for all possible combinations of decision alternatives up to a certain length of time. The predicted states for each combination are ranked by the evaluation of an objective function, and the alternatives resulting in the best future state are suggested. The objective function considers criteria, a cost-to-go function and the Blue kill chain as well as the changes of its phase. The use of the MDH approach is demonstrated to find TTP rules for the decisions. In addition, an example sensitivity analysis is carried out for the developed TTP to find its feasible limits by changing the threat presentation. In the demonstration, the TTP rules are successfully identified for each decision. The identified rules are dependent on the air combat state. They are also chained as the earlier decisions affected the later decisions. Hence, the MDH approach is a suitable support tool for the development of TTPs for modern air combat.

Keywords:	Air combat, Multi-criteria decision analysis, Moving decision horizon, Tactics, techniques and procedures, Simulation
Language:	English

Aalto-yliopisto
Perustieteiden korkeakoulu
Systeemi- ja operaatiotutkimuksen maisteriohjelma

DIPLOMITYÖN TIIVISTELMÄ

Tekijä:	Jani Laine		
Työn nimi: Liikkuvan päätöshorisontin monikriteerilähestymistapa ilmataistelun taktiikoiden, tekniikoiden ja menetelmien suunnitteluun			
Päiväys:	13. marraskuuta 2023	**Sivumäärä:**	106
Pääaine:	Systeemi- ja operaatiotutkimus	**Koodi:**	SCI3055
Valvojat:	Professori Kai Virtanen		
Ohjaaja:	Professori Kai Virtanen		

Taktiikat, tekniikat ja menetelmät (eng. tactics, techniques and procedures, TTP) ohjaavat taistelulentäjien toimintaa ilmataistelussa. Perinteisin tavoin kehitetyt TTP:t eivät ota huomioon nykyilmataistelun uhkien ennakoimatonta käytöstä. Ne suunnitellaan käyttämällä kiinnitettyä uhkamallia, joka kuvaa uhkan pitkän aikavälin käyttäytymisen. Näin on syntynyt tarve kehittää TTP:eitä, jotka ottavat huomioon päätöksentekohetkellä ilmataistelun tilan. Lisäksi aikaisempien päätöksien tulee vaikuttaa myöhempiin päätöksiin eli TTP:n tulee ketjuttua. Kehitystyötä varten tässä työssä määritellään yksi vastaan yksi -ilmataisteluskenaariolle TTP:eiden suunnitteluongelma. Määrittelyssä tunnistetaan muun muassa päätökset, joilla voidaan edetä kohti ilmataistelun tavoitteita.

TTP:eiden suunnitteluongelman ratkaisemisen tueksi esitellään uusi etenevän päätöshorisontin monikriteerilähestymistapa (EPM-lähestymistapa). Lähestymistapa koostuu dynaamisesta monikriteeripäätösanalyysimallista (DMKPA-malli) ja sen ratkaisumenetelmästä, jota käyttää päätöksentekijä graafisen käyttöliittymän avulla. DMKPA-malli sisältää oman Sinisen päätökset sekä ennalta määritellyn uhkamallin eli Punaisen käyttäytymisen ja se kuvaa ilmataisteluskenaariota ilmataistelutilalla. Ilmataisteluskenaarion eteneminen esitetään kill- ja live-ketjuilla. Kill-ketju esittää Sinisen tehtävätyöskentelyä. Live-ketju esittää Sinisen kykyä estää Punaisen tehtävätyöskentelyn etenemisen. Molemmissa ketjuissa on kolme perättäistä vaihetta eli etsi-, maalita- ja hyökkää-vaiheet. DMKPA-mallin ratkaisumenetelmä antaa päätöksentekijälle päätösehdotuksia. Ne perustuvat ennustuksiin ilmataistelutilan etenemisestä tietyn ajan päähän. Jokaiselle päätösvaihtoehtoyhdistelmälle ennustetut tilat arvioidaan kohdefunktion avulla. Kohdefunktiossa otetaan huomioon arviointikriteerit, tilan kehittyminen pitkän aikavälin päähän sekä Sinisen kill-ketjun vaihe ja sen muutokset. Arvioinnin perusteella parhaaseen tilaan johtaneita päätösvaihtoehtoja ehdotetaan päätöksentekijälle. EPM-lähestymistavan käyttö demonstroidaan tunnistamalla TTP-sääntöjä ilmataistelun kannalta tärkeille päätöksille. Lisäksi säännöistä koostetulle TTP:lle toteutetaan herkkyysanalyysi, jolla etsitään sen käypä alue suhteessa uhkamallin muutoksiin. Demonstraatiossa onnistuttiin tunnistamaan tilariippuvat TTP-säännöt jokaiselle tarvittavalle päätökselle. Lisäksi aikaisemmat päätökset vaikuttavat myöhempiin eli säännöt ovat ketjuttuneita. Nämä tulokset osoittavat, että EPM-lähestymistapa on käyttökelpoinen modernin ilmataistelun TTP-kehityksen tukityökaluna.

Asiasanat:	Ilmataistelu, Liikkuva päätöshorisontti, Monikriteerinen päätösanalyysi, Simulaatio, Taktiikat, tekniikat ja menetelmät
Kieli:	Englanti

Acknowledgements

I want to thank Professor Kai Virtanen for providing me the platform to undertake this thesis within his group. His consistent mentorship, support, and insight have been instrumental for the success of this project.

I also wish to recognize Adjunct Professor Heikki Mansikka for his deep domain knowledge. Our collaborative exchanges and his timely recommendations have contributed significantly to this work.

Further, a nod to the experts who have lent their knowledge to this thesis. Collaborating with such professionals has been a constructive experience.

Espoo, November 13, 2023

Jani Laine

Contents

Nomenclature

Greek symbols

β^{Blue}_{radar} Angle between D^{Blue}_{radar} and a vector pointing towards the favorable search point

β^{Red}_{radar} Angle between D^{Red}_{radar} and a vector pointing towards the favorable search point

$\Delta\phi^{Blue}$ Decision variable for change of roll rate of Blue

$\Delta\phi^{Red}$ Control variable for change of roll rate of Red

$\Delta\theta^{Blue}$ Decision variable for change of pitch rate of Blue

$\Delta\theta^{Red}$ Control variable for change of pitch rate of Red

δ^{Blue}_{DMC} Digital Maneuvering Cue (DMC) number of Blue

δ^{Red}_{DMC} Digital Maneuvering Cue (DMC) number of Red

ϕ^{Blue} Roll rate of Blue

ϕ^{Red} Roll rate of Red

ψ^{Blue} Angle between the direction to Red from Blue and the nose of Blue in x-y-plane

ψ^{Red} Angle between the direction to Blue from Red and the nose of Red in x-y-plane

τ_{ϕ} Time constant for roll rate

τ_{θ} Time constant for pitch rate

θ^{Blue} Pitch rate of Blue

θ^{Red} Pitch rate of Red

Scalars

Δn Planning horizon length

ΔT Time step of the cost-to-go function evaluation

Δt Constant time interval between time steps

A_{score}^{Blue} Altitude score of Blue

A_{score}^{Red} Altitude score of Red

C_{engage} Cost-to-go function of the engage phase

C_{search} Cost-to-go function of the search phase

C_{target} Cost-to-go function of the target phase

$D_{radar,component}^{Blue}$ Radar direction component of Blue

$D_{radar,component}^{Red}$ Radar direction component of Red

D_{radar}^{Blue} Radar direction of Blue

D_{radar}^{Red} Radar direction of Red

$DMC_{component}^{Blue}$ DMC component of Blue

$DMC_{component}^{Red}$ DMC component of Red

h^{Blue} Height, i.e, coordinate on the z-axis of Blue

h^{Red} Height, i.e, coordinate on the z-axis of Red

$h_{missile,j}^{Blue}$ Height of a missile of Blue of sequence number j

$h_{missile,j}^{Red}$ Height of a missile of Red of sequence number j

H_{score}^{Blue} Heading score of Blue

H_{score}^{Red} Heading score of Red

i Blue or Red

j Sequence number of a missile

J_{set}^{Blue} Decision variable for use of a jammer of Blue

K^{Blue} Phase of the kill chain of Blue

L^{Blue} Phase of the live chain of Blue

m Mass of aircraft

M_{launch}^{Blue} Decision variable for missile launch of Blue

M_{launch}^{Red} Control variable for missile launch of Red

N Final time step of the air combat scenario

n Time step

P Penalty for the regression of the kill chain

P_c^{Blue} Probability of cover of Blue

P_d^{Blue} Probability of detection of Blue

P_d^{Red} Probability of detection of Red

P_k^{Blue} Probability of kill of Blue

P_k^{Red} Probability of kill of Red

P_s^{Blue} Probability of survival of Blue

$P_{k,component}^{Blue}$ Probability of kill component of Blue

$P_{k,component}^{Red}$ Probability of kill component of Red

$P_{k,score}^{Blue}$ Probability of kill score of Blue

$P_{k,score}^{Red}$ Probability of kill score of Red

Q^{Blue} Roll rate of Blue

Q^{Red} Roll rate of Red

R Reward for the progression of the kill chain

R_{set}^{Blue} Decision variable for use of radar of Blue

$R_{target,component}^{Blue}$ Target range component of Blue

$R^{Red}_{target,component}$ Target range component of Red

R_{target} Target range

S^{Blue}_{jammer} State of the jammer of Blue

S^{Red}_{jammer} State of the jammer of Red

S^{Blue}_{radar} State of the radar of Blue

S^{Red}_{radar} State of the radar of Red

T Final time of the air combat scenario

t_n Discrete time instant

T^{Blue}_{comm} Decision variable for throttle setting of Blue

T^{Red}_{comm} Control variable for throttle setting of Red

TA^{Blue} Target aspect of Blue

TA^{Red} Target aspect of Red

$TA^{Blue}_{component}$ Target aspect component of Blue

$TA^{Red}_{component}$ Target aspect component of Red

$TOF^{Blue}_{missile,j}$ Time of flight of a missile of Blue of sequence number j

$TOF^{Red}_{missile,j}$ Time of flight of a missile of Red of sequence number j

$TOF_{missile,ref}$ Reference time of flight of the missiles

U Objective function

V Value function

$v_{missile}$ Velocity of a missile

W_C Weight of the cost-to-go function in the objective function

W_V Weight of the value function in the objective function

$w_{c,n}$ Weight of P^{Blue}_c in the value function at time step n

$w_{ctg,\Delta T}$ Weight of time step in the cost-to-go function

$w_{ctg,pd}$ Weight of P_d^{Blue} in the cost-to-go function

$w_{ctg,pk}$ Weight of P_k^{Blue} in the cost-to-go function

$w_{d,n}$ Weight of P_d^{Blue} in the value function at time step n

$w_{k,n}$ Weight of P_k^{Blue} in the value function at time step n

$w_{s,n}$ Weight of P_s^{Blue} in the value function at time step n

x^{Blue} Coordinate on the x-axis of Blue

x^{Red} Coordinate on the x-axis of Red

$x_{missile,j}^{Blue}$ Coordinate on the x-axis of a missile of Blue of sequence number j

$x_{missile,j}^{Red}$ Coordinate on the x-axis of a missile of Red of sequence number j

y^{Blue} Coordinate on the y-axis of Blue

y^{Red} Coordinate on the y-axis of Red

$y_{missile,j}^{Blue}$ Coordinate on the y-axis of a missile of Blue of sequence number j

$y_{missile,j}^{Red}$ Coordinate on the y-axis of a missile of Red of sequence number j

Vectors

$\boldsymbol{\omega}^{Blue}$ Angular velocity of Blue

$\boldsymbol{\omega}^{Red}$ Angular velocity of Red

$\boldsymbol{B}^{Blue}$ Direction cosine matrix of Blue

$\boldsymbol{B}^{Red}$ Direction cosine matrix of Red

$\boldsymbol{F}^{Blue}$ Total aerodynamic force

$\boldsymbol{F}^{Red}$ Total aerodynamic force

$\boldsymbol{g}$ Acceleration due to gravity

$\boldsymbol{K}^{Blue}$ Vector containing K^{Blue} of different time steps

$\boldsymbol{M}_j^{Blue}$ State of a missile of Blue of sequence number j

$\boldsymbol{M}_j^{Red}$ State of a missile of Red of sequence number j

$\boldsymbol{q}^{Blue}$ Attitude quarternion of Blue

$\boldsymbol{q}^{Red}$ Attitude quarternion of Red

$\boldsymbol{R}_{elev}^{Blue}$ Vector of three decision variables for radar elevation of Blue

$\boldsymbol{U}^{Blue}$ Speed of Blue in three dimensions

$\boldsymbol{U}^{Red}$ Speed of Red in three dimensions

$\boldsymbol{U}_{missile,j}^{Blue}$ Speed of a missile of Blue of sequence number j in three dimensions

$\boldsymbol{U}_{missile,j}^{Red}$ Speed of a missile of Red of sequence number j in three dimensions

$\boldsymbol{X}^{Blue}$ State of Blue including $x^{Blue}, y^{Blue}, h^{Blue}, \boldsymbol{U}^{Blue}, \boldsymbol{\omega}^{Blue}$ and $\boldsymbol{q}^{Blue}$

$\boldsymbol{X}^{Red}$ State of Red including $x^{Red}, y^{Red}, h^{Red}, \boldsymbol{U}^{Red}, \boldsymbol{\omega}^{Red}$ and $\boldsymbol{q}^{Red}$

$\boldsymbol{Y}^{Red}$ Control vector of Red

$\boldsymbol{Y}_{engage}^{Blue}$ Decision vector of Blue for the engage phase

$\boldsymbol{Y}_{search}^{Blue}$ Decision vector of Blue for the search phase

$\boldsymbol{Y}_{target}^{Blue}$ Decision vector of Blue for the target phase

$\boldsymbol{Z}$ Air combat state including $\boldsymbol{X}^{Blue}, S_{radar}^{Blue}, S_{jammer}^{Blue}, \boldsymbol{X}^{Red}, S_{radar}^{Red}, S_{jammer}^{Red}, K^{Blue}, L^{Blue}, \boldsymbol{M}_j^{Blue}$ and $\boldsymbol{M}_j^{Red}$

Chapter 1

Introduction

Air combat means combat between aircraft taking place in the air. It can occur between, e.g., individual aircraft or flights. A flight consists of four aircraft where one of the pilots is the flight lead who directs the combat of the flight. The main goal of an individual pilot or a flight is to achieve the conditions for a missile launch, i.e., a position from which a launched missile is likely to hit the target, and minimize the probability for a counter hit [1]. Achieving this goal requires coordinated actions from the pilots which can be successfully carried out by adhering to tactics, techniques and procedures (TTP) [2]. TTPs consist of quantitative and qualitative rules which guide decision making during air combat [3]. For example, "Minimum missile launch altitude is 10 000 ft" is a quantitative rule and "A member of a flight must inform the flight of a detected enemy radar lock" is a qualitative rule. Adherence to inappropriate TTPs would likely prohibit a flight from efficiently achieving its goals [4].

Since TTPs play such an important role in the success of air combat missions they must remain effective and up-to-date. The development of TTPs is carried out by utilizing the expertise of military personnel as well as simulation studies [3] [4]. Traditionally, the development of TTPs starts with a fixed threat presentation which follows a predetermined pattern of behavior. For example, an opponent aircraft flying towards its target, launching a missile and turning away afterwards is predictable behavior. Then, a long chain of actions is developed to address this fixed threat. This kind of thinking results in TTPs that are effective only when the threat indeed behaves predictably which is often not the case in the chaotic environment of air combat. In addition, the long chains of actions are not applicable in a dynamically evolving situation. Thus, there is clearly a need for state-dependent TTPs, i.e., TTPs that address the current state of the air combat. In addition, the TTPs need to be chained, i.e., the decisions made earlier affect the decisions later. Hence, methods for supporting the development of such TTPs need to be introduced.

TTPs dictate the taskwork of the pilots, which is represented by two parallel chains by the US Joint Doctrine [5] (see also [6]). The chains have six phases that describe the progress of the taskwork. The chain considering the taskwork of friendly pilots is called the kill chain. The other chain, called the live chain, describes how well the friendly pilots manage to deny the progression of the taskwork of the opponent pilots. Chains similar to these, but modified to have three phases, are used also in this thesis to describe the taskwork of the pilots.

In the beginning of the development of TTPs, a TTP planning problem is formulated. The planning problem includes every component that is needed for the development of a TTP. In this thesis, the following components are included in the formulation of the TTP planning problem. First, objectives for every combination of the phases of the kill and live chains are defined. The completion of the objectives needs to be evaluated, and thus criteria for the evaluation are identified for the phase combinations. The criteria represent the most important aspects that affect the progress towards the completion of the prevailing objectives. Then, relevant decisions, in terms of air combat, are identified for the phases of the kill chain, and alternatives are generated for them.

For addressing the planning problem of TTPs for an individual aircraft, a novel approach, called the moving decision horizon multi-criteria approach (MDH approach), is introduced in this thesis. The approach is used as a support tool for the development of TTPs. It helps to produce chained and state-dependent TTPs which provide reactive instructions for the current air combat state. The air combat state describes, e.g., the aircraft involved and their relationship in terms of air combat. It evolves in discrete time steps of a fixed length according to the behavior of the friendly and opponent pilots. Taking action against the prevailing air combat state rather than against an assumption of the long chain of actions of the opponent provides better adaptability to the decision making. The MDH approach is used for a one versus one air combat scenario, where the friendly aircraft is referred to as Blue and the opponent as Red, and the behavior of Red is fixed. The approach includes a new dynamic multi-criteria decision analysis (DMCDA) model, which contains the air combat state, and its solution procedure. The MDH approach is operated by the decision maker (DM) who uses the approach in the planning of TTPs.

The DMCDA model includes the decisions of Blue as well as the fixed behavior of Red and it describes the air combat scenario. The air combat scenario is represented by the air combat state at all times and the state is affected by the decision of Blue. The behavior of Red is predefined and based on certain conditions, e.g., Red launches a missile when the distance to Blue is 25 nautical miles. Auxiliary models included in the DMCDA model represent aircraft, their systems and environment in which the air combat is taking place. The aircraft model describes the flying capabilities of the aircraft such as acceleration and turn rate. The aircraft systems refer to missiles, radars and jammers. The environment model covers the air space in which the air combat scenario occurs with regards to, e.g., the air density and temperature. The air combat states ultimately includes the states of aircraft, their systems and missiles as well as phases of the Blue kill and live chain.

The solution procedure is used to solve the DMCDA model as follows. Predictions of the evolution of the air combat state are made up to a length of a planning horizon into the future for every combination of decision alternatives. Then, the predicted air combat states of the planning horizon are evaluated with an objective function. The objective function evaluation takes into account weighted criteria, cost-to-go function and the Blue kill chain as well as the changes of its phase during the planning horizon. A ranking of the predicted air combat states is established according to the evaluations. The combination of decision alternatives, that resulted in the best predicted state, is presented to the DM as decision suggestions. The DM decides whether to implement the suggestions as decisions of Blue in the current air combat state or to modify them. After the decisions of Blue are made, the air combat state progresses one time step forward. The solution procedure is repeated for the new air combat state. In addition, when the objective of the prevailing phase of the Blue kill chain is completed the chain progresses to the next phase. On the other hand, the completion of the objective of the live chain phase ensures that the Blue live chain does not progress. When the objective of the last phase of the kill chain is completed, the air combat scenario is terminated.

The MDH approach is also used to carry out a sensitivity analysis. It requires a reference TTP which can be any existing TTP. The idea of the sensitivity analysis is to find out the feasible limits of the reference TTP with regards to changes of the threat presentation. These limits are determined by the variation of specific factors in the threat presentation, e.g., the initial altitude of Red. The amount of variation is gradually increased until the reference TTP does not produce desired results. The reference TTP can be used against the threat which lies inside the feasible limits found in the sensitivity analysis.

In order for the DM to use the MDH approach, a graphical user interface (GUI) is created in this thesis. Through the GUI the DM operates the solution procedure by, e.g., adjusting the weights of the criteria and approving or modifying the decision suggestions.

In this thesis, the use of the MDH approach is demonstrated by the development of a TTP for an example air combat scenario. The planning problem of the TTP presents the DM with the decisions for which the TTP rules need to be identified. The DM operates the solution procedure of the DMCDA model to identify these rules. Once every individual TTP rule is identified they are combined to form a complete TTP. Lastly, an example sensitivity analysis is carried out for the formed TTP. The sensitivity analysis is conducted mainly to demonstrate the benefits of such an analysis in the development of TTPs. Therefore, it is limited in terms of the variation of the threat presentation to reduce the required effort from the DM.

Although the MDH approach is introduced and demonstrated in this thesis as a stand-alone tool to support the development of TTPs, it can also be used alongside existing virtual air combat simulators and constructive air combat simulation models. The benefit of using existing constructive simulations is that they are more sophisticated in terms of, e.g., models for aircraft and their systems than the models created in this thesis. The use of the MDH approach remains similar even though the existing simulation models are incorporated. On the other hand, by applying the MDH approach to a virtual simulator, it can be used to assist the DM with decision suggestions in real time. The suggestions can also be used to aid a pilot who is training air combat in the simulator.

The structure of the thesis is the following. Chapter 2 gives an overview of the existing literature considering the modeling of air combat. Chapter 3 contains the formulation of the planning problem of TTPs. It includes the definition of objectives for kill and live chain phases, decisions and their alternatives as well as criteria. Chapter 4 introduces the MDH approach which consists of the DMCDA model including auxiliary models, the solution procedure, the GUI and numerical considerations. Chapter 5 demonstrates how the approach is used in the development of TTPs. In addition, the example sensitivity analysis is conducted. Finally, Chapter 6 provides discussion, and Chapter 7 concludes the thesis.

Chapter 2

Related approaches for modeling air combat

As mentioned in the introduction, simulations have been used previously in the development of TTPs [3] [7] [8] [9]. They are categorized into live, virtual and constructive simulations [3]. A live simulation means that real systems are operated by real people, virtual simulation that simulated systems are operated by real people and constructive simulation that simulated systems are operated by simulated entities [3]. However, the effect of weapons are simulated also in live simulations. In constructive simulations, where both the system and the operator are simulated, computer models are used to describe the operator's decision making. Combinations of the three different simulations are useful tools in the development of TTPs in the testing and evaluation phase [3].

For modeling the decision making of pilots in air combat, many methodologies have been used. Game theory is utilized by creating a game model for one versus one air combat with medium range air-to-air missiles [10]. The missiles are assumed to have a communication link [11] to the shooter, i.e., the aircraft launching a missile, for relaying target information to the missile after it is launched. The game model provides game optimal support times of the missiles. As another example of a game theoretic approach, a matrix game [12] is created to describe two groups of entities on the opposite sides of military forces. The goal of the game, for each group, is to destroy the opponent. The groups choose the strategies independently and simultaneously and get a pay-off according to the outcome of the selected strategies. The strategies are chosen based on similar factors to the ones affecting the decision making of a pilot in air combat.

Rule based methods incorporate rules to govern the decision making of pilots regarding the relevant factors in air combat such as the maneuvering of aircraft and the use of weapons. A rule-based logic program [13] is developed and used against human opponents in simulated air combat. The logic program is shown to be successful against the human pilots. Deep reinforcement learning with neural networks [14] is used to train two opposing aircraft models for air combat. A reinforcement learning algorithm learns by interacting with the environment and getting feedback from it as rewards or penalties. The air combat of the study is broken down to smaller segments of maneuvering to which the deep reinforcement learning algorithm is applied. The goal of the algorithm is to optimize the maneuvering decisions.

The decision making problem of a pilot in air combat can be formulated as a multistage influence diagram [15] [16] [17]. Influence diagrams are used for modeling the decision making in air combat because they allow for convenient representation of uncertainties and sequential decision making. In addition, network optimization [18] has been used for the optimization of an aerial route for an air-to-ground operation. Air operations, and the decision making they include, can be conveniently represented by a network. However, the complexity of the network grows quickly when multiple decision alternatives are introduced, which can hinder computations.

Dynamic optimization problems [19] [20] [21] are used, e.g., for generating optimized trajectories for aircraft or missiles. Such problems are time-variant, and their solution procedure usually includes finding a control policy which moves the controllable system towards a desirable state. This control policy can be, e.g., a set of maneuvering decisions. Solving dynamic optimization problems can provide highly accurate results, in terms of, e.g., maneuvering trajectories, provided that the underlying equations describing the movement of aircraft are accurate. In addition, feedback from the air combat state can be used in the solution procedure with low latency, which makes it adaptable to changes in the state. However, if only poor or no feedback is available, the solution process relies on the model of the dynamics of the air combat which can negatively affect the accuracy of the model.

The DMCDA model and its solution procedure introduced in this thesis contain similarities to the previously mentioned methodologies. For example, the DMCDA model is, fundamentally, a multi-criteria dynamic optimization problem. In addition, the solution procedure of the DMCDA model uses a moving planning horizon method, which is often used in the context of trajectory optimization [15] [16] [21] [22]. However, in the formulation of the DMCDA model, adjustments to the existing methodologies have been made. The air combat scenario is described by the air combat at each time and its progress, from the perspective of Blue, by the kill and live chains. The phases of the kill chain are defined with decisions. In addition, the combinations of the phases of both chains are associated with objectives and criteria. The air combat state is evaluated by multiple criteria, and the DM is responsible for assigning their weights. Thus, the combination of methodologies used in this thesis has not been used before. Consequently, the MDH approach to the development of chained and state-dependent TTPs is novel. Such TTPs cannot be obtained with the existing approaches due to the lack of consideration of the prevailing air combat state.

Chapter 3

Tactics, techniques and procedures (TTPs) in air combat

In this chapter, the selection of TTPs during actual air combat is explained and the planning problem of TTPs is introduced. The TTP selection in air combat is often time-sensitive. Understanding the selection is beneficial for the development of TTPs because, e.g., developing too complex TTPs may prohibit them from ever being selected for usage. The definition of the planning problem of TTPs includes all the necessary components to define and develop TTPs. In addition, modeling assumptions and delimitations are discussed. The naming Blue and Red for the friendly and opponent aircraft, respectively, is used in this chapter for clarity.

3.1 Selection of TTPs in air combat

This section deals with the selection of a TTP during real air combat when there is already a set of TTPs available. The selection is carried out in a dynamic and often chaotic environment of air combat. It is mostly affected by the primary task of the flight, e.g., reaching the conditions for a missile launch while negating the response of the opposing force in the prevailing circumstances [3]. These circumstances include, e.g., the objectives of the broader mission, the number and type of opponents and weather conditions. In addition, the weapons and friendly aircraft available, the performance of the aircraft and the highest accepted risk level can also be considered. TTPs contain instructions for how to best use the available resources to achieve the goal. Recall that a TTP consists of qualitative and quantitative rules.

Tactics in a TTP can be defined as the means and ways to accomplish the goal of a particular mission. Tactics cover how to utilize the flight as a whole and they are generally a responsibility of the flight lead. An example of a four-ship tactic is to establish a side-by-side wall formation, find targets and launch missiles at a specific point. Techniques comprise of the means for performing a specific task, and they usually focus on the level of an individual aircraft and pilot. For example, an evasive maneuver to dodge a missile is a procedure. The concrete actions that the pilot carries out in the cockpit are described by procedures in a TTP. These might involve, e.g., setting the correct throttle position or arming the weapon systems. [23]

TTPs are often structured according to a dynamic targeting framework [5]. The framework serves as a guideline on how a target can be dynamically found, tracked and engaged. The dynamic targeting can be described as a hierarchial process with six phases. The process, also referred to as the "kill chain", is illustrated in Figure 3.1. The kill chain describes the taskwork of Blue. In addition, the live chain is defined for Blue which describes how Blue is able to deny the progression of the taskwork of Red. The phases of the live chain are similar to the kill chain phases but they are denoted with a "deny" prefix. The phases of the kill and live chain exist in parallel, i.e., Blue is at all times in a phase of the kill chain and in a phase of the live chain. The kill and live chains do not depend on each other and all combinations of the phases of the kill and the live chains are generally possible.

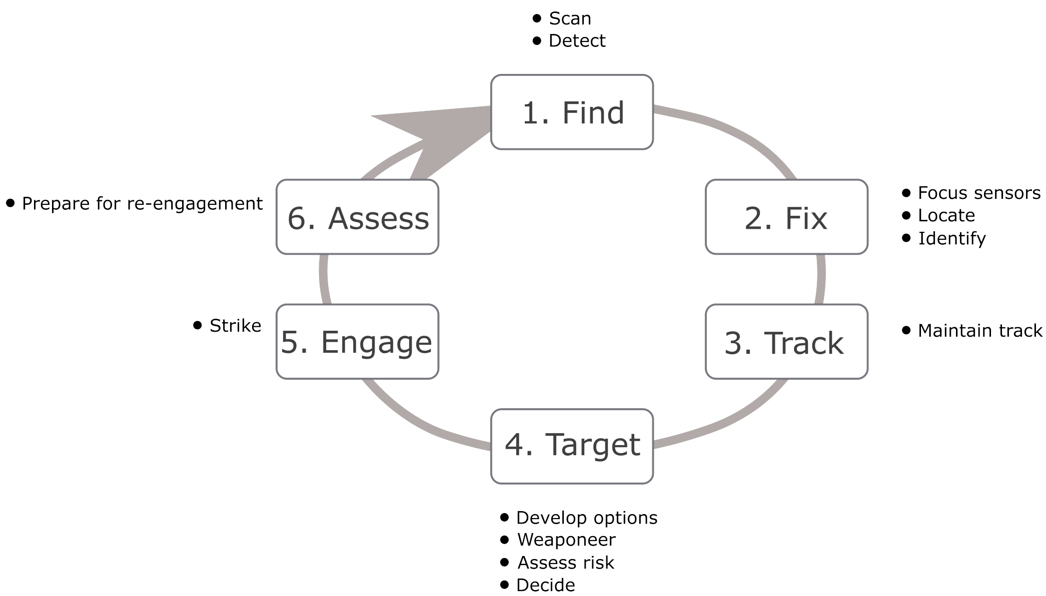


Figure 3.1: The six phase targeting cycle, i.e., the kill chain.

The kill chain is referred to as F2T2EA which originates from the phases of the kill chain: find, fix, track, target, engage and assess [5]. The phases of the live chain, on the other hand, are called deny find, deny fix etc. The phases of both chains progress and regress one after the other. The following list provides brief explanations of the objectives and decisions presented in Figure 3.1 for each phase of the kill chain. The objectives of the phases of the live chain are to deny Red from completing the ones defined for the corresponding phases of the kill chain. For example, the objective of the deny search phase of the live chain is to deny Red from completing the objectives defined for the search phase of the kill chain.

1. Find
    - Sensors are used for scanning the environment
    - Targets are detected
2. Fix
    - Sensors are focused on the targets
    - Previously detected targets are precisely located and identified as real flying objects
3. Track
    - Location and movement of the targets are tracked and monitored
    - Sensors are kept focused on the targets
4. Target
    - Options to react against the target are generated in terms of available resources and the governing rules of engagement
    - Weaponeering, i.e., selection of weapons is performed
    - Risk assessment is carried out
    - Decision of engaging or not engaging the target is made
5. Engage
    - Weapons are used against the target
6. Assess
    - Evaluation of weapon effectiveness is carried out
    - Preparations for a re-engagement are made

The selection of a TTP in air combat is dynamic and requires a quick analysis of the rules included in a TTP. It is often not possible for the pilot to remember all the rules of each TTP under consideration. However, the pilot needs to be able to quickly recognize a potential TTP through certain key events [24] [25]. After the recognition, the pilot analyzes the likely outcome that the TTP produces. The depth of the quick analysis comes down to the expertise of the pilot. The pilot chooses the first TTP that produces an acceptable outcome according to the brief analysis [26].

The quick analysis during the selection of the TTP is based on how well the rules of the TTP in each phase of the kill and live chains align with their respective objectives. For instance, a TTP rule for the engage and assess phases might be to reserve an option for a re-engagement. The re-engagement option is necessary if, e.g., Red cannot be allowed to fly any further towards the territory of Blue and there is a chance that Red is not destroyed during the first engagement. Another TTP might have a rule stating that multiple missiles should be launched against the target at once to maximize the probability of destroying Red. However, these rules contradict each other in the sense that if all missiles are used there is no option for a re-engagement. Therefore, in this case, the selection of the correct TTP depends on the objectives of the engage and assess phases.

In this thesis, the focus of the TTP development is on the level of an individual aircraft. It is thus sensible to review the selection of a TTP also on such a level. The TTP selection for an individual aircraft during air combat stays the same, although the complexity of combat decreases because there are less aircraft involved in comparison with, e.g., a four-ship. Consequently, there are less delays when selecting a TTP for an individual aircraft compared to a four-ship.

3.2 Planning problem of TTPs

In this section, the planning problem of TTPs is introduced. First, the scope and delimitations of the problem are discussed. Next, the objectives for each combination of the phases of the Blue kill and live chains are defined. After the objectives are defined, criteria need to be identified for the combinations of the phases. The criteria are used to evaluate the air combat state from the perspective of Blue. Then, for Blue, decisions are identified and their alternatives are generated. The alternatives are evaluated and ranked using the MDH approach presented in this thesis. The best alternatives of each decision according to the evaluation reveal TTP rules and their values.

3.2.1 Scope and delimitations

The planning of TTPs is separate from the real-time selection of TTPs during actual air combat because the planning is conducted off-line outside of air combat. The guidelines for the planning of TTPs, however, stem from the use of TTPs, i.e., the planning also needs to take the selection of TTPs into account. In this thesis, the planning follows the dynamic targeting framework and considers the kill and live chains of Blue. However, pilots in modern aircraft tend to carry out the first three phases of the kill chain quickly [27]. Thus, simplified versions of the kill and live chains for the purposes of the planning of TTPs in this thesis are introduced. Find, fix and track phases are grouped together and named the search phase. The target phase is left unchanged. The objective of the assess phase is to prepare for a re-engagement. The preparation can also be made in the engage phase by, e.g., analyzing the number of available weapons or maintaining an offensive position. Therefore, there is no need for the assess phase and thus, it is combined with the engage phases to form the new engage phase. The simplified version of the Blue kill chain is presented in Figure 3.2. The new phases are completed only in succession. The phases of the Blue live chain correspond to the phases of the kill chain, i.e., they are the deny search, deny target and deny engage phases. They consider denying the progression of the taskwork of Red.

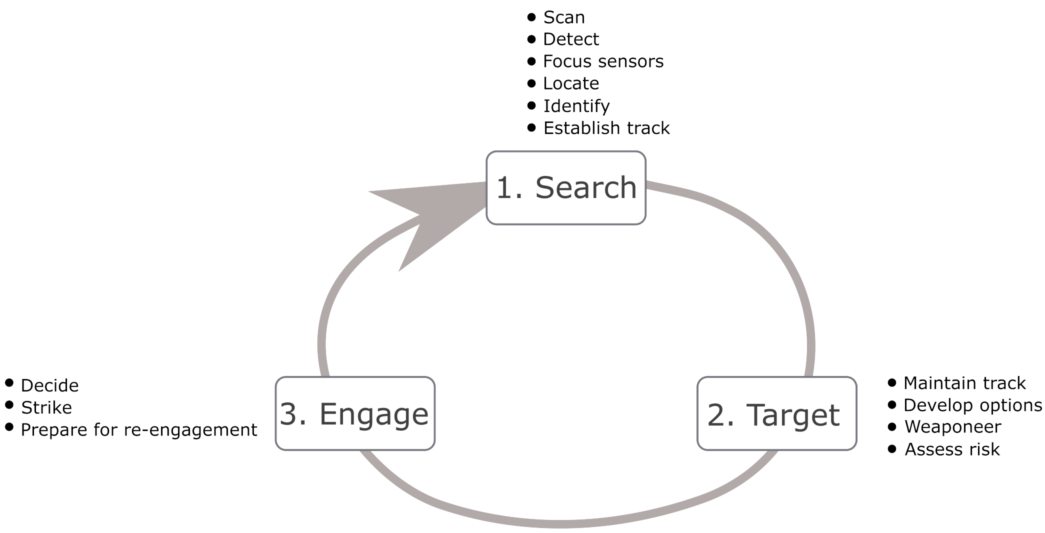


Figure 3.2: The simplified kill chain used in the MDH approach developed in this thesis.

To keep the planning problem simple enough for the purpose of this thesis, the following delimitations are considered. When the kill chain of Blue is in the search phase, the live chain of Blue can only be in the deny search phase. The reason is that Blue is assumed to receive information of Red only with its sensors, i.e., a radar. Thus, the information Blue receives is not perfect. In the search phase, Red is not yet found with the radar and the phase of the Blue live chain cannot be reliably estimated. Therefore, the Blue live chain is assumed to be in the deny search phase even though the assumption is not entirely realistic. For example, consider a situation where the radar of Red is known to have a significantly longer detection range than Blue. Then, it would be only sensible to assume that the live chain of Blue is already in the target phase, i.e., Red has established a radar track of Blue, even though the kill chain of Blue is still in the search phase. However, the assumption in this thesis is that Blue and Red have equally capable aircraft in all terms including radars. Therefore, in this thesis, the rules and rule values are determined only for the combinations of the phases of the Blue kill and live chains presented in Table 3.1.

Table 3.1: The combinations of the kill and live chain phases of Blue considered in the MDH approach developed in this thesis.

Kill chain	**Live chain**
Search	Deny search
Target	Deny search
Target	Deny target
Target	Deny engage
Engage	Deny search
Engage	Deny target
Engage	Deny engage

It should be noted that the description of air combat used in the MDH approach developed in this thesis is not a perfect replicate of real world air combat nor is it designed to be. The goal of this thesis is to introduce a support tool for the development of TTPs. Modeling assumptions and delimitations do not interfere with this goal. Instead, they allow the formulation of the TTP planing problem and the development of the MDH approach in a way that fits to the scope of this thesis.

3.2.2 Definition of objectives

The combinations of the phases of the simplified Blue kill and live chains are associated with different objectives. They are introduced for the individual phases of both chains and then composed for the combinations of the phases. The objective of the search phase of the Blue kill chain is to find Red with the radar and consequently establish a radar track of Red. Red is found when it flies into the radar search cone of Blue and is within the detection range of Blue's radar. Once the objective has been completed, i.e., Red has been detected, the radar automatically establishes the track of Red. The radar track is also maintained automatically provided that the radar is pointed to the direction of Red. Consequently, the kill chain progresses to the target phase because in this thesis there are no other targets for Blue.

When the kill chain of Blue is in the target phase, the calculation of the launch acceptability region (LAR) starts. Similarly, it is calculated for Red when Red finds Blue with its radar. The LAR represents the volume around the target aircraft inside of which a launched missile is expected to hit the target if the target continues flying with current speed on an extrapolation of the current trajectory [28]. However, in this thesis, the calculation of the LAR is simplified to consider only the present heading, altitude and speed of the target. A missile launched from further inside the LAR increases its probability of intercepting the target. In real world air combat, after the minimum launch range of the missile is surpassed, different factors, such as the fuzing of the missile warhead, may limit the launched missile from intercepting and destroying the target [28]. In this thesis, the LAR is determined by the type of the missile and the target aspect (TA) angle, speed and altitude as well as the shooter's heading, speed and altitude [29]. The TA angle is defined as the angle between the line of sight from the target to the shooter and the heading of the target [30]. The objective of the target phase is to maneuver to get inside the LAR. Once the objective of the target phase is completed, the kill chain progresses to the engage phase.

The objective of the engage phase is to launch and deliver a missile to its target and to prepare for a possible re-engagement [5]. The engage phase ends when the target is destroyed or the engagement ends for other reason, e.g., the target bugging out, i.e., flying away from the engagement without the intent of coming back [31]. Additionally, the kill chain can revert back to the target phase if Blue maneuvers out of the LAR or even to the search phase if the radar track of Red is lost.

The objectives of the Blue live chain phases stem from the objectives of the phases of the kill chain. When the Blue live chain is in the deny search phase, denying its progression means remaining undetected by the radar of Red. Blue can affect the likelihood of being detected by the radar of Red with the choice of altitude, heading and the use of a jammer. On the other hand, when the Blue live chain is in the deny target phase, its progression is denied by prohibiting Red from reaching the LAR. Additionally, in the deny engage phase, Red must be prevented from launching and delivering a missile to Blue to deny the progression of the live chain. The means for denying Red from reaching the LAR or launching and delivering a missile to Blue consist mainly of maneuvering. However, the use of a jammer might also cause Red to lose the radar track of Blue and consequently revert the Blue live chain back to the deny search phase.

Blue is in a specific phase of the kill chain as well as of the live chain simultaneously at all times of the air combat scenario. Therefore, the objectives for the feasible combinations of the phases of the Blue kill and live chains are identified and summarized in Table 3.2. The objective of the prevailing phase of the Blue kill chain needs to be completed to progress to the next phase. On the other hand, the completion of the objective of the phase of the Blue live chain ensures that the live chain does not progress. The completion of all the objectives can be achieved with proper TTPs. The development of these TTPs is supported by the MDH approach introduced in this thesis.

Table 3.2: The objectives of Blue for each combination of the phases of the Blue kill and live chains.

Kill chain	**Live chain**	**Objectives**
Search	Deny search	Find Red Remain undetected by Red
Target	Deny search	Reach the LAR Remain undetected by Red
Target	Deny target	Reach the LAR Deny Red from reaching the LAR
Target	Deny engage	Reach the LAR Deny Red from launching and delivering a missile to Blue
Engage	Deny search	Launch and deliver a missile to Red Remain undetected by Red
Engage	Deny target	Launch and deliver a missile to Red Deny Red from reaching the LAR
Engage	Deny engage	Launch and deliver a missile to Red Deny Red from launching and delivering a missile to Blue

3.2.3 Identification of criteria

Solving the TTP planning problem requires the evaluation of every air combat state with regards to the prevailing objectives of Blue. In practise, the completion of the objectives of each feasible combination of the phases of the Blue kill and live chains are evaluated by criteria. The criteria of Blue are selected by air combat experts in a dedicated workshop. They represent the most relevant aspects for evaluating the completion of the objectives considered in this thesis. Similarly to the objectives, the criteria are first discussed individually and then combined for the combinations of the Blue kill and live chain phases.

For the criteria of Blue, the probability of detecting Red with the radar is denoted by P_d^{Blue} and the probability of destroying Red with a launched missile by P_k^{Blue}. In addition, the probability of remaining undetected, i.e., in cover, and the probability of survival are denoted by $P_c^{Blue} = 1 - P_d^{Red}$ and $P_s^{Blue} = 1 - P_k^{Red}$, respectively. P_d^{Red} measures the probability of detecting Blue with Red's radar and P_k^{Red} the probability of Red destroying Blue with a launched missile. The progression of the kill chain of Blue is promoted by making decisions which maximize P_d^{Blue} and P_k^{Blue}. On the other hand, the progression of the live chain of Blue is denied by decisions which maximize P_c^{Blue} and P_s^{Blue}.

In total, there are four criteria. The importance of a criterion depends on the phases of the Blue kill and live chain. Every distinct phase of the kill and live chains of Blue has one relevant criterion. The objective of the search phase is to find Red. Finding Red is measured with P_d^{Blue}, and therefore it is the relevant criterion for the search phase of the kill chain. The progression of the Blue live chain is denied by remaining undetected by the radar of Red in the deny search phase. It is measured with P_c^{Blue}, and thus this is the relevant criterion for the deny search phase.

When the Blue kill chain is in the target phase, the objective is to reach the LAR. P_k^{Blue} indicates how likely a missile launched by Blue destroys Red. This likelihood increases as Blue approaches the LAR and further increases by flying deeper into the LAR. Thus, the relevant criterion for the target phase is P_k^{Blue}. The altitude, airspeed, heading and distance to Red at the time of missile launch affect P_k^{Blue} the most.

The objective of the Blue engage phase is to launch and deliver the missile to Red and prepare to re-engage. Prioritizing P_k^{Blue} directly improves the likelihood of a launched missile intercepting and destroying Red, and thus it is chosen as the relevant criterion. In addition, maintaining a high P_k^{Blue} after the missile launch improves the ability of Blue to re-engage if, e.g., Red evades the first missile.

The means of Blue for denying the progression of the Blue live chain in the deny target and deny engage phases are alike. The progression of the Blue live chain is denied by prohibiting Red from reaching the LAR or launching and delivering a missile to Blue. Both of these objectives are achieved by maximizing P_s^{Blue}, i.e., minimizing P_k^{Red}. Thus, P_s^{Blue} is the relevant criterion for the deny target and deny engage phases of the Blue live chain.

In general, in a multi-criteria decision analysis problem, multiple criteria are aggregated into a single overall criterion with criteria weighting [32]. The weights represent the relative importance of the criteria. In the planning problem of TTPs, the two relevant criteria of each combination of the Blue kill and live chain phases are given a weight between values 0 and 1. Other non-relevant criteria are given a weight of 0. The weights are normalized such that their sum is 1. By increasing the weight of P_d^{Blue} or P_k^{Blue} more emphasis is assigned to offense, i.e., finding Red or aggressive maneuvering for improving the conditions for a missile launch by Blue. On the other hand, by increasing the weights of P_c^{Blue} or P_s^{Blue} defense is emphasized, i.e., remaining undetected by Red or negating the ability of Red to launch and deliver a missile to Blue.

In practise, there exists a specific combination of the phases of the Blue kill and live chains at all times of an air combat scenario. The combinations of phases are analyzed with the MDH approach introduced in this thesis. Therefore, it is sensible to combine the relevant criteria for every feasible combination of the phases. For clarity, they are presented in Table 3.3.

Table 3.3: Criteria of Blue for each combination of the phases of the Blue kill and live chains considered in the MDH approach developed in this thesis.

Kill chain	**Live chain**	**Criteria**
Search	Deny search	P_d^{Blue} and P_c^{Blue}
Target	Deny search	P_k^{Blue} and P_c^{Blue}
Target	Deny target	P_k^{Blue} and P_s^{Blue}
Target	Deny engage	P_k^{Blue} and P_s^{Blue}
Engage	Deny search	P_k^{Blue} and P_c^{Blue}
Engage	Deny target	P_k^{Blue} and P_s^{Blue}
Engage	Deny engage	P_k^{Blue} and P_s^{Blue}

3.2.4 Generation of decision alternatives

The overall goal of the TTP development is to identify TTP rules and rule values for guiding the decision making of a pilot. In order to identify the rules, decisions, that are to be considered in the TTP, must be determined for each phase of the kill chain for Blue. In addition, alternatives are needed for each decision. When the alternatives of each decision are evaluated and ranked using the MDH approach developed in this thesis, the best alternatives constitute the TTP rules and rule values for Blue. Note that the objectives and criteria introduced in the previous subsections depend on the phases of the Blue kill and live chains. Therefore, the TTP rules and their values are ultimately identified for the combination of the phases of both chains. However, the decisions of Blue depend only on the phase of the Blue kill chain. This dependency is appropriate because the decisions allow Blue to promote the progression of the kill chain as well as deny the progression of the live chain. Hence, there is no need to generate separate sets of decisions related to the phase of the Blue live chain. The decisions of Blue and their alternatives are identified by air combat experts in a dedicated workshop, and they are introduced in this subsection. The alternatives remain the same for each decision regardless of phase of the Blue kill chain.

Search phase

The use of a radar, maneuvering and the use of a jammer are Blue's decisions in the search phase and they are presented in Table 3.4. The decision regarding the radar includes choosing its setting and elevation angle. Operate and standby are the alternatives when choosing the radar setting. Operate means that the radar is searching for or tracking a target. On standby the radar does not search or track. The radar setting is chosen as a decision because it enables Blue to find Red. Deciding about the radar elevation angle affects the vertical angle which the search of the radar covers. Choosing the radar elevation gives more freedom to direct the radar of Blue where it is effective. Alternatives for radar elevation are three different directions: upwards, level and downwards. Many fourth generation fighter jets have mechanically scanning radars [33], which implies a limited area of scanning. By moving the direction to which the radar is looking in the vertical plane, the scanning area can be altered.

Table 3.4: Blue's decisions and their alternatives in the search and target phases of the Blue kill chain considered in the MDH approach developed in this thesis.

Decision	**Alternatives**
Use of radar	
Radar setting	Operate
	Standby
Radar elevation	Up
	Level
	Down
Maneuvering	
Throttle position	Idle power
	Intermediate power
	Full power
Bank angle rate of change	Left
	None
	Right
Pitch angle rate of change	Up
	None
	Down
Use of jammer	
Jammer setting	Operate
	Standby

The maneuvering decisions are made in order to achieve a favorable position for Blue. The decisions and their alternatives include adjusting the throttle position from idle to full power, roll rate left and right as well as pitch rate up or down in a way that Blue flies to the desired position. These decisions are important because maneuvering greatly impacts the ability of Blue to detect Red or to remain undetected.

The use of a jammer is chosen as a decision because it reduces the probability of being detected by Red. However, it also reduces the capabilities of the radar of Blue. The decision alternatives are to adjust the jammer setting to operate or to standby. Setting the jammer on operate creates a cone which points forward from the nose of Blue and jams the radar of Red making it less likely to detect Blue. Standby means that the jammer is not jamming, and therefore it does not affect the capabilities of any radars.

Target phase

Decisions of Blue and their alternatives in the target phase are the same as in the search phase, and they are also presented in Table 3.4. The use of a radar is defined the same way as in the search phase. Note that setting the radar on standby also causes the Blue kill chain to revert back to the search phase. Similarly, choosing the radar elevation includes the same alternatives as in the search phase. Even though the radar is already tracking the target, it must be guided correctly to maintain the track using the radar elevation.

Jamming is used to reduce the chance of being found by Red while simultaneously maintaining Blue's radar track of Red. However, when Blue is jamming, the capability of the radar of Blue is also reduced and thus the decision is of importance.

Maneuvering decisions are made by Blue to reach the LAR. The decision alternatives include the same adjustments for the roll and pitch rates as well as for the throttle position as in the search phase. Decisions regarding maneuvering are included in this phase because reaching the LAR is practically achieved by maneuvering.

Engage phase

The use of a radar, maneuvering, the use of a jammer and launching a missile are Blue's decisions in the engage phase. Their decision alternatives are presented in Table 3.5.

The use of a radar includes only the choice of radar elevation in the engage phase. The alternatives of directing radar elevation are the same as in the previous phases. It is used to maintain the radar track of Red. Similarly, the decisions regarding the maneuvering and their alternatives are the same as in the previous phases. Deciding about maneuvering is of importance because the likelihood of a missile launched by Blue intercepting Red is increased by maneuvering further into the LAR before the missile launch. In addition, after launching a missile, Blue has a choice of, e.g., preparing for a re-attack or to fly away from Red. The decision thus greatly affects the re-engagement ability of Blue.

The decision of the use of a jammer has the same alternatives as in the previous phases. The decision affects the balance of prioritizing jamming and preserving the capabilities of the radar. Setting the jammer on operate impedes the ability of Red to find or maintaining the radar track of Blue. However, it is only beneficial if Blue is able to maintain the radar track of Red.

The decision of launching a missile can be made from any point in the engage phase. The decision is relevant because it allows for the completion of the objective of the engage phase, i.e., to launch and deliver the missile to Red. Additional missiles can be launched if the engagement is continued or a re-engagement is carried out. For instance, the first missile may miss Red, and therefore maintaining the option for additional missile launches is important.

Table 3.5: Blue's decisions and their alternatives in the engage phase of the Blue kill chain considered in the MDH approach developed in this thesis.

Decision	**Alternatives**
Use of radar	
Radar elevation	Up
	Level
	Down
Maneuvering	
Throttle position	Idle power
	Intermediate power
	Full power
Bank angle rate of change	Left
	None
	Right
Pitch angle rate of change	Up
	None
	Down
Use of jammer	
Jammer setting	Operate
	Standby
Missile launch	Launch
	Hold

Chapter 4

Moving decision horizon multi-criteria approach (MDH approach)

This chapter introduces the moving decision horizon multi-criteria approach (MDH approach) and the included dynamic multi-criteria decision analysis (DMCDA) model. In the first section, the auxiliary, i.e., environment, aircraft and system models included in the DMCDA model are presented. The environmental model covers the airspace in which the aircraft operate. The aircraft model includes the performance characteristics for Blue and Red, both of which have similar aircraft. In addition, the state representation for Blue and Red is defined. The system models describe a radar, a jammer, a missile as well as the calculation of the probability of detection and the probability of kill. The DMCDA model and its solution procedure are then presented. The graphical user interface (GUI) is also introduced. Finally, a section containing numerical considerations concludes the chapter.

The MDH approach is introduced from the perspective of supporting the development of a TTP for Blue with fixed behavior of Red. Therefore, only the decisions of Blue are evaluated and ranked by the solution procedure of the DMCDA model. However, to produce the threat presentation of Red for the TTP development, control variables for Red are included in the model. In addition, an air combat scenario is defined which contains the one versus one air combat between Blue and Red. The scenario is described at each time by the air combat state included in the DMCDA model.

4.1 Auxiliary models

4.1.1 Environment

The environment model describes the airspace and surroundings in which the aircraft operate. It is subject to a few assumptions. The ground is assumed to be flat, and both Blue and Red must remain above ground level at all times. The terms altitude and height are used interchangeably in this thesis, and they mean perpendicular distance from the ground. The acceleration due to gravity is assumed to be constant. The air in the environment is still, i.e., there is no wind. However, the air density is assumed to depend on the altitude. The simplifications do not significantly impact the air combat state and the accuracy of, e.g., the effect of gravity is still adequate for supporting the development of TTPs. However, they help to run the solution procedure of the DMCDA model faster by reducing the requirements for the computational resources.

4.1.2 Aircraft

The performance characteristics for Blue and Red are defined by the aircraft model. In the model, the sideslip, i.e., the yaw angle is assumed to be zero and thus not affecting the flight. In other words, the aircraft model allows maneuvering in five degrees of freedom. The fuel of the aircraft is constant, i.e., it acts only as additional mass on the aircraft. All of the systems on the aircraft are assumed to function normally, i.e., there are no malfunctions. The performance characteristics in terms of, e.g., turn rate are defined by a performance dataset for the General Dynamics F-16 Fighting Falcon fighter aircraft [34]. The maneuvering is controlled by adjusting the throttle position, bank angle rate and pitch angle rate. Thus, maneuvering follows the constraints of the performance dataset. The aircraft model includes a radar, a radar jammer and active radar guided missiles as capabilities.

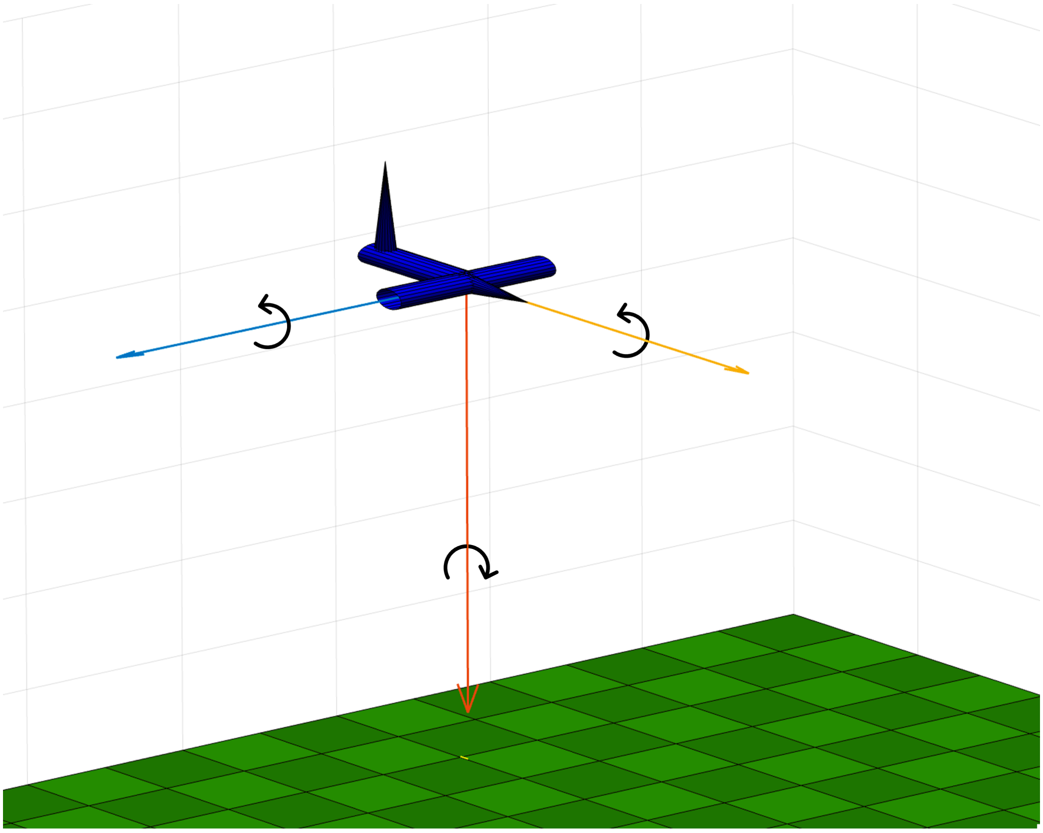


Figure 4.1: The aircraft, its axes and positive rotational directions. The yellow arrow represents longitudinal, blue arrow lateral and red arrow vertical axis, respectively.

A visualization of the aircraft, its axes and the positive rotational directions are presented in Figure 4.1. The yellow, blue and red arrows represent longitudinal, lateral and vertical axes, respectively. The positive rotational direction is depicted with the respective curved arrows. The state of the aircraft is described by the state variables

$$\boldsymbol{X}^i = [x^i,\, y^i,\, h^i,\, \boldsymbol{U}^i,\, \boldsymbol{\omega}^i,\, \boldsymbol{q}^i]^T, \tag{4.1}$$

where $i =$ Blue, Red. The state variables $[x^i, y^i, h^i]$ describe the three dimensional position of the aircraft. Height h^i is defined as the distance between the aircraft and the surface, i.e., the vertical coordinate. The coordinates x^i and y^i are the horizontal coordinates. The state variable $\boldsymbol{U}^i = [u_x^i\ u_y^i\ u_z^i]$ represents the velocity of the aircraft in three dimensions. The velocity $\boldsymbol{U}^i$ points to the direction of movement of the aircraft and is measured in knots. These four state variables together with the range between Blue and Red are also referred to as flight parameters in this thesis.

Angular velocities about all three axes are represented by the state variables $\boldsymbol{\omega}^i = [\omega_x^i \; \omega_y^i \; \omega_z^i]$. They are mainly used to determine the change in the attitude and speed of the aircraft. The attitude is represented with the attitude quarternion $\boldsymbol{q}^i$ which is a 4 by 4 matrix. The quarternion representation allows for convenient calculations of the attitude and its changes. The attitude in conjunction with the velocity is used to calculate the change in the 3D-position of the aircraft.

The states of the aircraft evolve according to the state equations

$$
\begin{aligned}
[\dot{x}^i \; \dot{y}^i \; \dot{h}^i]^T &= \boldsymbol{B}^i \cdot \boldsymbol{U}^i && (4.2)\\
\dot{\boldsymbol{U}}^i &= \frac{1}{m} \cdot \boldsymbol{F}^i - (\boldsymbol{\omega}^i \times \boldsymbol{U}^i) + \boldsymbol{B}^i \cdot \boldsymbol{g} && (4.3)\\
\dot{\omega}_x^i &= \frac{1}{\tau_\theta} \cdot (\Delta\theta^i - \theta^i) && (4.4)\\
\dot{\omega}_y^i &= \frac{1}{\tau_\phi} \cdot (\Delta\phi^i - \phi^i) && (4.5)\\
\dot{\omega}_z^i &= 0 && (4.6)\\
\dot{\boldsymbol{q}}^i &= -\frac{1}{2} \cdot \boldsymbol{q}_\omega^i \cdot \boldsymbol{q}^i. && (4.7)
\end{aligned}
$$

In Equation (4.2), $\boldsymbol{B}^i$ is the direction cosine matrix and $\boldsymbol{U}^i$ is the velocity. In Equation (4.3), m is the mass of the aircraft, $\boldsymbol{F}^i$ the total aerodynamic force, $\boldsymbol{\omega}^i$ the angular velocity and $\boldsymbol{g}$ the acceleration due to gravity. Aircraft is controlled by the changes of pitch $\Delta\theta^i$ and roll $\Delta\phi^i$ rates, see Equations (4.4) and (4.5). P^i and Q^i are the pitch and roll rates, respectively. In addition, τ_θ and τ_ϕ are time constant for roll and pitch rate changes. In Equation (4.7), $\boldsymbol{q}^i$ is the attitude quarternion.

4.1.3 Radar

The radar of the aircraft is assumed to be a basic airborne fire control radar [35]. The radar model includes similar capabilities for target detection and track as a 4th generation fighter jet fire control radar, e.g., APG-73 of an F-18 fighter jet [33]. It can be set on operate and standby. The state of the radar is described by a binary state variable S^i_{radar} where i = Blue, Red. A value of 1 for S^i_{radar} means the radar is on operate and a value of 0 that it is on standby.

The radar can detect and track a target when it is on operate. When it is not tracking it searches for a target, i.e., scans the airspace in front of the aircraft at an angle between the values $[-60, 60]$ degrees in azimuth and $[-50, 50]$ degrees in elevation and a straight-line distance of up to 43 nm. The actual detection of a target is ultimately represented by the probability of detection introduced later in Subsection 4.1.7. Once the radar has detected a target it creates a track and is able to track the target within the same limits as for the detection. If those limits are surpassed, the radar loses the track and then returns to the search mode.

4.1.4 Jammer

A radar jammer in general disrupts airborne radars by, e.g., blocking or interfering with the radio signal that the radar receives [36]. The jammer model in this thesis is assumed to use interference as the method of jamming. The jammer, when on operate, creates a jamming cone up to 32 nm. The cone has a vertical angle of 40 degrees from the longitudinal axis of the aircraft up and down. The cone's horizontal angles are 50 degrees from the same axis left and right. The burn through range of the jammer is 16 nm. After the burn through range from the target, the effect of the jammer becomes negligible due to the radar of the target overpowering it. The effective and burn through ranges of a jammer depend on the ratio of useful signal and jamming noise which is dependent on a number of factors such as the jammer's power output and target aspect [36]. However, the values for the ranges are fixed in this thesis for simplicity.

When a radar is under jamming the detection range decreases to 70% of its pre-jamming value. In addition, when an aircraft operates its jammer, the detection range of its own radar decreases by 10% due to interference from the jammer. The state of the jammer is described by a binary state variable S^i_{jammer}, where $i =$ Blue, Red. When $S^i_{jammer} = 1$, the jammer is on operate and $S^i_{jammer} = 0$ means that the jammer is on standby.

4.1.5 Missile

Air-to-air missiles can be classified into two main groups: infrared-seeking and radar-guided missiles [37]. The infrared-seeking missiles are generally used for within-visual-range air combat because of the shorter detection range of the seeker of the missile due to the quickly dissipating infrared signature of the target [38]. The radar-guided missiles can be further categorized into two groups: semi-active and active radar-guided missiles [39]. Semi-active radar-guided missiles require the shooter to illuminate the target with its radar. The launched missile uses the reflection of the radar illumination to navigate to the target [40]. Active radar-guided missiles are given the position of the target at launch time, and they use inertial navigation combined with information via a datalink from the shooter in the beginning of their flight towards the target [11]. Then, at a certain distance, the radar of the missile becomes active which the missile uses for terminal guidance [41].

In this thesis, active radar-guided missiles are considered. They fly at the speed of a generic medium-range active radar-guided air-to-air missile, i.e., $v_{missile} = 1250\frac{m}{s}$ and they are able to do high-G turns. For comparison, the top speed of an AIM-120 AMRAAM medium-range air-to-air missile is approximately 1360 $\frac{m}{s}$, and it can sustain turns up to 40G [41]. The missile only needs the initial position of the target at launch time and is assumed to find and keep track of the target during its entire flight.

The missile kinematics used in this thesis is simplified. Upon launch the missile instantly accelerates to the flying velocity and maintains it until the termination of the flight. The missile maintains a pure pursuit to the target, i.e., its heading is directly to the target until it intercepts the target or runs out of energy. The energy of the missile is described by time of flight (TOF). It depends on the altitudes of the shooter and the target and is calculated as

$$\begin{aligned} TOF_{missile,j}^{Blue} =& TOF_{missile,ref} \cdot \frac{1}{2}(\frac{h^{Blue}}{12000} + \frac{h^{Red}}{12000}) \cdot \\ & (1 + \frac{1}{4} \cdot \max(\min(\frac{h^{Blue} - h^{Red}}{10000}, 1), -1)), \end{aligned} \tag{4.8}$$

where Blue is the shooter, Red is the target, j is the sequence number of the missile and $TOF_{missile,ref} = 40s$ is a reference time of flight. After $TOF_{missile,ref}$, the rest of the formula consists of two parts. First, the absolute altitudes of Blue and Red are considered. Either altitude above approximately 39400ft increases TOF. Otherwise TOF is decreased. Then, the effect of the relative altitudes of Blue and Red is calculated. Any relative difference, where the shooter is higher, increases TOF up to a relative difference of 32800ft, i.e., 10km, where $TOF_{missile,ref}$ is doubled. Similarly, relative difference the other way decreases TOF until it goes to zero at the difference of 32800ft. The missile's TOF depends on the altitudes of both aircraft because the air density decreases with increasing altitude. Denser air produces more drag on the missile thus reducing TOF. However, the way TOF of a missile depends on the altitudes is an approximation created for this thesis and does not accurately represent real world conditions.

The state of the missile is described by the state variables

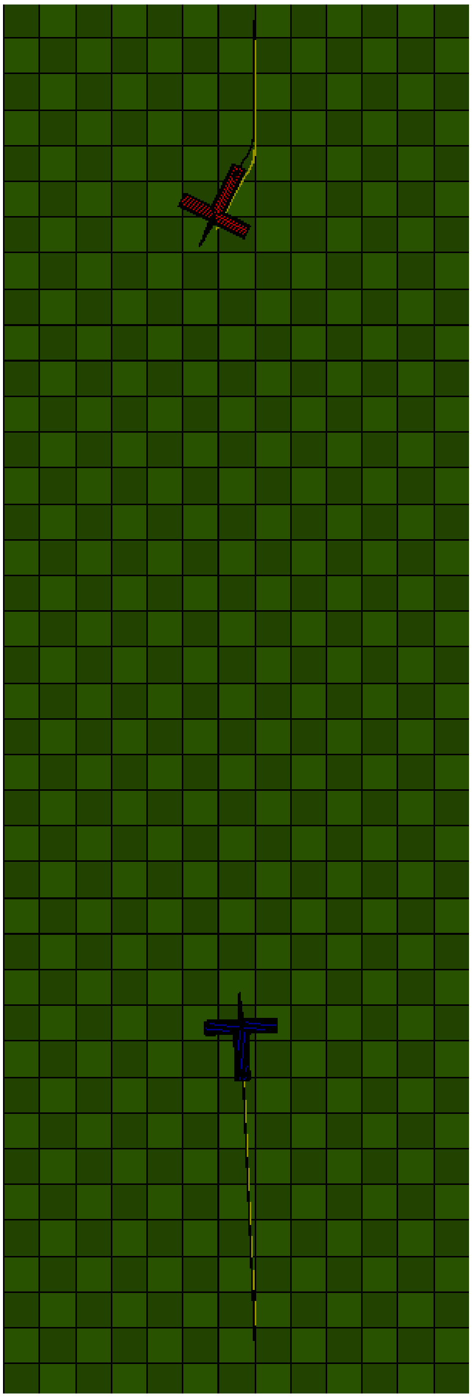
$$\boldsymbol{M}_j^i = [x_{missile,j}^i, y_{missile,j}^i, h_{missile,j}^i, \boldsymbol{U}_{missile,j}^i, TOF_{missile,j}^i], \tag{4.9}$$

where i = Blue, Red. The variables $[x^i_{missile,j}\ y^i_{missile,j}\ h^i_{missile,j}]$ describe the position of the missile. The velocity of the missile is denoted by $\boldsymbol{U}^i_{missile,j}$ and TOF of the missile by $TOF^i_{missile,j}$. Blue can launch a missile at any time as long as the kill chain of Blue is in the engage phase. However, a missile launched, e.g., from too far away has a low chance of intercepting the target. Red launches a missile according to predefined conditions.

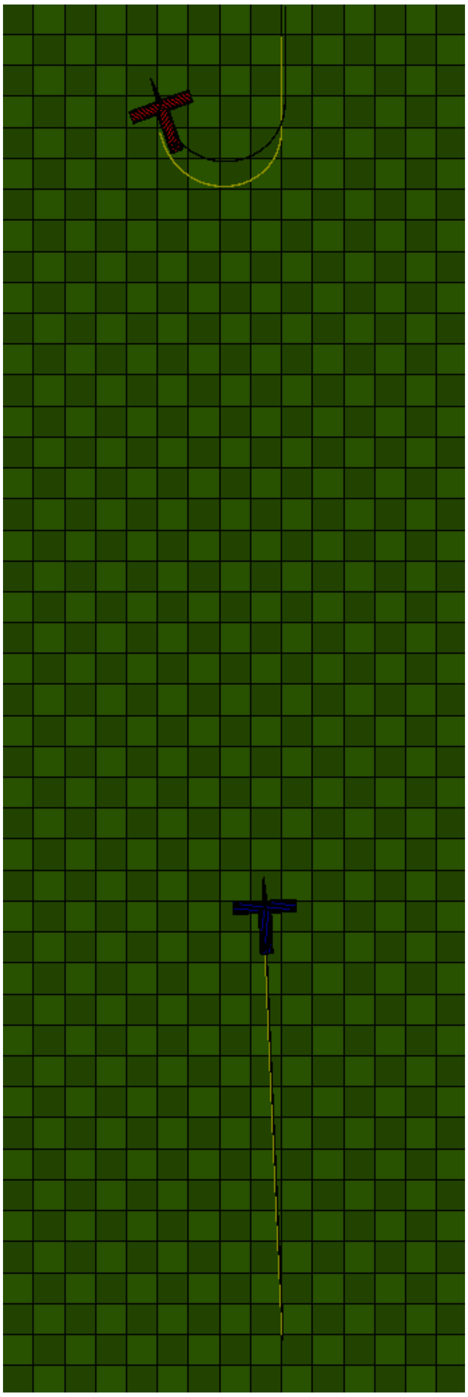
4.1.6 Maneuvers

In the planning of TTPs, the maneuvering of Red is fixed. There are, however, maneuvers that Red can execute during air combat. The maneuvers are an out maneuver and a turn maneuver to either side, and they are presented in Figure 4.2. They can be set to be executed on the command of the DM, who is using the MDH approach, or when a certain condition is fulfilled. Such a condition can be, e.g., Red reaching a certain distance from Blue. These kind of maneuvers are not used for Blue.

The turn maneuvers that Red can make are roughly 40 degrees on either side depending on the velocity of Red. Turns can be used to alter the heading, e.g., for searching the target or for minimizing the rate of closure to the target. In the out maneuver, a turn is executed away to a cold aspect from the target. This aspect is defined as having the target at an angle off nose of about 150 to 180 degrees [31]. The out maneuver can be executed, e.g., to evade the opponent's missile. The out maneuver of Red is carried out while maintaining a roughly constant altitude. Red performs a hard, level turn away form Blue when the out maneuver is initiated. Once Red reaches the cold aspect the out maneuver is finished and Red continues to fly straight with the resulting heading.



(a) The turn maneuver for Red.



(b) The out maneuver for Red.

Figure 4.2: The turn (a) and out (b) maneuvers for Red.

4.1.7 Probability of detection and probability of kill

The calculation of the probabilities of detection P_d^i and kill P_k^i, where $i =$ Blue, Red, is introduced in this subsection. For clarity, they are considered from the perspective of Blue (P_d^{Blue} and P_k^{Blue}) but the same principles apply for Red. Both probabilities are needed for the evaluation of the air combat state. There are three components that affect the calculation of the probability of detection: target aspect component ($TA_{component}^{Blue}$), target range component ($R_{target,component}$) and radar direction component ($D_{radar,component}^{Blue}$). These components depend on four factors explained in this subsection and illustrated in Figure 4.3. $TA_{component}^{Blue}$ depends on TA^{Red}, which is defined as the angle between the nose of Red and the line of sight from Blue to Red. TA^{Red} affects $TA_{component}^{Blue}$ and consequently P_d^{Blue} because the radar cross section of Red varies with TA^{Red} [42]. In addition, the Doppler shift of Red decreases as TA^{Red} approaches 90 degrees [42] which makes the detection more difficult. In this thesis, P_d^{Blue} depends linearly on TA^{Red} from zero degrees of TA^{Red} to 90 degrees of TA^{Red}. The TA component of Blue is calculated as

$$TA_{component}^{Blue} = 1 - \max(\frac{TA^{Red}}{90}, 1). \tag{4.10}$$

The TA component of Blue maps TA^{Red} to a value interval of $[0, 1]$.

The target range R_{target} is the distance between Blue and Red. It has an effect on the strength of the signal reflected off of the target, i.e., the return signal of the radar. The further away the target is the weaker the return signal gets thus making detection more difficult [42]. In this thesis, P_d^{Blue} depends linearly also on the target range. It reaches the maximum effect at 70% of the detection range of the radar and starts affecting 11 nm further away. The target range component is calculated as

$$R_{target,component}^{Blue} = \max(1 - \frac{R_{target} - 0.7 \cdot R_{radar}^{Blue}}{20000}, 0), \tag{4.11}$$

where R_{radar}^{Blue} is the detection range of the radar. $R_{target,component}^{Blue}$ gets values between 0 and 1.

The radar direction describes where the radar of Blue is pointed towards. The radar coverage, and consequently also P_d^{Blue}, depends on the radar direction. The likelihood of detection increases when more radar coverage is directed to the area, where the target is. In this thesis, radar direction D_{radar}^{Blue} is defined as a unit vector which points to the center point of the radar search cone. Similarly to the other factors, P_d^{Blue} depends on the radar direction linearly. The effect of the radar direction is measured as its deviation in degrees from a favorable search point in space. The favorable search point is defined as a point 16 nm along the x-axis and 16 000 ft in altitude towards the assumed direction of opponent, i.e., along the x-axis, see Figure 4.3. The point is defined such that the radar search covers a considerable amount of airspace in front of Blue, where Red is likely to be, when the radar is directed towards it. Consequently, the radar direction component is calculated as

$$D^{Blue}_{radar,component} = \min(\frac{1}{\beta^{Blue}_{radar}}, 1), \tag{4.12}$$

where β^{Blue}_{radar} is the angle between D^{Blue}_{radar} and a vector which points to the favorable search point from Blue's nose. Similarly to the other components, $D^{Blue}_{radar,component}$ gets values between 0 and 1. Smaller deviation from the favorable search point is considered better.

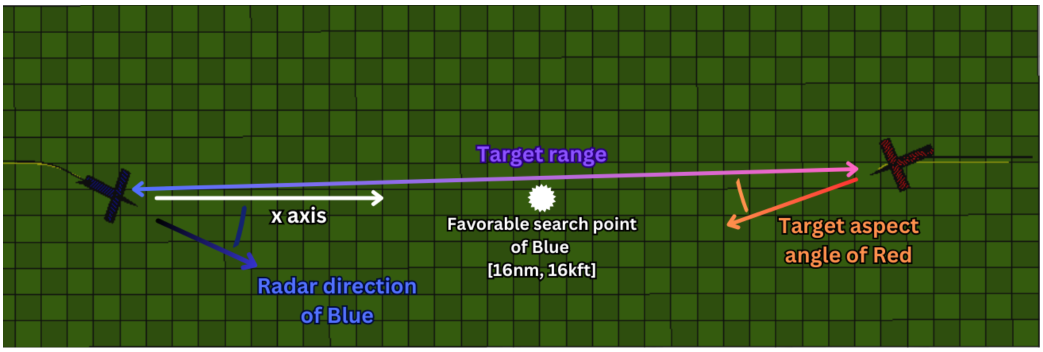


Figure 4.3: Target aspect of Red, target range, favorable search point of Blue and radar direction of Blue.

P^{Blue}_{d} is a weighted sum of its components

$$P^{Blue}_{d} = TA^{Blue}_{component} \cdot 0.05 + R^{Blue}_{target,component} \cdot 0.7 + D^{Blue}_{radar,component} \cdot 0.25, \tag{4.13}$$

where the weights sum up to 1. The weights represent the effect that the corresponding component has on P^{Blue}_{d}. The most important component is the target range. This is due to the strength of the radar signal quickly decreasing when traveling long distances [43]. In addition, the signal-to-noise ratio increases with longer distances. The second largest weight is assigned to the radar direction. It is important to direct as much radar signal to the expected area of the target to increase P^{Blue}_{d}. Finally, the TA component of Blue is given the smallest weight as the linear dependency does not take into account the absence of the Doppler effect at 90 degrees of TA^{Red}.

In this thesis, the calculation of the probability of kill of a missile is based on the likelihood of the missile having enough potential and kinetic energy to intercept the target. Generally, more factors are taken into account, such as guidance and fuzing uncertainties [44]. However, considering only the energy of the missile serves the purpose of this thesis well, because it can be easily affected by maneuvering the aircraft.

The calculation of the probability of kill for Blue P_k^{Blue} is divided into two components: a probability of kill component ($P_{k,component}^{Blue}$) and a digital maneuvering cue component ($DMC_{component}^{Blue}$). $P_{k,component}^{Blue}$ is a weighted sum of the probability of kill scores for both aircraft $P_{k,score}^{Blue}$ and $P_{k,score}^{Red}$. $P_{k,score}^{i}$ is a weighted sum of an altitude score A_{score}^i and a heading score H_{score}^i for both aircraft, i.e., i = Blue, Red. The calculation of P_k^{Blue} is divided into many subparts because it makes weighting the different factors more convenient.

The altitudes and headings of both aircraft affect $P_{k,score}^{i}$. A higher altitude generally means lower air density where the missile flies further. The headings affect the closing velocity of the missile and the target, and also the missile's need to turn towards the target after launch. The altitude and heading scores get values between 0 and 1 and they are

$$A_{score}^i = \min(1, \frac{h^i}{12000}), \tag{4.14}$$

$$H_{score}^i = 1 - \frac{\psi^i}{180}, \tag{4.15}$$

for i = Blue, Red. Assuming that i = Blue, h^i is the altitude of Blue and ψ^i is the angle in the the $x-y$-plane between the nose of Blue and the direction of Red from the perspective of Blue.

A_{score}^i gets the maximum value when the altitude is 12km, i.e., 39000ft. It is based on the service ceilings of 4th generation fighter jets, which are around 50000ft [45]. The service ceiling is the highest altitude at which an aircraft can maintain a specified positive rate of climb [46]. The service ceiling is determined for an aircraft without any loaded missiles or other combat equipment. Hence, 39000ft is determined to be a reasonable altitude that Blue should try to achieve in terms of maximizing $P_{k,score}^{i}$ because of the extra weight and drag from the missiles on board. The heading affects $P_{k,score}^{i}$ by determining the need for the missile to turn towards the target. For example, if the missile is launched directly at Red by Blue, i.e., at $\psi^{Blue} \approx 0$, the missile is given a more efficient flight path. However, if the missile is launched at $\psi^{Blue} = 50$, it needs to maneuver to compensate for the offset in its initial heading, which requires energy. Note that the missile in this thesis assumes a heading directly towards the target regardless of the heading of the shooter. Therefore, the effect of ψ^i is considered only in the calculation of H^i_{score}.

$P^i_{k,score}$ is calculated as a weighted sum of A^i_{score} and H^i_{score} as follows

$$P^i_{k,score} = A^i_{score} \cdot 0.8 + H^i_{score} \cdot 0.2, \tag{4.16}$$

where $i =$ Blue, Red. The altitudes of the aircraft affect $P^i_{k,score}$ more than the headings. Thus, the altitudes are usually assigned a higher weight than the heading when calculating the probability of kill [47]. Hence, the weights are assigned as in Equation (4.16). $P^{Blue}_{k,component}$ is then formulated as

$$P^{Blue}_{k,component} = P^{Blue}_{k,score} \cdot 0.7 + P^{Red}_{k,score} \cdot 0.3. \tag{4.17}$$

The components affecting $P^{Blue}_{k,component}$ of the shooter are given a higher weight than of the target aircraft. This is due to the shooter being able to adjust these factors more easily. Thus, in this thesis, the weights are as shown in Equation (4.17).

The DMC component of Blue, $DMC^{Blue}_{component}$, depends on the DMC number δ^{Blue}_{DMC}. The DMC number, in general, represents a turn in degrees that the target aircraft has to make in order to kinematically defeat a missile launched by the other aircraft. It is used, e.g., in the F-18 Hornet fighter jet simulator of Digital Combat Simulator (DCS) [48]. For instance, a DMC number of 90 means that the target has to make a 90 degree turn away from the shooter in order to kinematically defeat the launched missile. The maximum value of δ^{Blue}_{DMC} is 180 because Red can fly a maximum of 180 degrees away from Blue. The DMC component is then formed as $DMC^{Blue}_{component} = \frac{\delta^{Blue}_{DMC}}{180}$. It depends on the missile's kinematics which in turn depends on the altitudes of the shooter and target aircraft. Finally, P^{Blue}_k is

$$P^{Blue}_k = P^{Blue}_{k,component} \cdot 0.3 + DMC^{Blue}_{component} \cdot 0.7. \tag{4.18}$$

In this thesis, the kinematic performance of the missile is deemed to be the most significant factor in determining the likelihood of a successful interception of a missile. Thus, $DMC^{Blue}_{component}$ is given a higher weight than $P^{Blue}_{k,component}$ in Equation (4.18).

4.2 Dynamic multi-criteria decision analysis model

This section introduces the dynamic multi-criteria decision analysis (DMCDA) model of the MDH approach. Blue's decision and Red's control variables, end state conditions for the phases of the Blue kill and live chain, time evolution of air combat state and an objective function are defined for the model. The decision variables of Blue represent the alternatives of Blue's decisions introduced in Subsection 3.2.4. On the other hand, the control variables of Red are used to carry out the predefined maneuvers of Red discussed in Subsection 4.1.6 according to the threat presentation. The end state conditions determine when each phase of the Blue kill and live chains is completed. The representation of the time evolution of the air combat state is used for generating future states. The future air combat states are evaluated with the objective function. It consists of the criteria introduced in Subsection 3.2.3, a cost-to-go function as well as on the changes of the phase of the Blue kill chain and its prevailing phase.

4.2.1 Decision and control variables

The decisions and their alternatives for Blue are represented with decision variables. The radar setting R_{set}^{Blue} is associated with a binary decision variable with 0 meaning the radar is on standby and 1 meaning the radar is on operate. Radar elevation $\boldsymbol{R}_{elev}^{Blue}$ is described with a vector containing three decision variables. These decision variables contain two values representing the angle between the upper and lower extreme of the radar cone and the aircraft longitudinal axis, respectively. The throttle setting T_{comm}^{Blue} is a decision variable and its feasible values are percentages of maximum power. The bank angle rate $\Delta\theta^{Blue}$ is a decision variable, which can have a value of $40°/s$ for either side or $0°/s$. Similarly, the pitch angle rate $\Delta\phi^{Blue}$ is a decision variable for which the possible values are $5°/s$ down, $0°/s$ or $8°/s$ up from the aircraft's point of view. The jammer setting J_{set}^{Blue} is described with a binary decision variable similarly to the radar setting, i.e., its feasible values are 0 for standby and 1 for operate.

For the search and target phases, all decision variables except the one regarding the missile launch are included. On the other hand, the engage phase has the missile launch decision variable M_{launch}^{Blue} but it is missing the decision variable regarding the radar setting. The missile launch decision variable is binary, i.e., it gets a value of 0 for hold and 1 for launch. The decision variables for every phase of the Blue kill chain and their feasible values are presented in Tables 4.1 and 4.2.

Table 4.1: Decision variables of Blue and their feasible values for the search and target phases of the Blue kill chain.

Subject	Variable	Feasible values
Radar setting	R_{set}^{Blue}	0, 1
Radar elevation	$\boldsymbol{R}_{elev}^{Blue}$	$[50°, 10°], [20°, -20°], [-10°, -50°]$
Maneuvering	T_{comm}^{Blue}	0%, 30%, 70%, 100%
	$\Delta\theta^{Blue}$	$-40°/s, 0°/s, 40°/s$
	$\Delta\phi^{Blue}$	$-5°/s, 0°/s, 8°/s$
Jammer	J_{set}^{Blue}	0, 1

Table 4.2: Decision variables of Blue and their feasible values for the engage phase of the Blue kill chain.

Subject	Variable	Feasible values
Radar elevation	$\boldsymbol{R}_{elev}^{Blue}$	$[50°, 10°], [20°, -20°], [-10°, -50°]$
Maneuvering	T_{comm}^{Blue}	0%, 30%, 70%, 100%
	$\Delta\theta^{Blue}$	$-40°/s, 0°/s, 40°/s$
	$\Delta\phi^{Blue}$	$-5°/s, 0°/s, 8°/s$
Jammer	J_{set}^{Blue}	0, 1
Missile launch	M_{launch}^{Blue}	0, 1

Overall, the decisions for Blue are represented with the following decision vectors. For the search and target phases of the Blue kill chain,

$$\boldsymbol{Y}_{search}^{Blue} = \boldsymbol{Y}_{target}^{Blue} = [R_{set}^{Blue},\ \boldsymbol{R}_{elev}^{Blue},\ T_{comm}^{Blue},\ \Delta\theta^{Blue},\ \Delta\phi^{Blue},\ J_{set}^{Blue}], \tag{4.19}$$

and for the engage phase,

$$\boldsymbol{Y}_{engage}^{Blue} = [\boldsymbol{R}_{elev}^{Blue},\ T_{comm}^{Blue},\ \Delta\theta^{Blue},\ \Delta\phi^{Blue},\ J_{set}^{Blue},\ M_{launch}^{Blue}]. \tag{4.20}$$

The decision making of Red is not evaluated with the MDH approach as it is designed to support the development of TTPs for Blue in this thesis. Therefore, the behavior of Red is controlled by control variables in the DM-CDA model. They remain constant until a change in the behavior of Red is desired, i.e., a missile launch or one of the maneuvers defined in Subsection 4.1.6 is required. The control variables and their initial values in the first air combat state are presented in Table 4.3.

Table 4.3: Control variables of Red and their initial values.

Subject	**Variable**	**Initialized values**
Maneuvering	T_{comm}^{Red}	60%
	$\Delta\theta^{Red}$	$0°/s$
	$\Delta\phi^{Red}$	$0°/s$
Missile launch	M_{launch}^{Red}	0

The control variables for maneuvering change according to the executed maneuver. The missile launch variable gets a value of 1 when a missile is launched by Red. The radar of Red is always on operate and its elevation is at $[20°, -20°]$. The jammer is always on standby. The control vector containing the control variables is

$$\boldsymbol{Y}^{Red} = [T_{comm}^{Red}, \Delta\theta^{Red}, \Delta\phi^{Red}, M_{launch}^{Red}]. \tag{4.21}$$

4.2.2 End state conditions

The end state conditions are first defined for each phase of the Blue kill chain. In addition, the engage phase and the whole air combat scenario adhere to the same end state conditions. That is, when the end state conditions of the engage phase are met, the air combat scenario ends.

For the kill chain of Blue to progress from the search phase to the target phase, the end state conditions are $P_d^{Blue} > 0.75$ and Red inside the radar search cone of Blue. For progressing from the target phase to the engage phase, the end state condition is accomplished when Blue is in the LAR. Finally, for the engage phase, and thus for the air combat scenario, the end state conditions are met when Red is destroyed and the missiles of Red are evaded.

Similar end state conditions as discussed above apply also for the phases of the live chain of Blue from the perspective of Red. The Blue live chain progresses from the deny search phase to the deny target phase when Red finds Blue with the radar, i.e., $P_d^{Red} > 0.75$ and Blue is inside the radar search cone of Red. Further progression to the deny engage phase occurs when Red reaches its LAR. The end state conditions for the deny engage phase are satisfied when Blue is destroyed by a missile of Red. Then, the air combat scenario also ends regardless of the kill chain phase of Blue.

It should be noted that when Blue is turning away from Red during the out maneuver, Blue loses the radar track of Red eventually. Consequently, the kill chain of Blue reverts to the search phase. Even though the Blue kill chain is in the search phase at that time, the end state conditions of the engage phase are still considered. The decision to initiate the out maneuver is made to deny Red from launching and deliver a missile to Blue while Blue is still in the engage phase. Therefore, it is sensible to consider the end state conditions of the engage phase until the missiles of Blue and Red have either intercepted their respective targets or run out of energy.

4.2.3 Time evolution of the air combat state

The air combat state describes the air combat scenario at every time step. The state progresses in discrete time instants $t_n = n\Delta t$, where n is the time step and Δt a constant time interval between two time steps. The time step n gets values $0, 1$, ..., N, where N is the time step of the final air combat state. The final time $T = N\Delta t$ is free and determined by the end state conditions. The states of Blue and Red and their radars and jammers, the phases of the Blue kill and live chains and the states of any launched missiles are included in the air combat state. Hence, the air combat state is defined as follows

$$\begin{aligned} \boldsymbol{Z} = [&\boldsymbol{X}^{Blue}, \boldsymbol{X}^{Red}, S^{Blue}_{radar}, S^{Red}_{radar}, S^{Blue}_{jammer}, \\ &S^{Red}_{jammer}, K^{Blue}, L^{Blue}, \boldsymbol{M}^{Blue}_j, \boldsymbol{M}^{Red}_j], \end{aligned} \tag{4.22}$$

where j is the sequence number of the launched missile. The variables K^{Blue} and L^{Blue} represent the phases of the kill and live chains of Blue. The feasible values for K^{Blue} and L^{Blue} are 0, 1 and 2. They correspond to the search or deny search phase, the target or deny target phase and the engage or deny engage phase, respectively.

The evolution of the states of Blue and Red is computed by integrating the state equations (4.2) - (4.7) with the Euler method [49]. Let $\dot{\boldsymbol{X}}^i = f(\boldsymbol{X}^i, \boldsymbol{Y}^i)$, where $i =$ Blue, Red, represent the state equations. By applying the Euler method, the successive state at time step $n+1$ is obtained as

$$\boldsymbol{X}^i_{n+1} = \boldsymbol{X}^i_n + f(\boldsymbol{X}^i_n, \boldsymbol{Y}^i_n) \cdot \Delta t, \tag{4.23}$$

where n is the current time step. The integration is carried out with Blue's decision and Red's control variable values included in $\boldsymbol{Y}^i_n$. In addition, the states of the missiles of Blue and Red $\boldsymbol{M}^i_j$ are integrated similarly but with constant speed towards the target. Note that for the states of the radars and jammers, S^{Red}_{radar} and S^{Red}_{jammer} are constant and S^{Blue}_{radar} and S^{Blue}_{jammer} are updated by the corresponding decisions made by Blue. Similarly, the kill chain K^{Blue} and live chain L^{Blue} variables are updated at each time step when the end state conditions are evaluated.

In the solution procedure introduced in Section 4.3, future air combat states are generated up to a planning horizon length Δn for all combinations of Blue's decision variable values. That is, at each time step n, future air combat states are generated for $n+1, ..., n+\Delta n$ time steps with all possible values for the elements of $\boldsymbol{Y}_n^{Blue}$. As the time step progresses, the number of possible future states, represented by the decision tree, grows exponentially. An illustration of a generic growing decision tree for three different combinations of decision variable values is presented in Figure 4.4. The value combinations are represented by the numbers 1, 2 and 3 and the current time step by n.

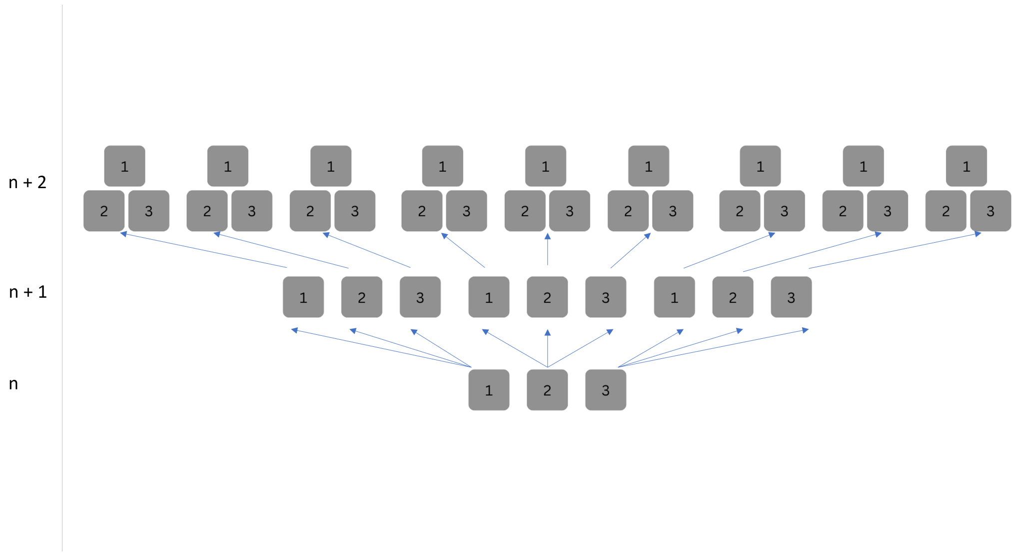


Figure 4.4: A growing decision tree for three different combinations of decision variable values (1, 2 and 3) where n represents the current time step and the planning horizon length is $\Delta n = 2$.

To counter the exponential growth of the number of possible states, a reduced decision tree is used. The possible combinations of the decision variable values are formed for time step $n+1$. Then, these value combinations are used to generate the states for time steps $n+2, ..., n+\Delta n$. Hence, the decision tree does not grow after $n+1$. The benefits and limitations of this mean are discussed in Section 4.5.

4.2.4 Objective function

The objective function $U_n(\boldsymbol{Z}_n, \boldsymbol{Y}_{phase,n}^{Blue})$ is used to identify the best values for the decision variables amongst the feasible values at time step n. It consists of a value function $V_n(\mathbf{Z}_{n+\Delta n})$, a penalty for the regression of the kill chain $P_n(\mathbf{K}^{Blue}_{n+\Delta n})$, a reward depending on the phase of the Blue kill chain $R_n(K^{Blue}_{n+\Delta n})$ and a cost-to-go function $C_{phase,n}(\boldsymbol{Z}_{n+\Delta T})$. $n+\Delta T$ is the time step at the end of the cost-to-go evaluation and *phase* corresponds to the prevailing phase of the kill chain of Blue. $\mathbf{K}^{Blue}_{n+\Delta n}$ is a vector containing the values of K^{Blue} at time steps $n, n+1, n+2, ..., n+\Delta n$. The objective function is formulated as follows

$$\begin{aligned} U_n(\boldsymbol{Z}_n, \mathbf{Y}^{Blue}_{phase,n}) = & W_V \cdot V_n(\mathbf{Z}_{n+\Delta n}) - P_n(\mathbf{K}^{Blue}_{n+\Delta n}) + \\ & R_n(K^{Blue}_{n+\Delta n}) + W_C \cdot C_{phase,n}(\mathbf{Z}_{n+\Delta T}). \end{aligned} \tag{4.24}$$

The value and cost-to-go functions are weighted with the weights W_V and W_C, respectively. They represent the relative importance between these functions. The weights get values between 0 and 1, and they sum up to 1.

The value function evaluates the air combat state at the end of the planning horizon, i.e., at time step $n+\Delta n$. It is a weighted sum of the criteria introduced in Subsection 3.2.3, i.e.,

$$V_n(\mathbf{Z}_{n+\Delta n}) = w_{d,n} \cdot P^{Blue}_{d,n+\Delta n} + w_{k,n} \cdot P^{Blue}_{k,n+\Delta n} + w_{c,n} \cdot P^{Blue}_{c,n+\Delta n} + w_{s,n} \cdot P^{Blue}_{s,n+\Delta n}. \tag{4.25}$$

The weights represent how each criterion is emphasized. The weights get values between 0 and 1, and they sum up to 1. The weights of the value function depend on the phases of the Blue kill and live chains. That is, certain weights are forced to have a value of 0 for certain combinations of the kill and live chain phases. The other remaining weights are adjustable. The weighting is presented in Table 4.4.

Table 4.4: The weights of the criteria in the value function for each combination of the phases of the Blue kill and live chains.

Kill chain	**Live chain**	**Weights forced to 0**	**Controllable weights**
Search	Deny search	w_k, w_s	w_d, w_c
Target	Deny search	w_d, w_s	w_k, w_c
Target	Deny target/ Deny engage	w_d, w_c	w_k, w_s
Engage	Deny search	w_d, w_s	w_k, w_c
Engage	Deny target/ Deny engage	w_d, w_c	w_k, w_s

The conventional usage of a value function includes the evaluation over all states of the planning horizon, i.e., at all time steps $n+1, n+2, ..., n+\Delta n$.

In this thesis, due to the nature of the planning problem of TTPs, only the state at time step $n + \Delta n$ is evaluated with the value function. However, in the intermediate states at time steps $n+1, n+2, ..., n+\Delta n-1$, the phase of the Blue kill chain is taken into account. If the kill chain reverts one phase at any time step during the planning horizon, the objective function is given a penalty of $P_n(\mathbf{K}^{Blue}_{n+\Delta n}) = 1$. If the kill chain reverts two phases, a penalty of $P_n(\mathbf{K}^{Blue}_{n+\Delta n}) = 2$ is given. In addition, a later phase of the kill chain is rewarded. If the kill chain at time step $n + \Delta n$ is in the target phase, the reward is $R_n(K^{Blue}_{n+\Delta n}) = 1$. In the engage phase, the reward is $R_n(K^{Blue}_{n+\Delta n}) = 2$. No reward is given in the search phase.

The idea of the penalties and rewards from the changes of the phase of the Blue kill chain is to ensure that the progression of the kill chain is always preferred by the decision suggestions. For example, assume that the kill chain is in the target phase at time step n. With a certain set of decision variable values, the air combat state evolves such that the kill chain reverts to the search phase by the end of the planning horizon. Due to the kill chain being in the search phase, the value function considers P^{Blue}_d instead of P^{Blue}_k in the evaluation of the state at time step $n + \Delta n$. Assume the objective function gives a value of 0.8 for the state at the end of the planning horizon. Then, by applying another set of decision variable values the kill chain stays in the target phase. This time the value function considers P^{Blue}_k in the evaluation and the objective function gets a value of 0.4. The state, where the kill chain is in the search phase, got a higher evaluation even though a later phase of the kill chain means that Blue is closer to achieving the overall goal of the mission, i.e., destroying Red. However, by applying the penalty of $P_n(\mathbf{K}^{Blue}_{n+\Delta n}) = 1$ for the regression of the kill chain back to the search phase, the objective function value decreases to -0.2. Consequently, now the air combat state, where the kill chain is in the target phase, has a higher value.

The penalty is useful also in another situation where the kill chain of Blue only briefly reverts a phase or two but then progresses again during the same planning horizon. In the real world, this could mean, e.g., that the radar track of Red was briefly lost and then re-acquired. Even though the kill chain would be in a desirable phase at the end of the planning horizon, a loss of the radar track is not preferred. Therefore, a penalty is applied to such cases. In addition, an expert might analyze the situation and conclude that the loss of the radar of Red does not significantly affect P^{Blue}_k or other relevant aspects of Blue. However, such a holistic view of the situation can not be obtained using only the objective function consisting of the value and cost-to-go functions. Such a view is enabled by the penalties and rewards that indicate the changes of the Blue kill chain phase during the planning horizon.

Lastly, consider a case where all combinations of the decision variables result in the same changes in the phase of the Blue kill chain. Even then, the obtained values of the objective function are comparable because they all get the same penalty and reward. The differences in the values of the objective function are then caused by the value function whose value depends on the criteria and their weights.

The cost-to-go function is used to calculate the cost associated with getting to the end state of the prevailing phase of the Blue kill chain from the current air combat state at time step n. Therefore, in the evaluation of the cost-to-go function, the end state conditions, defined in Subsection 4.2.2, are needed. Generally the value of the cost-to-go function is minimized, but in this thesis a larger value of the function is better.

In the evaluation of the cost-to-go function in the Blue search or target phases, the air combat state at the end of the evaluation at time step $n+\Delta T$ is calculated as follows. At time step n, the air combat states are generated $n+1, n+2, ..., n+\Delta T$ time steps into the future. The states of Blue and Red are integrated with their current velocities. Blue's decision variables and Red's control variables for states $n+1, n+2, ..., n+\Delta T$ are the same as at time step n. ΔT is the amount of time steps the evaluation is carried out into the future which has a sensible maximum value discussed in Section 4.3. If the end state conditions for the prevailing phase of the kill chain are met at a time step $n+\Delta T$, where ΔT is smaller than its maximum value, the generation of the states is stopped. Otherwise, the generation of the future states is continued until the maximum value ΔT.

The value of the cost-to-go function in the Blue search and target phases is mostly based on the time it takes to reach the end state. For the search phase, P_d^{Blue} is also considered. This way, the cost-to-go function evaluations get different values even if the end state conditions are not fulfilled. The cost-to-go function for the search phase is

$$C_{search}(\boldsymbol{Z}_{n+\Delta T}) = w_{ctg,\Delta T} \cdot \frac{1}{\Delta T} + w_{ctg,pd} \cdot P^{Blue}_{d,n+\Delta T}, \tag{4.26}$$

where $w_{ctg,\Delta T}$ and $w_{ctg,pd}$ are the weights. They get values between 0 and 1 and sum up to 1. The weights reflect the relative importance of the corresponding parts of the cost-to-go function.

Similarly for the target phase, the time taken to reach the end state conditions as well as P_k^{Blue} are considered. The cost-to-go function for the target phase is

$$C_{target}(\boldsymbol{Z}_{n+\Delta T}) = w_{ctg,\Delta T} \cdot \frac{1}{\Delta T} + w_{ctg,pk} \cdot P^{Blue}_{k,n+\Delta T}, \tag{4.27}$$

where, $w_{ctg,\Delta T}$ and $w_{ctg,pk}$ are the weights which again get values between 0 and 1 and sum up to 1.

The cost-to-go function evaluation for the Blue engage phase is different. The end state conditions for the engage phase are completed when Red is destroyed and the missiles of Red are evaded. However, the first concern of Blue, after reaching the engage phase, is to reach the conditions for a missile launch and consequently launch a missile against Red. These conditions are improved by increasing P_k^{Blue} which is achieved by flying closer to Red. However, the end state conditions also include evading the missiles of Red which suggests to increase the range to Red. Hence, the means for satisfying the end state conditions contradict each other if pursued simultaneously. During the generation of the future states of Blue and Red for the cost-to-go function evaluation, decisions of Blue are not changed from the ones at time step n. The end state conditions are unlikely to be reached in the engage phase of the Blue kill chain by implementing the same decisions of Blue. Therefore, the cost-to-go function is not evaluated in the engage phase, i.e., $C_{engage}(\boldsymbol{Z}_{n+\Delta T}) = 0$.

The feasible values of the cost-to-go functions are $[0, 1]$. In functions (4.26) and (4.27), the cost of the time taken to reach the end state conditions is calculated by $\frac{1}{\Delta T}$, i.e., less time is better. The effects of P_c^{Blue} and P_s^{Blue} are not included in the cost-to-go functions. They depend on the phases of the Blue live chain that can change during the generation of the future states. Thus, they are not considered.

4.3 Solution procedure

In this section, the solution procedure of the DMCDA model is introduced. The goal of the solution procedure is to find the best combination of the decision variable values for every time step based on the evaluation of the objective function. The combinations ultimately constitute the chained and state-dependent TTP. The solution procedure is managed by the DM who uses the MDH approach for supporting the development of TTPs for Blue. The solution procedure management includes adjusting the weights of the criteria (see Table 4.4) as well as modifying the decision suggestions provided by the solution procedure when necessary.

Step 1

The solution procedure starts by the initialization of the air combat state. The length of one time step n is chosen to be $\Delta t = 0.5$ seconds as a compromise between computational accuracy and time. The initial time step is fixed to $n = 0$. At $n = 0$, the air combat state $\boldsymbol{Z}_0$ is fixed. The threat presentation, i.e., the behavior of Red, is also fixed. The length of the planning horizon is chosen to be $\Delta n = 5$ as a compromise between the accuracy of the DMCDA model and the use of computational resources. This means that for every time step n the state predictions are made at steps $n+1, n+2, ..., n+5$ into the future. The cost-to-go function evaluation is decided to have a maximum length of $\Delta T = 100$ time steps, i.e., starting from time step n the evaluation may continue up to $n + 100$. This length is determined to be enough to see if Blue reaches the end state conditions of the prevailing phase of the kill chain. For example, assume that Blue and Red are at the same altitude of 20 000ft at a range of 45 nm from each other flying level at the speed of 400 knots towards each other. After 100 time steps ($\Delta t = 0.5$) the range between the aircraft is 31nm and P_d^{Blue} has increased from 0.07 to 0.74. In the target and engage phases, the changes happen quicker and thus $\Delta T = 100$ is selected. For discussion about the choices of assigning $\Delta t = 0.5$ and $\Delta n = 5$, see Section 4.5. After the initialization is complete, the DM can adjust the weights of the criteria of the value function (4.25) before continuing the solution procedure.

The weights of the value and cost-to-go functions in the objective function are fixed such that $W_V = 0.99$ and $W_C = 0.01$. The weights emphasize the value function more because of the rough approximations in the state predictions of the cost-to-go function. The weights in the cost-to-go functions (4.26) and (4.27) is such that $w_{ctg,\Delta T} = 0.9$, $w_{ctg,pd} = 0.1$ and $w_{ctg,pk} = 0.1$. The value of the cost-to-go function mainly depends on the time taken to reach the next phase of the Blue kill chain. Thus, the weights are assigned in a way that rewards quick progression of the Blue kill chain.

Step 2

When the DM decides to continue the solution procedure, the future air combat states are generated for the planning horizon. The states are predicted for every combination of decision variable values by the logic introduced in Subsection 4.2.3. Then, they are evaluated with the objective function (4.24) and ranked.

Step 3

After the generated future states are evaluated, the best combinations of the decision variable values are obtained. This combination is presented to the DM as decision suggestions. The DM then reviews the suggestions, and decides whether to implement them as decision of Blue or modify them. If the DM chooses to modify one or more values of the decision variables, the modifications are fixed. Then, future states, with the fixed modifications, are generated and ranked and the result is again presented to the DM. Once the DM is satisfied, the chosen combination of decision variable values is implemented only for the $n = n + 1$ time step.

Step 4

At time step $n + 1$, it is checked whether or not the end state conditions of the current phase of the Blue kill and live chains are met. If the kill chain is in the search or target phase, it progresses automatically to the next phase when the end state conditions are met. Same applies to the live chain regarding the deny search and deny target phases. After the progression to the next phase, the solution procedure is repeated from Step 2 for the time step $n + 1$. However, when the end state conditions of the engage or deny engage phase are satisfied, the air combat scenario ends. In addition, if the end state conditions of the prevailing phase of the kill or live chains are not reached, the solution procedure is repeated from Step 2 for the time step $n + 1$.

The DM can, at any time, also move backward to a previous air combat state. For example, the air combat state may progress into an unfavorable one with certain weights of the criteria. At that point, even though the DM can modify the decision variable values, there may not exist a combination of the values that produces a favorable outcome. Then, the DM can move backward to an earlier air combat state, adjust the weights of the criteria of the value function (4.25) and carry on from Step 2 of the solution procedure.

4.4 Graphical user interface

The MDH approach is controlled via a graphical user interface (GUI) by the DM. The GUI has two views; the air combat state view and the prediction view. The air combat state view is presented in Figure 4.5.

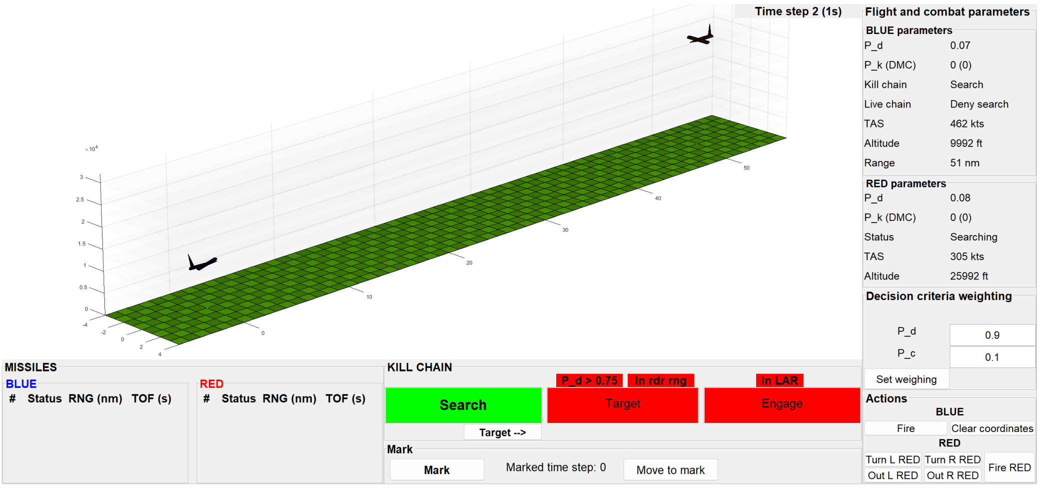


Figure 4.5: The air combat state view.

The air combat state view consists of four parts: the visualization of the aircraft (center), the flight and combat parameters panel (right), the missile bar (lower left) and the kill chain progress bar (lower middle). The visualization includes Blue and Red aircraft. The units are nautical miles (nm) for the horizontal axes and feet (ft) for the vertical axis.

The flight and combat parameters panel includes the current time step, the total time in seconds, the flight and combat parameters of Blue and Red, the objective function display and the action buttons for Blue and Red. The flight parameters consist of the altitudes in feet and velocities as true airspeeds (TAS) in knots (kts) of Blue and Red as well as the range between them in nautical miles. The combat parameters include P_d^i (probability of detection), P_k^i (probability of kill) and δ^i_{DMC} (DMC number) for $i =$ Blue, Red as well as K^{Blue} (phase of the Blue kill chain), L^{Blue} (phase of the Blue live chain) and the status of Red. The status of Red is "Searching" when Red has not yet found Blue, "Tracking" when Red has a radar track of Blue and "In LAR" when Red is in the LAR.

The objective function display includes the criteria of the current combination of the phases of the Blue kill and live chains as well as their respective weights in the value function. The weights can be modified by the DM who is using the GUI to develop TTPs for Blue. The action buttons are used to command Blue or Red. These buttons for Blue are "Fire" and "Clear coordinates". When "Fire" button is pressed, Blue launches a missile. The DM can use Matlab's data cursor feature to select coordinates from the visualization of the aircraft, towards which Blue starts maneuvering. "Clear coordinates" button is used to clear the selected coordinates. Consequently, Blue stops maneuvering towards the previously selected coordinates. The action buttons for Red are "Turn L RED", "Turn R RED", "Out L RED", "Out R RED" and "Fire RED". "Turn L RED" or "Turn R RED" buttons execute the turn maneuver to the left or right side for Red, respectively. When "Out L RED" or "Out R RED" is pressed, Red initiates the out maneuver to the left or right side, respectively. Red launches a missile, if "Fire RED" button is pressed.

The missile bar displays the following information for the launched missiles of Blue and Red: the sequence number, status, range to the target (RNG) and TOF. The sequence number starts from the missile that is first launched as one and continues on. The status can be either "Flying" for a missile still on the way to the target, "Lost" for a missile that did not intercept the target but lost all its energy or "Hit" for a missile that successfully intercepted the target. The range to the target is shown in nautical miles. TOF displays the current time of flight left for the missile. TOF is initially calculated by Equation (4.8) and then 0.5 seconds are subtracted from it at every time step until TOF is zero.

The kill chain progress bar displays information about the Blue kill chain. The green rectangle with bold text indicates the current phase of the Blue kill chain. The end state conditions of the previous phase are shown on top of the rectangles. Under the phase rectangles, there are buttons to fast forward to the next or go back to a previous phase of the kill chain. Fast forwarding to the next phase runs the solution procedure with the current weights of the criteria until the time step at which the end state conditions of the prevailing phase of the kill chain are met. During fast forwarding the prediction view is not shown to the DM. Therefore, the DM cannot adjust the weights of the criteria or make decisions for Blue. Going back to a previous phase of the kill chain loads the air combat state of the time step just before the kill chain progressed to the current phase.

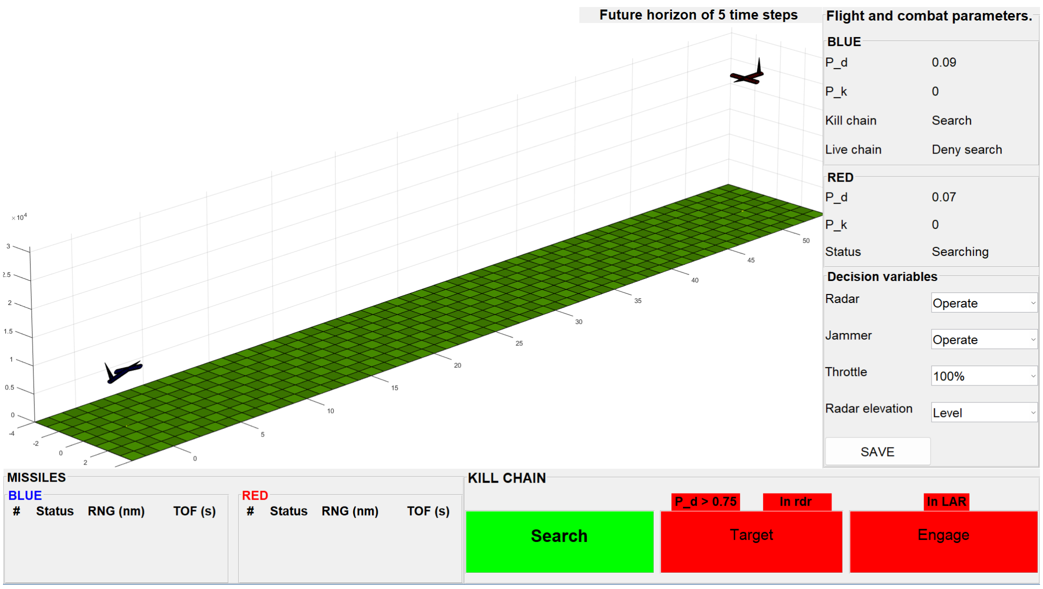


Figure 4.6: The prediction view.

The decision suggestions of the solution procedure are presented to the DM as depicted in Figure 4.6. The placement of features in the prediction view is similar to the air combat state view. The visualization is in the center, the flight and combat parameters panel is on the right, the missile bar is on the lower left and the kill chain progress bar on the lower middle part of the view. The visualization, the missile bar and the kill chain progress bar are similar to the air combat state view.

The flight and combat parameters panel shows P_d^i, P_k^i for $i =$ Blue, Red, and the current phases of the kill and live chain of Blue as well as the status of Red. Next below are the adjustable values of the decision variables: the radar setting, the jammer setting, the throttle setting and the radar elevation. The best combination of decision variable values according to the solution procedure, i.e., decision suggestions, is shown for the DM initially but they can be modified. If the DM changes any value of the decision variables and presses "Save" button, the solution procedure is carried out with the fixed modifications. Then, the best value combination according to the solution procedure corresponding to the changes of the DM is shown. However, in the engage phase of the kill chain of Blue, the radar setting cannot be modified.

Because the MDH approach is used as a support tool for the development of TTPs, the ability to manually modify the values of certain decision variables is important. Even though the solution procedure of the DMCDA model provides the DM with decision suggestions, she or he might disagree with the them. The model might miss a critical aspect of air combat that the DM can identify as a domain expert.

Parts of the DMCDA model and the GUI are hardcoded, i.e., they cannot be modified by the DM. Even though the rates for bank and pitch angles are decision variables, the DM cannot directly modify them. The possibility to adjust the maneuvering decision is implemented by allowing the DM to select coordinates towards which Blue starts flying. The calculations of P_d^i and P_k^i as well as the end state conditions for the progression of the Blue kill and live chains are also hardcoded.

4.5 Numerical considerations

This section considers key factors affecting numerical computations conducted with the solution procedure. The computations consist of the generation of the air combat states, the evaluation of them with the objective function and the air combat state approximation in the evaluation of the cost-to-go function. The runtime of the computations for the cost-to-go function evaluation is negligible ($<$0.01 seconds). On the other hand, the runtimes to compute the air combat states and the objective function values are significant, especially since the use of the moving planning horizon requires the generation and evaluation of a large number of states. Therefore, in terms of runtime, this section focuses on the factors affecting the computations of the states and their evaluation. In addition, the values of the penalty and reward of the objective function are considered in the end of this section.

One of the factors is the length of one time step. It determines how often the air combat state is updated. With a shorter length of one time step, the state is updated more frequently. Therefore, the precision of, e.g., maneuvering increases with the frequency of updates. However, the number of interactions with the MDH approach required from the DM also increases. The interactions require the DM to review decision suggestions provided by the solution procedure and control the weights of the criteria. Therefore, too frequent use of the GUI slows down the operation of the solution procedure. The chosen length of one time step is 0.5 seconds. With such a length the precision of the DMCDA model is high enough because it allows, e.g., for aggressive maneuvering to evade a missile. In addition, Blue's decision making every 0.5 seconds is enough to react to every observed action of Red. On the other hand, the operation of the DMCDA model is still manageable for the DM.

Another factor affecting the computations is the amount of air combat states that need to be generated. This amount depends on the number of decision variables and the number of their alternatives as well as on the length of the planning horizon which together constitute the decision tree. In this thesis, eight decision variables represent the most important decisions in air combat and all of them are needed. The length of the planning horizon is assigned to be $\Delta n = 5$. It is observed that when $\Delta n < 5$ the decision suggestions do not estimate the future events correctly enough. On the other hand, when Δn is increased, the runtime of the solution procedure also increases. Therefore, as $\Delta n = 5$ produces desired decision suggestions, it is not sensible to increase Δn any further.

The effect of the size of the decision tree on the runtime of the solution procedure is tested by first calculating the number of possible states for the eight decision variables and their alternatives when $\Delta n = 5$. The computations are carried out with a desktop PC which has an AMD Ryzen 7 5800 8-Core processor, NVIDIA GeForce GTX 3070 and 16GB of RAM. The number of states and the runtime for their computation for $\Delta n = 1, 2, ..., 5$ are presented in Table 4.5. The runtime for generating 432 future states for $\Delta n = 1$ is approximately 1.2 seconds. Consequently, to generate, e.g., all the future states for $\Delta n = 3$ takes already 224 000 seconds, i.e., 62 hours. Such a runtime is not practical for the DM when planning TTPs with the MDH approach. Thus, it is decided to use a reduced decision tree in which the possible combinations are formed only once. That is, 432 states are generated for all $\Delta n = 1, 2, ..., 5$. This way a horizon length of $\Delta n = 5$ corresponds to 2160 states. Consequently, the runtime of the solution procedure is approximately 6 seconds which is manageable for the DM. Even though the number of the states decreases significantly, decisions obtained with the solution procedure still allow Blue to maneuver in three dimensions, adjust power and use the systems of the aircraft. Therefore, there remains enough variety in the value combinations of the decision variables to produce adequate decision suggestions.

Table 4.5: The number of states and the runtime for their computation for different lengths of the planning horizon.

Length of planning horizon	**Number of states**	**Runtime (s)**
1	432	1.2
2	$19 \cdot 10^4$	520
3	$81 \cdot 10^6$	$22 \cdot 10^4$
4	$34 \cdot 10^9$	$97 \cdot 10^6$
5	$15 \cdot 10^{12}$	$42 \cdot 10^9$

Lastly, the reasoning behind the feasible values of the penalty and reward functions in the objective function (4.24) are explained. The value of the penalty function $P_n(\boldsymbol{K}^{Blue}_{n+\Delta n})$ is 0 if the Blue kill chain does not revert any phases, 1 if it reverts one phase and 2 if it reverts two phases during the planning horizon. On the other hand, the value of the reward function $R_n(K^{Blue}_{n+\Delta n})$ is 0 if the Blue kill chain is in the search phase, 1 if it is in the target phase and 2 if it is in the engage phase at the end of the planning horizon. Moreover, the weighted sum of the values of the value and cost-to-go functions in the objective function is 1 at maximum. The value of the penalty or reward function, when not 0, is larger than the sum of the value and cost-to-go function values. Therefore, a planning horizon of predicted future states with a penalty results in a worse objective function value than a prediction without a penalty. Similarly, a planning horizon with a reward gets a better objective function value than one without a reward. Thus, the values of the penalty and reward functions were chosen as stated previously.

Chapter 5

Utilization of the MDH approach

This chapter demonstrates the utilization of the MDH approach and its GUI for the development of TTPs. First, the problem for the demonstration is defined. Then, the DMCDA model and its solution procedure are demonstrated. After that, chained and state-dependent TTP rules are composed from the findings revealed during the demonstration. Finally, an example sensitivity analysis is conducted to find the feasible limits of the TTP rules determined in the demonstration. The air combat expert utilizing the MDH approach as a support tool in planning TTPs is still called the DM.

5.1 Definition of the TTP planning problem

The planning problem of a TTP in this demonstration includes a one versus one air combat scenario. The problem is to guide Blue to destroy Red, i.e., the TTP is planned for Blue. The air combat state is initialized as follows. Blue and Red have opposite headings and they are at a distance of 51 nm from each other. Blue is at an altitude of 10000 ft and Red at 26000 ft. Blue flies at the speed of 450 knots and Red at 300 knots. Both have approximate information of the position of each other in order to direct the radar search correctly. The capabilities of both aircraft include a radar, a jammer and four missiles.

The overall objective of Blue is to destroy Red while denying the progression of the Blue live chain. The end state conditions for the phases of the Blue kill and live chains are defined in Subsection 4.2.2. The specific conditions for a missile launch are dependent on the preferences of the DM. That is, the DM can order Blue to launch a missile provided that Blue is in the engage phase.

The threat presentation of Red is fixed. Red flies straight and level until a radar track of Blue and later the conditions for a missile launch are achieved. The radar of Red is always on operate and the jammer is on standby. Neither of the jammer settings significantly affect Blue. With the jammer on standby, the radar of Red detects Blue from a greater distance and thus the jammer of Red is kept on standby. Blue is considered to be found by Red when $P_d^{Red} > 75\%$ and Blue is inside the radar search cone of Red. Simultaneously, the live chain of Blue progresses to the deny target phase. Reaching the LAR is defined similarly for Red as for Blue, and it causes the live chain of Blue to progress to the deny engage phase. Red launches a missile when it achieves a DMC number of 15. After the missile launch, Red performs the out maneuver. Red also performs the out maneuver if the LAR is not reached within 75 consecutive time steps from finding Blue. This is due to increasing uncertainty of the behavior of Blue and the possible missile launch of Blue from the perspective of Red. 75 time steps equals approximately 38 seconds during which the air combat state can evolve unpredictably. The uncertainty increases risk, and therefore Red escapes the situation by performing the out maneuver after the 75 time steps.

Before the use of the MDH approach, decisions to be analyzed are reviewed. In this demonstration, chained and state-dependent TTP rules are to be identified to guide these decisions. They are expected to be identified at maximum for all the decisions included in the feasible combinations of the kill and live chain phases of Blue from which the state feedback is taken to the TTP rules. However, the progression of the air combat scenario in this demonstration dictates which combinations of phases are encountered. For example, the air combat state may never have the engage and deny search phases of the kill and live chains existing simultaneously. In such a case, no TTP rules are identified for the decisions of that combination. Objectives regarding each combination of the Blue kill and live chain phases and the decisions to be made to complete them are presented in Figure 5.1.

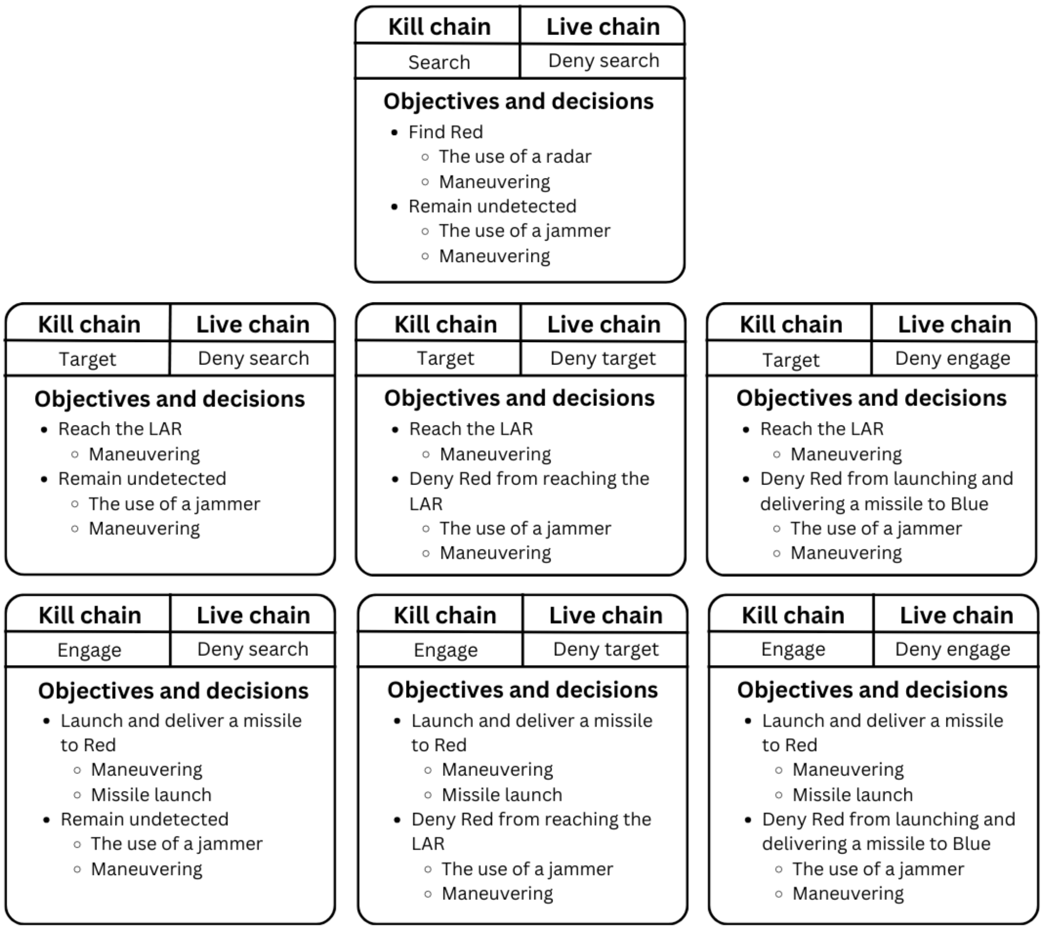


Figure 5.1: The combinations of the kill and live chain phases of Blue as well as their objectives and decisions considered in the demonstration.

5.2 Demonstration of the solution procedure

This section demonstrates the solution procedure for generating chained and state-dependent TTP rules for the decisions defined above. The procedure includes the DM operating the solution procedure of the DMCDA model and identifying the rules. It starts from the initialization. After the initialization, the flight and combat parameters are calculated correctly for time step 2 in the DMCDA model which is presented in Figure 5.2. The kill and live chains of Blue are in the search and deny search phases, respectively. As a reminder, the objectives of this combination of phases of Blue is to find Red with the radar and remain undetected by Red. The visualization in the center of the figure shows the separation in altitude and range between Blue and Red. In addition, it gives a visual overview of the evolving air combat state.

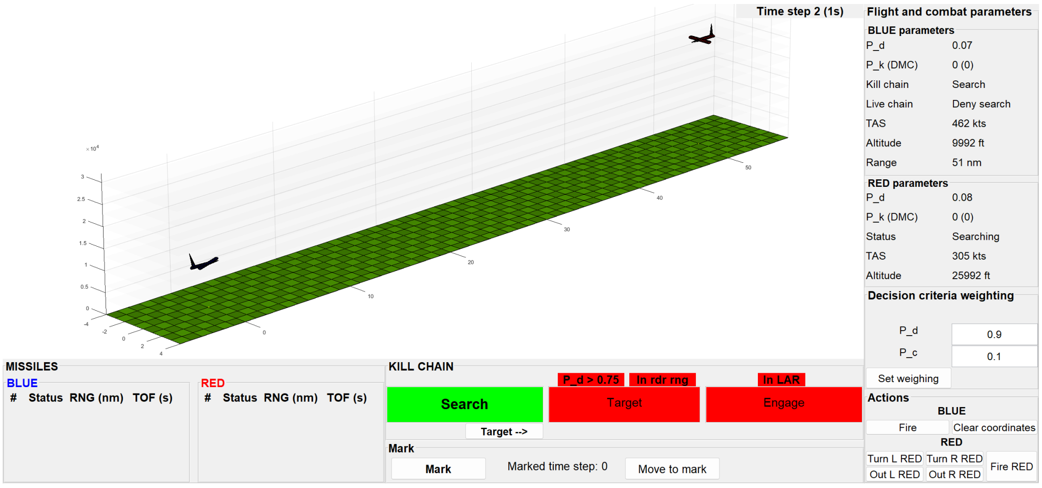


Figure 5.2: The air combat state view of time step 2 after the initialization.

5.2.1 Search phase

After the initial air combat state, the DM is presented with the suggested values for the decision variables in the prediction view, see Figure 5.3. The decision variables and their values are highlighted with a blue rectangle. The values for the decision variables are "Operate" for radar setting, "Operate" for the jammer, "100%" for the throttle and "Level" for the radar elevation. The DM is satisfied with the suggestions and decides to implement them. However, the end state conditions of the search phase are not met yet. Thus, the solution procedure is repeated at the next time step.

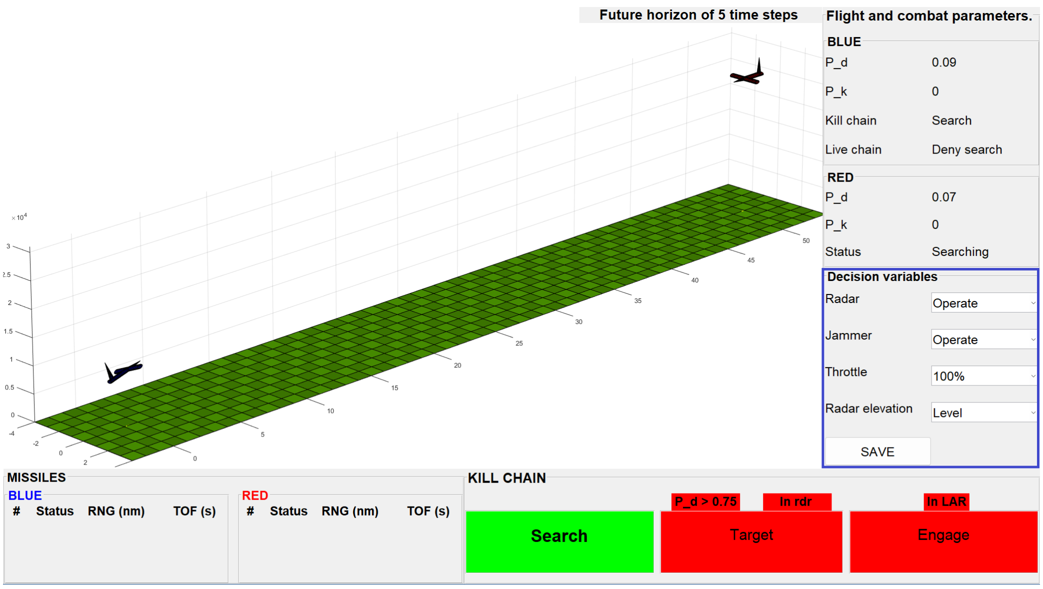


Figure 5.3: The prediction view with the decision variables and their values highlighted with a blue rectangle.

After moving forward ten more time steps, the DM notices that P_d^{Blue} is increasing and the flight path of Blue looks promising. Thus, the DM estimates that by continuing with the suggested decision variable values, Red is likely to be found. Therefore, TTP rules can be identified.

The TTP rules to be identified for the combination of the search phase of the Blue kill chain and the deny search phase of the Blue live chain are related to the use of a radar, maneuvering and the use of a jammer. A TTP rule for directing the radar search to increase the chance of finding Red are: "Keep the radar on operate and its search centered on the assumed location on the enemy". For maneuvering, a TTP rule states: "Maintain a fairly low altitude during the search phase". A low altitude decreases the chance of being found by Red. These rules are suitable for the corresponding air combat state in which Red flies straight and level at a medium altitude. That is, the TTP rules and rule values are state-dependent.

The jammer is kept on operate by the DM in the beginning of the air combat scenario. It can be kept on operate as a precaution to prevent Red from finding Blue. However, the DM notes that the setting the jammer on standby increases the detection range of the radar of Blue. The DM also anticipates that the decision suggestions obtained with the solution procedure take it into account when approaching the range from which Red can be found with the radar. The DM identifies a TTP rule and rule value stating "Set the jammer on standby to maximize the detection range of the radar".

After identifying the rules for the combination of the search and deny search phases, the DM decides to comply with the decision suggestions obtained. Thus, the DM fast forwards to the target phase of the Blue kill chain by pressing "Target –>" button on the kill chain progress bar.

5.2.2 Target phase

The fast forwarding stops at time step 122 when the end state conditions of the search phase of the Blue kill chain are met. The corresponding air combat state is presented in Figure 5.4. The kill chain progress bar in the figure shows the end state conditions of the search phase as green and that the kill chain of Blue is now in the target phase. However, the live chain of Blue is still in the deny search phase. Recall that the objectives of the combination of the target and deny search phases are to reach the LAR and to remain undetected by Red.

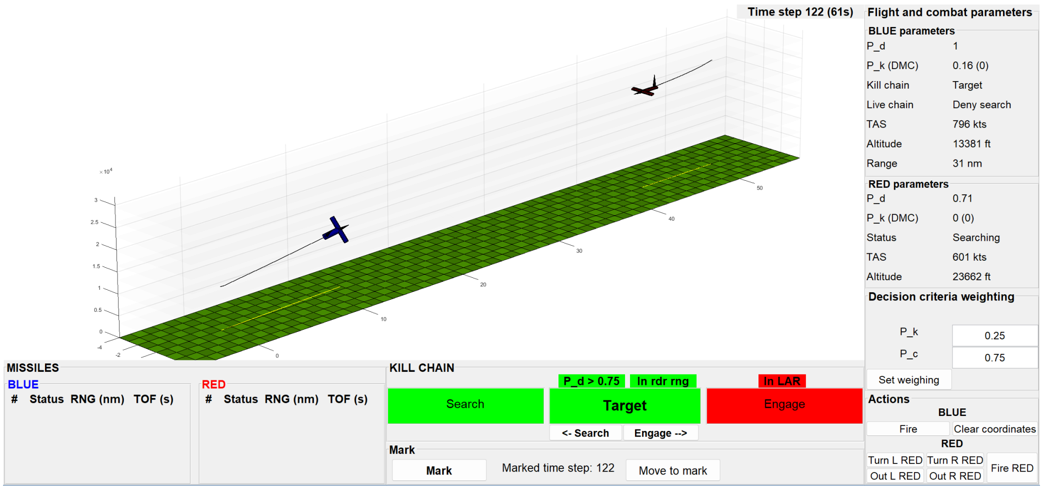


Figure 5.4: The air combat state view with the kill chain of Blue in the target phase.

Next, the DM focuses on the target phase. The DM chooses the weights of the criteria for the combination of the target and deny search phases of the Blue kill and live chains to be initially 25 % P_k^{Blue} and 75 % P_c^{Blue}. With these weights, remaining undetected by Red is prioritized. The DM marks the time step 122 in case of a need for a revisit. After that, the DM running the solution procedure to see whether the air combat state progresses in a favorable way or not. At time step 140, the live chain of Blue progresses to the deny target phase when Red finds Blue with the radar. Consequently, the criterion P_c^{Blue} switches to P_s^{Blue} and the objective from remaining undetected by Red to denying Red from reaching the LAR. However, the weight of P_s^{Blue} is kept at 75 %.

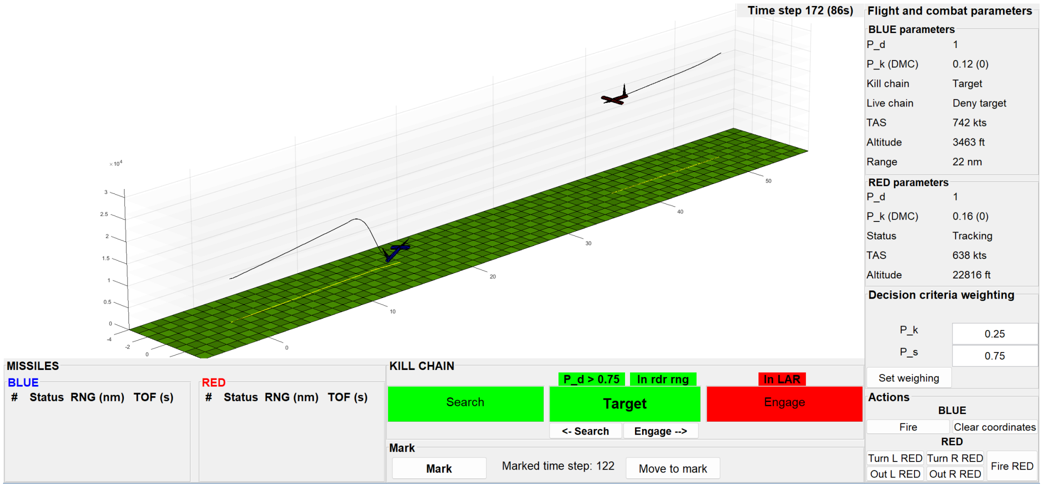


Figure 5.5: The kill chain of Blue in the target phase at time step 172 with the initial weights of the criteria.

A view of the air combat state at time step 172 is presented in Figure 5.5. The kill chain of Blue is in the target phase with $P_k^{Blue} = 12\%$ and the live chain in the deny target phase. The trajectory of Blue has drifted heavily downwards near the ground level, even though the LAR and a higher P_k^{Blue} are achieved faster with increasing altitude. This is due to the high weights of P_c^{Blue} at first and then of P_s^{Blue}, which cause Blue to maintain a low altitude. That is, at first, low altitude is maintained to remain undetected by Red and later to deny Red from reaching its LAR.

The benefit of using low altitudes is that P_k^{Red} has stayed fairly low at 16 %. This contributes to denying Red from reaching the LAR, which is currently one of the objectives. The DM identifies a TTP rule for the combination of the search and deny search phases of the Blue kill and live chains, respectively. It states that a low altitude is to be maintained to remain undetected by Red or preventing Red from reaching its LAR. However, only denying the live chain from progressing does not contribute to the other objective of maneuvering to reach the LAR. The DM is not satisfied with the direction Blue is maneuvering to and concludes that P_k^{Blue} needs more emphasis. Therefore, the DM goes back in the solution process to time step 122 using "Move to mark" button. The DM now changes the weights to 65 % for P_k^{Blue} and 35 % for P_c^{Blue} to prioritize reaching the LAR.

After adjusting the weights, the DM continues by repeating the solution procedure from time step 122. However, the DM notices that before adjusting the weights, the jammer of Blue was on standby, but after adjusting the weights the DMCDA model suggests to set the jammer on operate. The target range at this time is 31 nm, which is inside the operating range of the jammer (32nm). The DM decides to comply with the decision suggestion regarding the use of the jammer and set the jammer on operate for time step 123. P_d^{Red} decreased from 71% at time step 122 to 13% at time step 123 due to setting the jammer on operate. Blue now keeps the jammer on operate until time step 125 where it is again set on standby. Consequently, P_d^{Red} increases to 74%. The live chain progresses to the deny target phase at time step 126.

Blue sets the jammer on operate again for time step 127 which causes the live chain to revert back to the deny search phase. At time step 128, the jammer of Blue is again set on standby and the live chain progresses yet again to the deny target phase. The jammer is cycled between operate and standby a couple of times more but with no significant changes to the air combat state. Ultimately, the jammer is set on standby and the target phase of the kill chain of Blue is continued. The jammer of Blue significantly affects the detection capability of Red inside the operating range of the jammer. Thus, the DM identifies a TTP rule for the combination of the target and deny target phases of the Blue kill and live chains which state that the jammer should be set on operate when it does not break the radar track of the target.

The DM notices at time step 160, when the kill and live chains of Blue are in the target and deny target phases, that the trajectory of Blue is upwards and its nose pitched up, see Figure 5.6. With the initial weights, P_k^{Blue} at time step 172 was 12 %, whereas now it is 21 % already at time step 160. P_k^{Red} is also higher at 21 % because it depends on the altitude of Blue. Blue is, however, still climbing, and thus the DM can expect P_k^{Blue} to increase faster than P_k^{Red}.

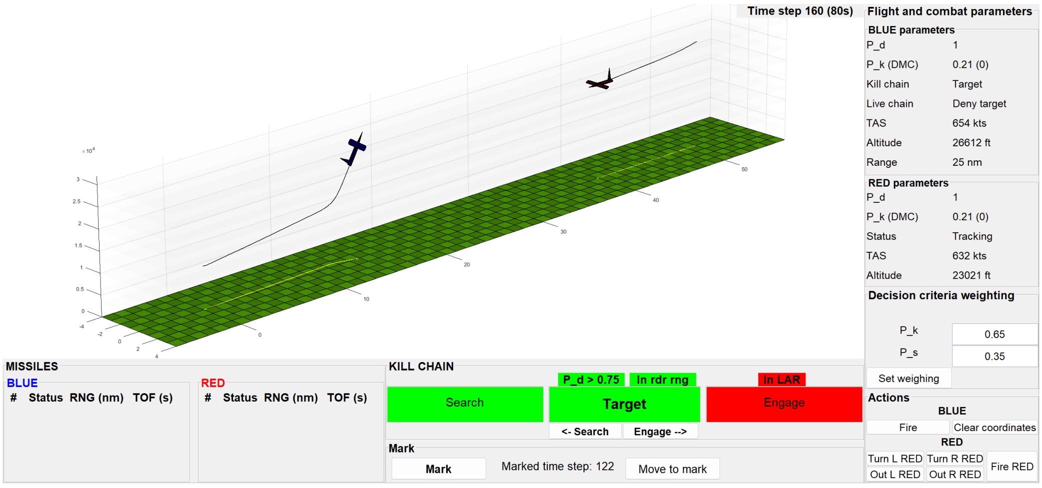


Figure 5.6: The kill chain of Blue in the target phase at time step 160.

A TTP rule for the combination of the target and deny target phases considering maneuvering to reach the LAR is to be found. The aggressively ascending maneuvering of Blue seems to increase P_k^{Blue} rapidly which contributes to reaching the LAR. Therefore, a TTP rule stating that as soon as the target is found at a medium altitude, a rapid climb while maintaining the radar track of the target is to be initiated. The aggressive climb of Blue allows Blue to increase P_k^{Blue} faster than P_k^{Red} increases. This causes the kill chain of Blue to progress to the engage phase faster than the live chain to the deny engage phase.

The rules and rule values for the prevailing combination of the phases are found and the DM is satisfied with the development of the air combat state. Thus, the DM decides to fast forward to the engage phase of the Blue kill chain and continue with the chosen weights of the criteria.

5.2.3 Engage phase

The kill chain progresses to the engage phase of the Blue kill chain at time step 168. The air combat state of time step 168 is presented in Figure 5.7. The trajectory of Blue is ascending aggressively. P_k^{Blue} has increased to 29 % and the DMC number to 15, i.e., it takes a 15 degree turn from Red to defeat a missile launched at that moment. The live chain of Blue is in the deny target phase. Note that P_k^{Red} has stayed at 21 %.

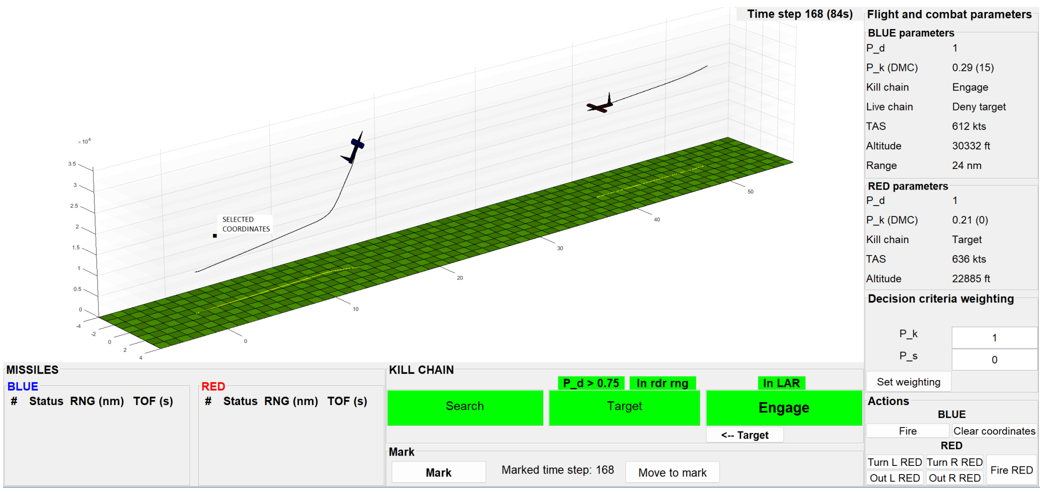


Figure 5.7: The kill chain of Blue has progressed to the engage phase.

The DM aims for a quick interception and decides to mark the time step 168. Blue is then ordered to launch a missile and perform the out maneuver. The out maneuver is performed by commanding Blue to fly to the coordinates presented in Figure 5.7. Blue now only tries to minimize the distance to the selected coordinates. Red continues to fly straight and level in the pursuit of the LAR.

The air combat state of the subsequent time step after the missile launch is presented in Figure 5.8. The missile launch panel shows that the first missile of Blue is flying. The range from the missile to the target is still 24 nm and the missile has 28.4 seconds of TOF left.

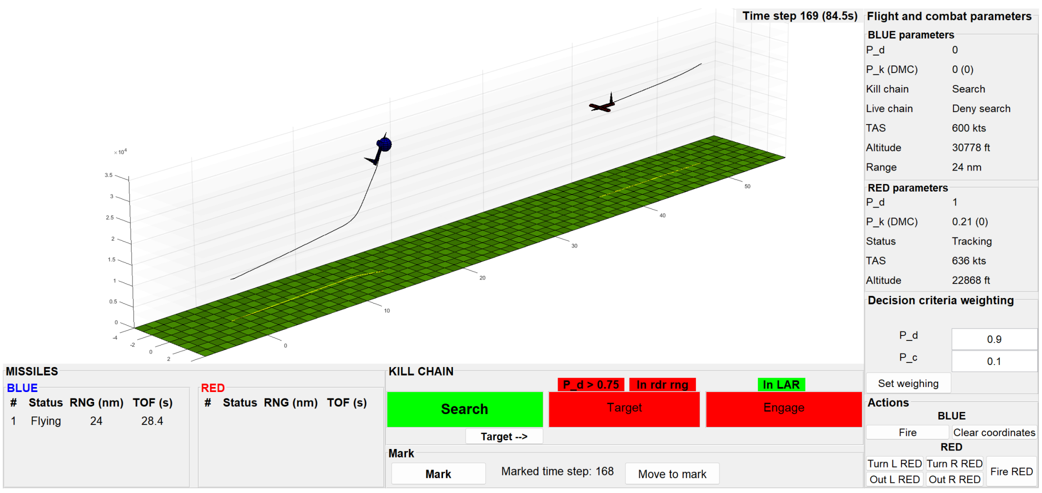


Figure 5.8: The subsequent time step after the missile launch of Blue.

At time step 201, the Blue live chain has stayed in the deny target phase for 75 consecutive time steps. Recall that it is the limit for Red for time spent after finding Blue without reaching the LAR. Hence, Red performs the out maneuver. The corresponding air combat state is presented in Figure 5.9. The figure shows that the missile of Blue has travelled roughly half of the distance required to reach Red. However, the missile still has 10 nm to go for the interception and only approximately 12 seconds of TOF left. The DM anticipates a lost missile due to Red performing the out maneuver.

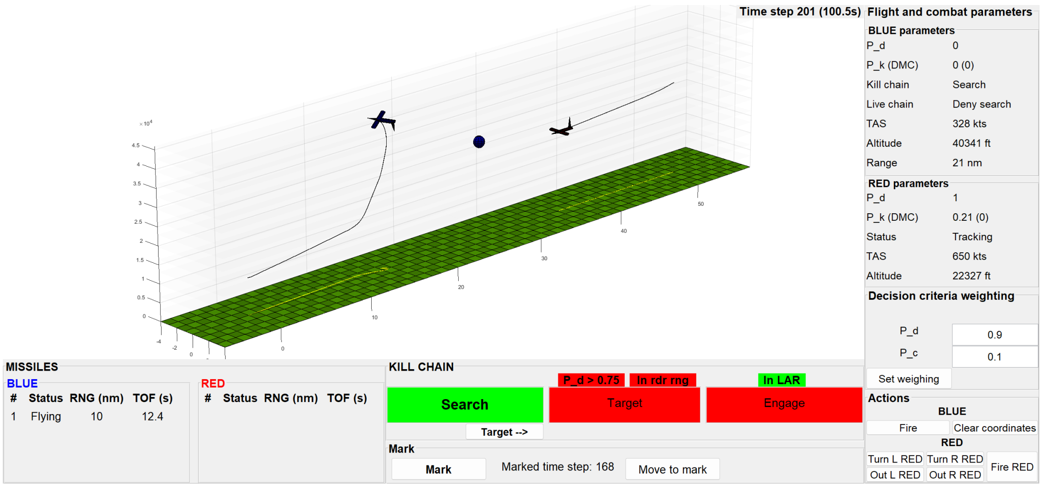


Figure 5.9: Red initiates the out maneuver.

At time step 225, the missile of Blue runs out of energy and is lost. The air combat state at this time step is presented in Figure 5.10. Red successfully evades the missile of Blue by performing the out maneuver. Red never reached the missile launch conditions and thus did not launch any missiles. The DM concludes that launching the missile as soon as Blue progresses to the engage phase does not produce a desired outcome. Red is able to evade the missile even though Red flies towards Blue for a while after the missile is launched. Hence, no TTP rules are identified. The DM now moves back to time step 168, where Blue reached the engage phase, to choose a different tactic. Recall that the air combat state of the time step 168 is presented in Figure 5.7.

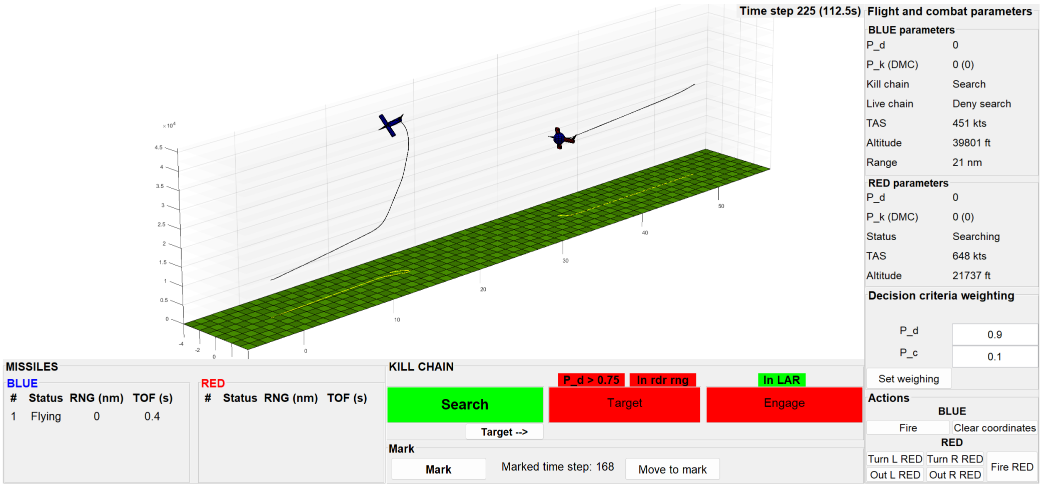


Figure 5.10: The missile of Blue has run out of energy.

The DM starts repeating the solution procedure again from time step 168 with the weights of P_k^{Blue} as 100 % and P_s^{Blue} as 0 %. The DM notices that the decision suggestion for the use of a jammer is to keep it on operate. It is sensible, because the jammer does not hinder the radar track of Red at such ranges anymore. Therefore, the DM identifies a TTP rule stating to keep the jammer on operate when flying towards the target in combination of the engage and deny target phases.

The air combat state at time step 194 is presented in Figure 5.11. Now, $P_k^{Blue} = 70\%$ and the DMC number $\delta_{DMC}^{Blue} = 115$. The live chain of Blue is in the deny target phase. The DM considers P_k^{Blue} and the DMC number to be acceptable for a missile launch when Red is flying straight towards Blue. The DM commands Blue to launch a missile and perform the out maneuver immediately after. Even though the current objective is to deny Red from reaching the LAR, the out maneuver is carried out also to evade any missiles launched later. The DM anticipates that Red reaches the LAR and possibly the conditions for a missile launch before Blue has turned to a cold aspect, i.e., 135 degrees or more away from Red.

Other aspects of interest besides P_k and the DMC number, in terms of the missile launch conditions, are the altitudes of the aircraft and the range between them. Blue has managed to climb above 40 000ft which is almost double the altitude of Red. This gives the missile of Blue much longer TOF when launched. The range between Blue and Red is 21 nm. Blue is flying at 490 knots whereas Red is flying faster at 647 knots. This difference in speed is due to Blue using energy to climb. The DM now identifies a TTP rule for the combination of the engage and deny target phases which states "Climb above 40 000ft for a missile launch". The prevailing target range of 21 nm seems appropriate for initiating the out maneuver. After the out maneuver is completed, the DM can assess whether the target range is enough in terms of denying Red from reaching the LAR or at least to evade a launched missile.

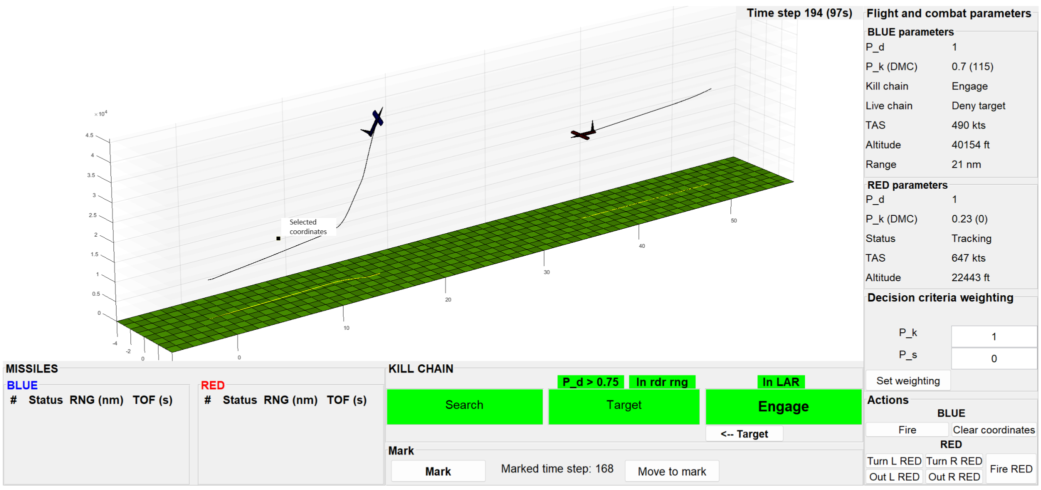


Figure 5.11: Blue launches a missile with a higher P_k^{Blue} compared to Figure 5.8.

The prediction view following the out command for Blue is presented in Figure 5.12. It shows the resulting air combat state when the value of the decision variable throttle is 0%. This is the best choice when minimizing the distance to the coordinates selected for the out maneuver. However, because of the domain expertise, the DM knows that maintaining kinetic or potential energy is crucial in air combat. Thus, the DM decides to overrule the suggested decision and select the throttle to 100%. The decision variables, their values and the corresponding air combat state with throttle selected to 100% are presented in Figure 5.13. Note by comparing Figures 5.12 and 5.13 that adjusting the throttle does not significantly alter the resulting air combat state. However, the cumulative effect of keeping the throttle at 100% instead of 0% for many consecutive time steps has a significant effect on the total energy of the aircraft.

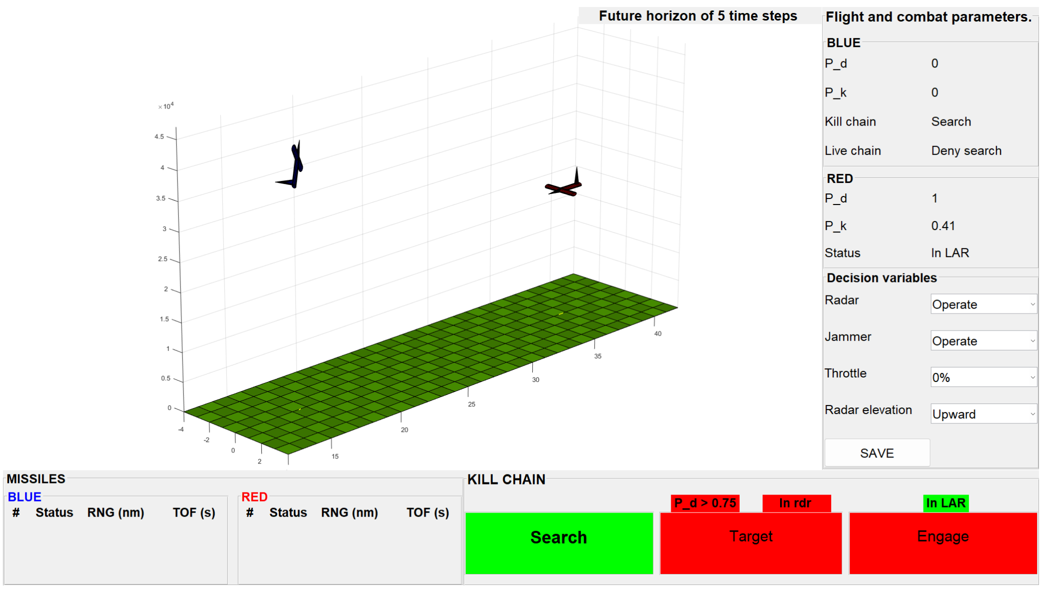


Figure 5.12: The prediction view when Blue is performing the out maneuver with throttle at 0%.

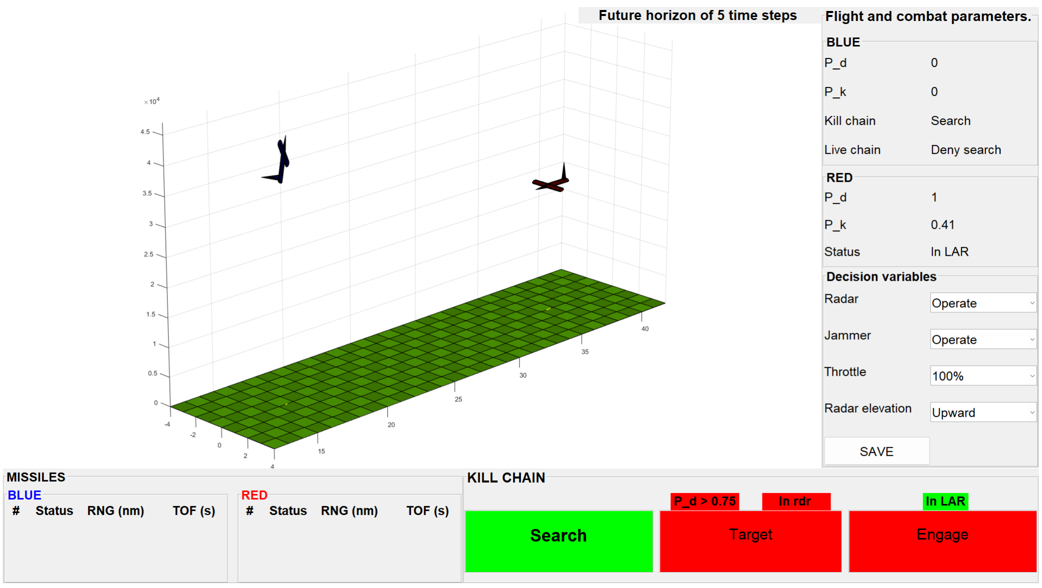


Figure 5.13: The prediction view when Blue is performing the out maneuver with throttle 100 %.

Shortly after the missile launch of Blue, at time step 197, the Blue live chain progresses to the deny engage phase. Consequently, at time step 199, Red reaches the conditions for a missile launch, launches a missile and initiates the out maneuver via a right turn. Blue continues its out maneuver. The air combat state at the time of the missile launch of Red is presented in Figure 5.14. The figure shows the missile of Blue flying towards Red with 19nm to go and approximately 34 seconds of TOF left.

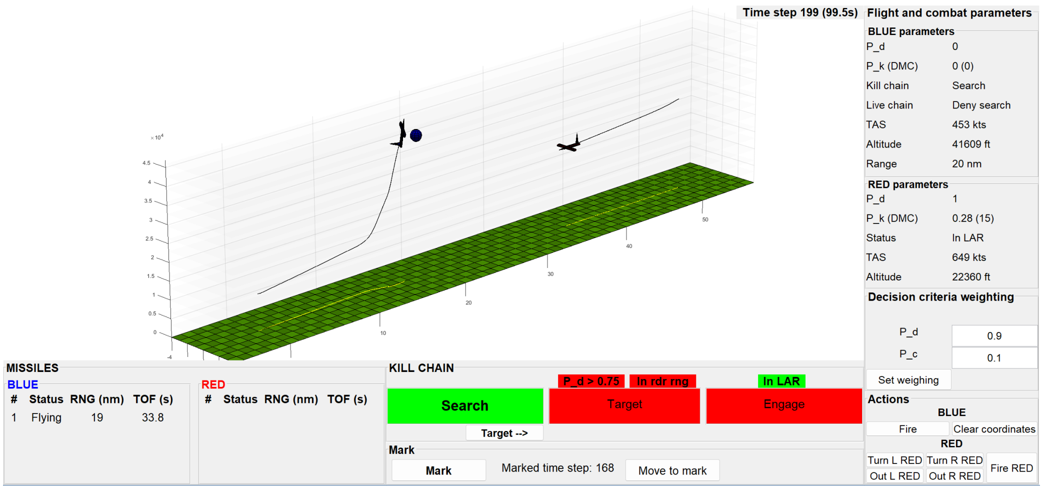


Figure 5.14: Red launches a missile.

The missile of Blue successfully intercepts Red at time step 251. The corresponding air combat state is presented in Figure 5.15. The missile of Red is still flying towards Blue at the distance of 2nm from Blue. However, as Blue is flying away from the missile and it has only 2 seconds of TOF left, the DM expects Blue to be able to evade the missile.

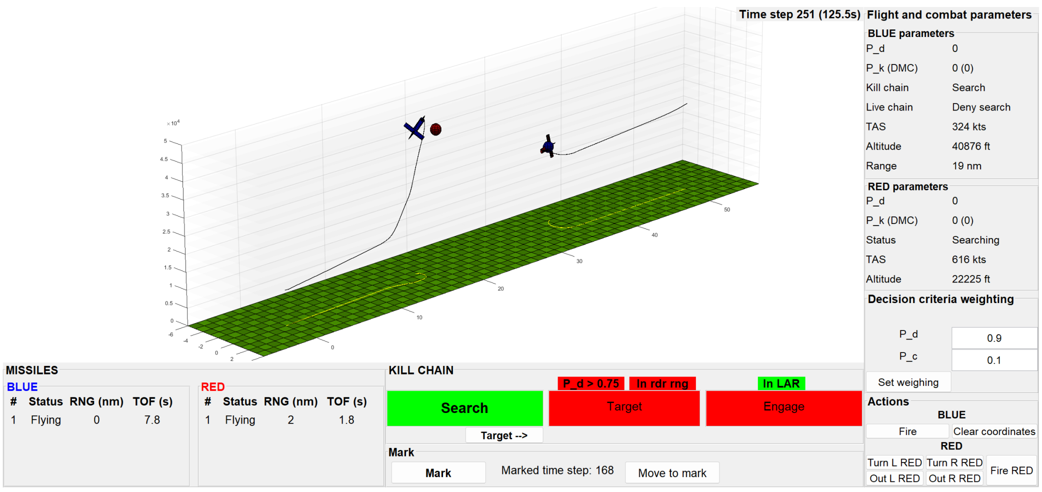


Figure 5.15: The missile of Blue intercepts Red.

The missile of Red is lost at time step 255. The air combat state before the missile is lost is presented in Figure 5.16. Hence, Blue manages to evade the missile launched by Red. However, the range between the missile and Blue is only 1 nm just before the missile runs out of energy. This implies that the range of 21 nm, at which Blue initiated the out maneuver, is just enough to defeat the missile when Red is at a medium altitude of approximately 20 000ft heading towards Blue. Thus, the DM concludes that a TTP rule for the engage and deny target phases of the kill and live chains "Initiate the out maneuver no later than 21 nm when the target is heading towards Blue at medium altitude" is appropriate. All the TTP rules for the combination of the engage and deny target phases are now found. As Blue successfully destroyed Red and managed to stay alive, the air combat scenario analyzed in the demonstration is completed.

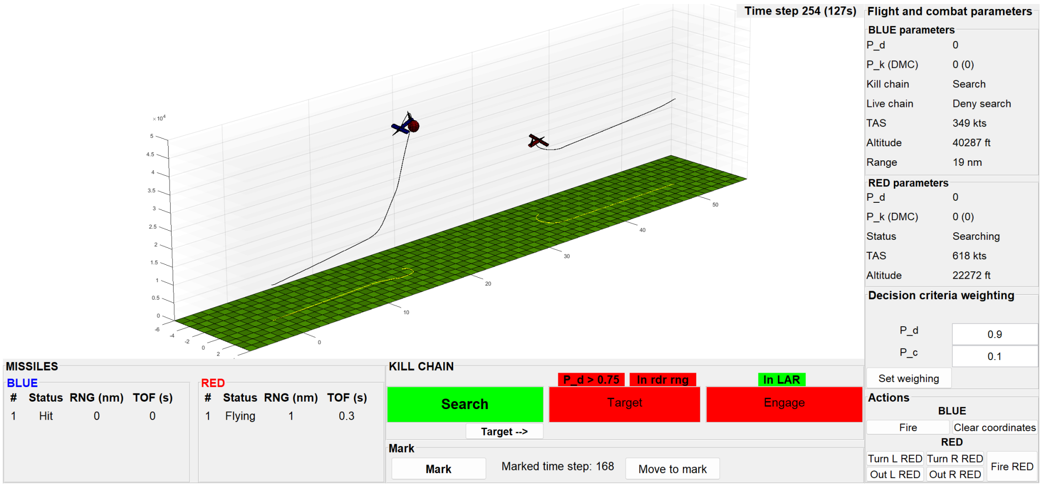


Figure 5.16: The missile of Red is lost.

5.3 Composition of the TTP

In this section, the TTP rules are summarized according to the results of the solution procedure obtained in Section 5.2. In addition, a complete TTP is formed. The rules are related to the decisions presented in Section 5.1. Recall that they are to be identified only for the combinations of the Blue kill and live chain phases that are encountered during the demonstration. These combinations are essentially the search and deny search phases, the target and deny target phases as well as the engage and deny target phases. In addition, the combination of the target and deny search phases briefly exists, and it is also considered.

5.3.1 Search and deny search phases

TTP rules need to guide the decision making of Blue towards finding Red and remaining undetected by Red in the search phase. The decisions considered by the rules are the use of a radar, maneuvering and the use of a jammer. The identified rules for the use of the radar are to keep it on operate and keep the radar search centered on the assumed position of the target. These rules contribute to finding Red. For maneuvering, the rule is to maintain a low altitude during the search phase in order to remain undetected. The TTP rule identified for the use of a jammer states that it is set to standby when the goal is to maximize the detection range of the radar.

5.3.2 Target and deny target phases

When the kill chain of Blue is in the target phase, the live chain is at first briefly in the deny search phase but mostly in the deny target phase. The decisions are made in order to reach the LAR and to deny Red at first from detecting Blue and later from reaching its LAR. The decisions that affect the completion of these objectives the most are maneuvering and the use of a jammer. An identified TTP rule for maneuvering to reach the LAR is to climb rapidly while tracking the target with the radar after progressing to the target phase. On the other hand, another identified rule for maneuvering for denying the progression of the live chain is to maintain a low altitude. The latter rule applies to both the deny search and deny target phases of the Blue live chain. Climbing and maintaining a low altitude, however, contradict each other and a compromise is made in terms of the rules based on the objectives. That is, when offense is prioritized more than defense, Blue should climb aggressively.

A TTP rule considering the use of a jammer is identified. The rule states that the jammer is set on operate inside the effective range of the jammer, i.e., 32nm whenever it does not interfere with tracking Red with the radar. Setting Blue's jammer on operate hinders the performance of Blue's radar and doing so too early may result in losing the track of Red.

5.3.3 Engage and deny target phases

TTP rules for the combination of the engage and deny target phases need to address the objectives of launching and delivering a missile to Red as well as denying Red from reaching its LAR. The decisions to be made to achieve the objectives are maneuvering, a missile launch and the use of a jammer. For maneuvering, an identified rule is to continue to prioritize P_k^{Blue} in order to reach the missile launch conditions, i.e., to keep climbing towards Red.

To prevent Red from reaching its LAR, a rule is to initiate the out maneuver immediately after the missile launch. The out maneuver is carried out with a steep turn and full throttle. In addition, a rule is found which states that the minimum target range, at which the out maneuver is initiated, is 21 nm. It is the minimum range from which Blue is still able to evade a missile launched by Red but not for denying Red from reaching the LAR or the conditions for a missile launch. The rule assumes that Red is at medium altitude heading towards Blue and Blue is at medium or high altitude. The out maneuver initiated at a target range of 21 nm ends with the loss of the missile of Red at a distance of approximately 1 nm from Blue. Hence, 21 nm allows Blue to evade the missile of Red.

For the missile launch, an identified rule states that a missile is launched at the earliest when $\delta_{DMC}^{Blue} = 115$ and $P_k^{Blue} = 70\%$ are achieved. The rule applies when Red is flying straight towards Blue. These conditions provide the missile of Blue enough energy, i.e., TOF, to intercept Red. In addition, the missile intercepts Red with 7.8 seconds of TOF left. This means that even if Red performs a more aggressive out maneuver, the missile of Blue still has a chance of intercepting Red.

A TTP rule for the use of a jammer which dictates that it should be kept on operate when flying towards the target. Keeping the jammer on operate at the ranges inside the LAR does not hinder with the radar track. However, the jammer still decreases the detection range of Red and thus it is sensible to keep on operate.

5.3.4 Complete TTP

The complete TTP can now be formulated based on the rules identified in the different phases of the Blue kill and live chains. The TTP is presented in Figure 5.17.

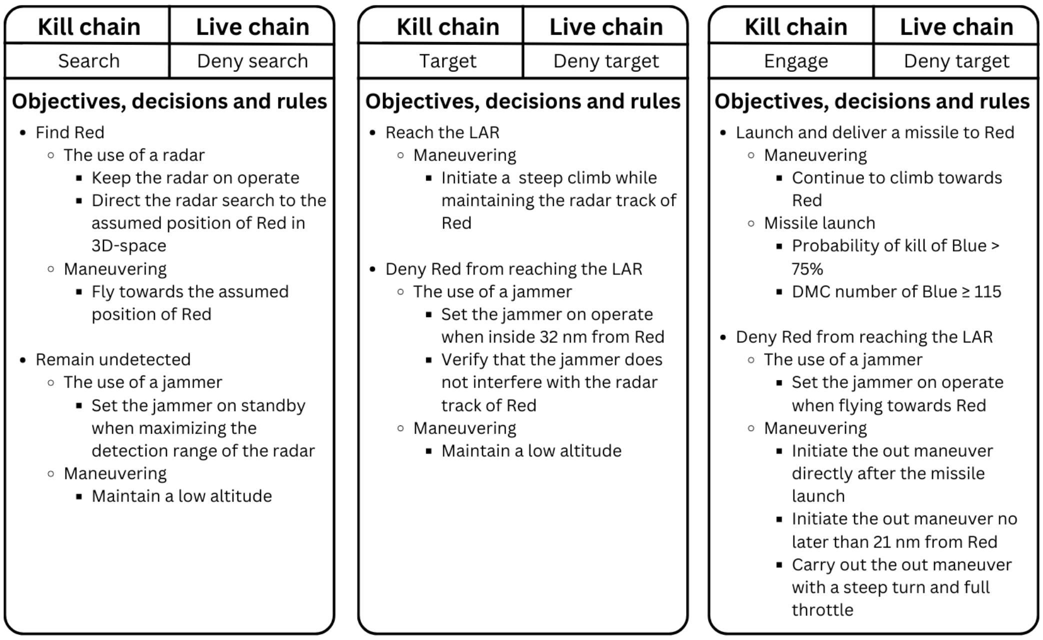


Figure 5.17: The objectives, decision and identified TTP rules for the combinations of the Blue kill and live chain phases considered in the demonstration of the MDH approach and its GUI.

5.4 Sensitivity analysis

This section demonstrates how a sensitivity analysis can be carried out in the development of TTPs. The TTP formulated in Section 5.3 is used as a reference TTP and the original air combat scenario as a reference scenario. The goal of the sensitivity analysis is to find out how much the threat presentation of Red can be varied and still achieve desirable outcomes with the reference TTP. The threat presentation, i.e., the initialization and behavior of Red, is modified in terms of three factors: altitude, target range and conditions for a missile launch. All other aspects remain the same as in the reference scenario. The variation of the altitude means initializing Red with a different altitude than in the reference scenario which Red approximately maintains. Similarly, the target range variation affects the initial range between Blue and Red. Lastly, the conditions for a missile launch are varied in terms of the DMC number at which Red launches a missile. All of the factors have three alternatives. The variations adhere to the real-life air combat conventions. For example, the maximum sensible variation of the altitude is to increase is up to 45 000ft, because that is around the maximum altitude used in air combat.

There are certain key events in the air combat scenario that the sensitivity analysis focuses on. The key events are the progressions of the kill and live chains of Blue, the missile launches and the status changes of the missiles as well as the out maneuvers. By the variation of the aforementioned factors in the threat presentation of Red, the limits of the reference TTP are identified with respect to the key events. That is, findings, such as changes in the time steps of the progression of the Blue kill chain or the ability of Blue to evade the missiles of Red, determine the limits.

The example sensitivity analysis is a simplification. In general, a sensitivity analysis should include more frequent variation for the selected factors. For example, the altitude of Red could be increased 500ft at a time until the reference TTP fails or until a sensible maximum altitude is reached. Now, the sensitivity analysis considers only three alternatives of each factor and is thus similar to a what if -analysis. However, the sensitivity analysis is carried out to demonstrate how and why such an analysis should be utilized in the development of TTPs.

5.4.1 Variation of altitude

The altitude of Red in the beginning of the reference air combat scenario is 26 000 ft. The altitude alternatives 5000ft, 35000ft and 45000ft are referred to as low, high and very high. For every alternative, the search phase of the Blue kill chain progresses similarly. It is sensible because Blue only directs the radar at the favorable search point and waits until Red is found. However, the time step at which Blue reaches the target phase occurs later as the altitude increases.

The key events and their respective time steps of occurrence of the low altitude alternative are presented in Table 5.1. When the initial altitude of Red is low, Blue progresses to the target phase at time step 117. Furthermore, Blue progresses to the engage phase at time step 185 while the Blue live chain is still in the deny target phase. Due to the low altitude of Red, Blue has the advantage in terms of TOF of the missile. Red initiates the out maneuver at time step 197 due to the limit of 75 consecutive time steps without reaching the LAR after finding Blue with the radar. Blue launches a missile at time step 208 which intercepts Red at time step 263. The progress of the air combat scenario, with the initial altitude of Red being low, is similar to the reference scenario, but more advantageous for Blue. Blue climbs to an altitude significantly higher than Red. Thus, Blue is able to launch the missile and perform the out maneuver before Red manages to escape. Therefore, the reference TTP performs well when Red starts at a lower altitude.

Table 5.1: The key events and their time steps of occurrence when the initial altitude of Red is 5kft. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Key event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the target phase	117	122
The live chain of Blue reaches the deny target phase	122	126
The kill chain of Blue reaches the engage phase	185	168
Red initiates the out maneuver	197	199
Blue launches a missile	208	194
The missile of Blue intercepts Red	263	251

Table 5.2 shows the key events of the high altitude alternative and their time steps at which they occur. For this alternative, the progress of the Blue kill and live chains is similar to the low altitude scenario up to time step 171. At that time, the live chain of Blue progresses to the deny engage phase and Red launches a missile as well as initiates the out maneuver. Blue continues to maximize P_k^{Blue} in the engage phase until the time step 185 at which Blue launches a missile. Both Blue and Red manage to evade the missiles of each other with the out maneuvers. The missile of Red is lost at time step 234

and the missile of Blue at time step 255. The higher altitude, compared to the reference scenario, gives Red now a slight advantage in terms of TOF of the missile. Hence, Red launches the missile and initiates the out maneuver earlier leading to Red being able to evade the missile of Blue. The TTP is thus not able to produce a desired outcome when the altitude of Red is 35kft. However, the outcome is not preferable from the perspective of Red either, because Blue evades the missile of Red. The outcome is thus deemed neutral, i.e., not preferable for either Blue or Red.

Table 5.2: The key events and their time steps of occurrence when the initial altitude of Red is 35kft. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the target phase	124	122
The live chain of Blue reaches the deny target phase	132	126
The kill chain of Blue reaches the engage phase	166	168
The live chain of Blue reaches the deny engage phase	171	197
Red launches a missile	172	199
Blue launches a missile	185	194
The missile of Red is lost	234	255
The missile of Blue is lost	255	-

The very high alternative is analyzed in order to see if Red is able to intercept Blue with a missile. Table 5.3 presents the key events of the high altitude alternative along with the time steps of their occurrence. At time step 153, Red launches a missile and initiates the out maneuver, while the kill chain of Blue is still in the target phase. However, Blue progresses to the engage phase at time step 154 and launches a missile at time step 176. Again, both aircraft evade the missiles of each other. Therefore, the reference TTP manages to produce a neutral outcome even if Red starts at a significantly higher altitude than Blue.

Table 5.3: The key events and their time steps of occurrence when the initial altitude of Red is 45kft. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the target phase	127	122
The live chain of Blue reaches the deny target phase	132	126
The live chain of Blue reaches the deny engage phase	152	197
Red launches a missile	153	199
The kill chain of Blue reaches the engage phase	154	168
Blue launches a missile	176	194
The missile of Red is lost	225	255
The missile of Blue is lost	245	-

5.4.2 Variation of target range

Blue and Red started 51nm apart in the reference air combat scenario. The range alternatives are labeled as long, medium and short, and their initial target ranges are 70nm, 30nm and 15nm.

For the long alternative, the key events and their time steps of occurrence are presented in Table 5.4. The flight path of Blue in the search phase of the Blue kill chain is similar to the reference scenario but it takes up to time step 211 for the kill chain of Blue to progress to the target phase. After that the progress continues as in the reference scenario. That is, Red initiates the out maneuver at time step 296 where the live chain of Blue is in the deny target phase. A missile that Blue launched earlier intercepts Red at time step 325. The longer initial range thus does not affect the performance of the reference TTP.

Table 5.4: The key events and their time steps of occurrence when the initial range between Blue and Red is 70nm. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the target phase	211	122
The live chain of Blue reaches the deny target phase	221	126
The kill chain of Blue reaches the engage phase	262	168
Blue launches a missile	273	194
Red initiates the out maneuver	296	199
The missile of Blue is lost	325	-

Table 5.5 presents the key events of the medium range alternative and the time steps at which they occur. The initial range is now shorter compared to the reference scenario. The target phase of the Blue kill chain as well as the deny target phase of the Blue live chain are reached significantly earlier. The kill chain progresses to the engage phase already at time step 93. The live chain also progresses to the deny engage phase. At time step 123 and consequently Red launches a missile as well as initiates the out maneuver. Blue follows with a missile launch and out maneuver at time step 126. However, the missile of Red is lost at time step 178 whereas the missile of Blue intercepts Red at time step 186. Even though the outcome of the scenario is desirable for Blue, Red performed seemingly better than in the long alternative. That is, the live chain of Blue reached the deny engage phase and Red launched a missile. It seems that the shorter initial range favors Red and might cause the reference TTP to become ineffective.

Table 5.5: The key events and their time steps of occurrence when the initial range between Blue and Red is 30nm. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the target phase	31	122
The live chain of Blue reaches the deny target phase	42	126
The kill chain of Blue reaches the engage phase	93	168
The live chain of Blue reaches the deny engage phase	121	197
Red launches a missile	123	199
Blue launches a missile	126	194
The missile of Red is lost	178	255
The missile of Blue intercepts Red	186	251

The short alternative starts with the Blue live chain already in the deny target phase. The key events for this alternative and the time steps of their occurrence are presented in Table 5.6. At time step 2, the Blue kill chain progresses to the target phase and the live chain to the deny engage phase. In addition, Red launches a missile. It takes Blue up to time step 23 to achieve the engage phase of the kill chain and up to time step 25 to launch a missile. During this time, the missile launched by Red is flying towards Blue and Red away from Blue. Consequently, the missile of Red intercepts Blue at time step 42. Red manages to evade the missile of Blue. Due to the short initial range, Blue is not able to climb fast enough to reach the conditions for a missile launch in time. On the other hand, due to Red being already at a higher altitude than Blue, Red manages to quickly launch a missile and initiate the out maneuver. Hence, the initial range of 15nm causes the reference TTP to fail at producing a desirable outcome.

Table 5.6: The key events and their time steps of occurrence when the initial range between Blue and Red is 15nm. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The live chain of Blue reaches the deny target phase	1	126
The kill chain of Blue reaches the target phase	2	122
The live chain of Blue reaches the deny engage phase	2	197
Red launches a missile	2	199
The kill chain of Blue reaches the engage phase	23	168
Blue launches a missile	25	194
The missile of Red intercepts Blue	42	-
The missile of Blue is lost	61	-

5.4.3 Variation of conditions for a missile launch

The conditions for a missile launch of Red in the reference scenario are that Red is in the LAR and the DMC number $\delta_{DMC}^{Red} \geq 15$. The alternatives in the sensitivity analysis are to launch the missile as soon as Red reaches the LAR, launch when $\delta_{DMC}^{Red} \geq 60$ and launch at the very last moment, i.e., before the missile of Blue intercepts Red. The alternatives are labeled as low risk, high risk and extreme risk, respectively. Launching the missile as soon as the LAR is reached has the lowest risk because it maintains the largest distance between Red and Blue or Red and the missile of Blue. On the other hand, waiting for the very last time step for the missile launch has the highest risk because the distance to Blue or the missile of Blue is shortest.

For all the missile launch condition alternatives, the air combat scenario progresses as the reference scenario until Red reaches the LAR at time step 197. In the low risk alternative, Red launches a missile and initiates the out maneuver. The key events and the time steps at which they occur are presented in Table 5.7. Note that Red reaches the LAR at the same time as the live chain of Blue progresses to the deny engage phase, the latter of which is depicted in the table. Even though Red initiates the out early, Red cannot evade the missile of Blue. It intercepts Red at time step 254. At the same time, the missile of Red is lost. The reference TTP performs well even if Red tries to launch a missile and leave the engagement as soon as possible.

Table 5.7: The key events and their time steps of occurrence when the missile launch conditions of Red is to launch as soon as the LAR is reached. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the engage phase	168	168
Blue launches a missile	194	194
The live chain of Blue reaches the deny engage phase	197	197
Red launches a missile	197	199
The missile of Blue intercepts Red	254	251
The missile of Red is lost	254	255

The time steps of the key events in the high and extreme risk alternatives are similar. They, along with the key events, are presented in Tables 5.8 and 5.9. The only difference is that Red launches the missile later in the latter alternative. Nevertheless, the outcome of the scenario obtained with both alternatives is that the missile of Blue intercepts Red and Blue evades the missile of Red. Even in the extreme risk alternative, where Red waits until the very last moment to launch the missile, it still does not intercept Blue. The success of the reference TTP is not dependent on the point at which Red launches a missile and it performs well against all of the alternatives.

Table 5.8: The key events and their time steps of occurrence when the missile launch conditions of Red is the DMC number $\delta_{DMC}^{Red} \geq 60$. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the engage phase	168	168
Blue launches a missile	194	194
The live chain of Blue reaches the deny engage phase	197	197
Red launches a missile	226	199
The missile of Blue intercepts Red	243	251
The missile of Red is lost	282	255

Table 5.9: The key events and their time steps of occurrence when the missile launch conditions of Red is to launch just before the interception of the missile of Blue. The rightmost column (ref) presents when the key events occur in the reference air combat scenario.

Event	**Time step**	**Time step (ref)**
The kill chain of Blue reaches the engage phase	168	168
Blue launches a missile	194	194
The live chain of Blue reaches the deny engage phase	197	197
Red launches a missile	243	199
The missile of Blue intercepts Red	244	251
The missile of Red is lost	297	255

5.4.4 Summary

For each modification of the threat presentation in the sensitivity analysis, the goal is to find how much it can be varied before the reference TTP becomes ineffective. For the alternatives of altitude and range, the reference TTP turns inefficient or fails at a certain point. However, varying the conditions for a missile launch of Red does not have the similar effect, i.e., the reference TTP produces a desirable outcome of the scenario regardless of the launch conditions of Red's missile.

For the variation of altitude, a higher altitude of Red hinders Blue. The reference TTP produces only neutral outcomes in the high and very high alternatives, i.e., both aircraft launch and evade the missiles. On the other hand, a shorter initial range benefits Red. The gain for Red is dependent on the fact that Red starts at a higher altitude than Blue. If the range is too short, Blue does not have enough time to climb to reach the conditions for a missile launch. By the time Blue launches a missile, Red has already launched a missile and initiated the out maneuver. This leads to Red achieving an intercept with the missile and evading the missile of Blue. Hence, the initial range of 15nm or less makes the reference TTP inadequate.

The results of the sensitivity analysis are summarized in Table 5.10. In terms of the initial altitude of Red, the limit is 35000ft according to the sensitivity analysis. However, the reference TTP still produces neutral outcomes with the altitude of Red being over 35000ft. Therefore, the altitude of Red does not limit the TTP. For the initial range, 15nm is identified as the limit. In addition, exceeding the limit causes Red to be able to intercept Blue with a missile and evade the missile of Blue. No limit is found for the reference TTP by varying the conditions for a missile launch of Red. On the contrary, the reference TTP produces desirable outcomes for Blue with all alternative conditions for a missile launch of Red.

Table 5.10: The summary of the outcomes of the sensitivity analysis.

Modification	**Outcome**
Altitude 5kft	Desirable for Blue
Altitude 35kft	Neutral
Altitude 45kft	Neutral
Range 70nm	Desirable for Blue
Range 30nm	Desirable for Blue
Range 15nm	Desirable for Red
Missile launch as soon as possible	Desirable for Blue
Missile launch when $\delta_{DMC}^{Red} \geq 60$	Desirable for Blue
Missile launch at the last moment	Desirable for Blue

Chapter 6

Discussion

This chapter provides discussion on the MDH approach and its usage as well as future research. Section 6.1 reviews the approach from a holistic perspective and Section 6.2 discusses topics for future research on the subject.

6.1 Comments on the MDH approach

Based on the solution of the example planning problem of TTPs using the MDH approach discussed in Chapter 5, the approach reveals to be a valid support tool for the development of chained and state-dependent TTPs. Recall that the state-dependency of TTP rules means they address the prevailing air combat state rather than a predefined assumption. For TTP rules to be chained, the effects of earlier decisions are taken into account in the rules that govern later decisions. In the demonstration, all necessary TTP rules are identified and a complete TTP is formed. Therefore, the development of the TTP is successful.

The example sensitivity analysis is carried out after the composition of the developed TTP. The required effort from the DM for the analysis is reduced compared to the development of the TTP. The DM only needs to adjust the threat presentation of Red, operate the solution procedure according to the reference TTP and observe the results. The example sensitivity analysis conducted in Section 5.4 contains only a limited amount of variations of the threat presentation. In reality, more variations would be included to find out more precisely where the TTP fails. However, the limitations of the reference TTP with respect to changes in the threat presentation are found in the example sensitivity analysis. Hence, its scope is enough for demonstrating the usefulness of such analysis.

In order to design chained and state-dependent TTPs, the TTP planning problem is formulated in Chapter 3. It begins by defining a one versus one air combat scenario for which a TTP is to be developed. The scenario is described by the air combat state at each time. Then, the progression of the air combat scenario is classified into different phases using kill and live chain representations from the perspective of Blue. Blue is in a phase pair of the chains at each time of the air combat scenario, i.e., there exists a combination of the phases constantly. In the DMCDA model developed in this thesis, the possible combinations, however, are limited even though in real air combat all combinations are possible. When Blue is in the search phase of the kill chain, the live chain can only be in the deny search phase. All other combinations of the phases are possible in the DMCDA model. The limitation is sensible because in this thesis the TTP planning is carried out for a simple one versus one air combat scenario where both Blue and Red have the same aircraft, their systems and capabilities. Overall the kill and live chain representations are useful in the DMCDA model, as the progress of Blue's taskwork is easily monitored with the phases of the chains using the GUI of the MDH approach.

Next in the formulation of the planning problem, objectives and criteria for the combinations of the phases of both chains are defined. Then, relevant decisions for each phase of the kill chain are identified and their alternatives are generated. The objectives consider the progression of the kill chain and denying the progression of the Blue live chain.

For the combination of the search and deny search phases, the objectives are exhaustive. That is, there is little else to do besides finding Red. Similarly, since the live chain is defined to be in the deny search phase, the only sensible objective is to remain undetected. The criteria P_d^{Blue} and P_c^{Blue} reflect the objectives well as they directly measure the probability of detection or remaining undetected, respectively.

For the target and engage phases of the Blue kill chain, the objectives and criteria have similarities. More precisely, reaching the LAR and the conditions for a missile launch require similar decisions. Both of them are also measured with P_k^{Blue}. The similarities question the necessity of both phases. However, in this thesis, there is known to be only one target, i.e., Red. In an air combat scenario, where there can be multiple targets, the target phase could have additional objectives such as determining which targets to focus on. Thus, the idea of separate target and engage phases is sensible even though it might not be completely necessary for the demonstration in this thesis. Same notions apply to the deny target and deny engage phases of the Blue live chain.

The objectives related to the Blue kill chain phases in general contribute to the overall goal of Blue to destroy Red. By completing all those objectives and reaching the end state conditions of the last phase, Red is destroyed. The contribution of the objectives regarding the Blue live chain phases is more difficult to confirm. However, it is observed in the demonstration, that paying attention to the denial of the progression of the live chain ultimately enables Blue to evade the missile of Red. Moreover, the demonstration illustrates that the changes made by the DM to the weights of the criteria correctly affect the behavior of Blue. That is, an increase in the weight of P_c^{Blue} or P_s^{Blue} results in defensive behavior. On the other hand, more offensive behavior is observed when the weight of P_d^{Blue} or P_k^{Blue} is increased.

Unlike objectives and criteria, decisions are identified only for the phases of the Blue kill chain. Decision alternatives are the same for each decision regardless of the kill chain phase in the formulation of the TTP planning problem. The set of decisions and their alternatives allow for prioritizing offense and defense in the planning of TTPs. The maneuvering can be offensive, e.g., climbing towards the threat to increase P_k^{Blue}, or defensive, e.g., turning away from the threat to increase P_s^{Blue}. Similarly, a jammer can be set to standby or to operate in order to increase the detection range of the radar of Blue or to decrease the detection range of the radar of Red, respectively. Hence, there is no need for identifying decisions separately for the phases of the Blue live chain.

When the decisions and the alternatives identified are implemented in the DMCDA model, the DM has enough options to progress the air combat state in the desirable direction according to the demonstration. The amount of decisions is also adequate to illustrate how decision recommendations are revealed with the MDH approach. However, introducing, e.g., additional targets or weapons would require more decisions and alternatives.

The auxiliary models for the environment, aircraft and its systems are simple in this thesis. For the purpose of demonstrating the MDH approach, they represent the important aspects of air combat, such as maneuvering and the utilization of radars, accurately enough. However, if higher accuracy is needed, e.g., for combat maneuvering within visual range, the models need to be modified. In addition, they could be extended to describe, e.g., fuel consumption or system malfunctions.

The objective function of the DMCDA model is used to evaluate air combat states. It consists of a value function including the weighted sum of the criteria, a penalty for the regression of the Blue kill chain, a reward based on the phase of the kill chain and a cost-to-go function. The penalties and rewards are used to prioritize the progression of the kill chain in decision suggestions provided by the MDH approach. Their values are larger than those of the value or the cost-to-go function. The penalties and rewards seem to have the desired effect since decision suggestions do not cause the

Blue kill chain to regress in the demonstration. The cost-to-go function is used because even though certain decisions are beneficial in the near future they might lead to undesirable outcomes later. The effect of the cost-to-go function on the value of the objective function is small because it is based on a rough approximation of the prediction of the air combat state. However, it is deemed important to demonstrate the possibility of the usage of the cost-to-go function. In this thesis, it essentially represents the likelihood of reaching the end state conditions of the prevailing phase of the Blue kill chain.

The value function creates differences in the value of the objective function for state predictions with similar penalties, rewards and cost-to-go function values. The value of the objective function is dependent on the air combat state. Therefore, also decision recommendations, and in turn TTPs, are state-dependent because they are based on the state feedback via the objective function.

The solution procedure of the DMCDA model, combined with the GUI, enable the DM to direct the air combat of Blue. The DM has enough freedom in the development of TTPs by adjusting weights of criteria and decision variable values suggested by the procedure. In addition, the DM is allowed to revisit earlier air combat states if needed. The GUI presents necessary information about the air combat state, including aircraft and missiles, for the DM to able to monitor and react to changes in the state.

Numerical computations carried out in this thesis allows the DM to use the MDH approach in a sensible time frame. That is, the computations are simple enough to be conducted in seconds. The precision of the computations, e.g., the integration of state equations, and the processing time are the product of a compromise. In this thesis, high precision is not needed in any computations because the idea of the MDH approach can be demonstrated with the models used in this thesis. However, a deficiency in computations of this thesis is due to a reduced decision tree used in the solution procedure. The tree contains only a fraction of possible combinations of decision alternatives after the first time step of state predictions. This means that it may degrade the quality of decision suggestions. In addition, the length of the planning horizon should be increased with more powerful computers. A longer planning horizon would enable the solution procedure to look further into the future and might thus improve decision suggestions and resulting TTPs.

The overall idea of chained and state-dependent TTPs appears promising based on the demonstration of the MDH approach. Blue is able to react to the behavior of Red with sensible decisions. By depending on the air combat state rather than on an assumption of the behavior of the threat, TTP rules address the threat more accurately compared to traditional TTPs. However, converting the state-dependent TTP rules into a written format poses a challenge. The air combat state changes constantly and does not progress the same way for two different air combat scenarios. Therefore, for a non-fixed threat, there needs to be a large amount of state-dependent TTP rules. However, sensitivity analysis can be used to identify feasible regions of TTPs by varying the threat presentation. By using each TTP against all threat presentations inside its feasible region, the total amount of TTPs needed decreases.

In the traditional TTP development, a chain of decisions would have been predefined for Blue. Predefined decisions do not allow for adaptations if the air combat state progresses unexpectedly. Most likely a traditional TTP would have performed adequately against a simple threat such as in the demonstration of this thesis. However, chained and state-dependent TTPs are suitable against every threat inside their feasible limits.

Chained and state-dependent TTPs have not been addressed in the existing literature. In addition, earlier approaches to the development of TTPs have not combined the kill and live chain representation with feedback from the air combat state. Such a representation by itself has been successfully used previously to describe the taskwork of pilots in air combat. In addition, it creates a convenient structure for describing the progress of the air combat scenario. Consequently, objectives, criteria, and decisions can be defined for the phases of the corresponding chains with ease. On the other hand, feedback from the air combat state has been used earlier only in models of air combat based on optimal control which can not be applied for supporting the planning of TTPs. By basing decision suggestions revealed with the MDH approach on the feedback from the air combat state, they contain more up-to-date information about the air combat state compared to a traditional assumption based planning of TTPs. Chained decision making is not a part of TTPs in existing literature even though they contain proactive chains of actions. Decisions made while planning TTPs with the MDH approach affect upcoming decisions which makes them chained. TTP rules are identified for the decisions, and thus the rules are chained as well. The combination of the kill and live chain representations and the chained and state-dependent decision suggestions is suitable for the planning of TTPs. They allow the MDH approach to meet the demands for a support tool of TTP development of modern air combat which is demonstrated in this thesis.

6.2 Future research

For future research, the TTP planning problem should be expanded for a more complex air combat scenario than one versus one. Since a flight consists of four aircraft, four versus four is a sensible expansion. Such a planning problem can be formulated in the same way as the formulation is conducted in this thesis. The goal is to develop similarly chained and state-dependent TTPs. However, computational requirements increase significantly due to the more complex air combat scenario. Thus, the simplification of the DMCDA model or more powerful computers are needed. In addition, incorporating the decision making of many aircraft would require more effort from the DM who is responsible for the TTP planning and the use of the MDH approach. To reduce the burden of the DM, the workload could be reduced by the use of multiple DMs. Each DM could be responsible for the decision making of a specific aircraft.

An extension of the MDH approach is to use a complete decision tree when predicting the time evolution of an air combat state. In this thesis, a reduced decision tree is used to decrease computational requirements. It significantly decreases the number of possible states to be evaluated. Consequently, the information received from the predicted states is limited. For example, if the prediction starts with Blue using full throttle and turning right, same decision alternatives are used until the end of the planning horizon. In reality, Blue could, e.g., reverse the turn on the next time step of the predictions.

The applicability of TTPs developed with the MDH approach are affected by the models used for, e.g., aircraft in the DMCDA model. By using more realistic models compared to the ones utilized in this thesis, resulting TTPs would address real air combat better. Existing sophisticated virtual and constructive simulators can be used to describe real air combat more accurately for the TTP development. The application of the MDH approach remains the same as in the demonstration of this thesis if the existing simulators are used. However, some additional modifications to the DMCDA model regarding, e.g., data transfer between the model and the simulator, are required.

By using the DMCDA model in virtual and constructive simulators, the MDH approach could be used for air combat training of pilots. For example, a flight instructor can operate the MDH approach as the DM alongside a virtual and constructive simulation where the virtual simulator is flown by a pilot trainee. The solution procedure of the DMCDA model can provide decision suggestions for the pilot trainee in real time. The pilot trainee can decide whether to accept the suggestions or to make dissenting decisions.

During or after the flight, the decisions of the trainee pilot can be reviewed and compared to the suggestions provided by the MDH approach with the flight instructor.

The chained and state-dependent TTPs introduced in this thesis can alleviate the need for pilots to study a large amount of written TTP rules. Even though TTPs still need to be documented in the written format, they could be studied using simulators alongside the MDH approach as described previously. Before utilizing simulators, general principles regarding TTP rules should be learned. Training in the simulators instead of memorizing written TTPs could expedite learning because it resembles more the application of TTPs during air combat.

Chapter 7

Conclusions

The objective of this thesis was to introduce an approach - the moving decision horizon multi-criteria approach (MDH approach) - for the development of chained and state-dependent tactics, techniques and procedures (TTPs). Such TTPs have not been considered earlier in unclassified literature. In a chained TTP, the decisions made earlier have an effect on the later decisions. The state-dependency means that the TTP rules address the prevailing air combat state rather than the assumption of the threat. Traditional TTPs contain predefined actions that consider the assumed behavior of the threat. They often fail to adapt to the unpredictable environment of air combat. The chained and state-dependent TTPs take into account the previous decisions as well as the current air combat state and thus perform better in modern air combat.

In this thesis, the development of TTPs required the formulation of a planning problem for a one versus one air combat scenario including two aircraft, i.e., the friendly Blue and the opponent Red. To represent the taskwork of pilots, kill and live chains were created. The chains have three successive phases, and they exist in parallel. Feasible combinations of the phases of the kill and live chains were determined. The Blue kill chain describes the progress of the taskwork of Blue towards destroying Red. On the other hand, the Blue live chain considers denying the taskwork of Red from progressing. Blue is in a specific phase of both chains at all times, and thus objectives for each combination of the phases were defined. Completing the objective of the prevailing phase of the Blue kill chain causes it to progress to the next phase and towards the overall goal of Blue to destroy Red. For the prevailing phase of the Blue live chain, the completion of its objective prevents the chain from progressing and therefore increases the chance of the survival of Blue. To evaluate the completion of the objectives and the air combat state, criteria were identified for the combinations of the phases. Then, relevant decisions regarding air combat were defined for the phases of the Blue kill chain. In addition, alternatives were generated for the decisions.

To support the solution of the TTP planning problem, the MDH approach was created. It includes the dynamic multi-criteria decision analysis (DMCDA) model and its solution procedure. The DMCDA model consists of the decisions of Blue as well as their alternatives and the fixed threat presentation, i.e., the behavior of Red. In addition, it includes the air combat state which describes the air combat scenario at all times. Auxiliary models in the DMCDA model represent aircraft, their systems and environment.

The solution procedure of the DMCDA model is operated by the decision maker (DM) who uses the MDH approach as support for the planning of TTPs. In the solution procedure, the predictions of states are made for each combination of the decision alternatives from the current air combat state up to the length of a planning horizon. The predicted states at the end of the planning horizon are evaluated with an objective function based on the criteria, cost-to-go function and the phase of the Blue kill chain as well as the changes of its phase before the end of the planning horizon. Decision alternatives, that result in the best future air combat state, are presented to the DM as decision suggestions. The DM decides whether to implement the suggestions as decisions of Blue in the current air combat state or to modify them. TTP rules are ultimately formed from the decisions of Blue. After the decisions are implemented, the air combat state progresses one time step forward. The solution procedure is repeated for the new air combat state regardless of the changes in the phases of the Blue chains. However, when the objective of the last phase of the Blue kill chain is completed, Blue has reached its ultimate goal, the solution procedure is not repeated anymore and the air combat scenario ends. Note that the scenario and the repetition of the solution procedure also end if Red destroys Blue.

For the use of the solution procedure, a graphical user interface (GUI) was created. The GUI presents visualizations of the air combat state and allows the DM to modify the values of decision suggestions and to adjust the weights of the criteria. In addition, the DM can move back and forth in the air combat scenario via the GUI.

The use of the MDH approach was demonstrated with an example air combat scenario. First, the feasible combinations of the phases of the Blue kill and live chains as well as their objectives and decisions were reviewed. The TTP rules were to be identified for the decisions of the feasible combinations of the phases that are encountered during the demonstration. Then, the DMCDA model was initialized and the DM started the solution procedure. Eventually, three combinations of phases were encountered and TTP rules were found for all of them. In addition, Blue progressed through the kill chain and destroyed Red. The TTP rules were combined to form a complete TTP. Moreover, an example sensitivity analysis was conducted where the constructed TTP was used as a reference. The goal was to find the feasible region of the TTP in terms of changes in the threat presentation. The sensitivity analysis successfully revealed the limits of the TTP.

Overall, the TTP was successfully developed with the MDH approach in the demonstration. Thus, it is concluded that the formulation of the TTP planning problem adequately describes the necessary components of the development of TTPs. The Blue kill and live chain representation of the progress of the air combat scenario proves to be useful as it is clear to monitor. The criteria, along with the penalties and rewards from the changes of the phase of the Blue kill chain as well as the cost-to-go function, allow for convenient evaluation of the air combat state and its evolution from the perspective of Blue. The objectives of the Blue kill and live chain phases are straight-forward and logical when compared to the overall goal of destroying Red. The criteria, on the other hand, are aligned with the different objectives of the phases. The auxiliary models describe aircraft and their systems as well as environment adequately for the purposes of this thesis. The aircraft manage to maneuver offensively as well as defensively. The radar, the jammer and the missiles enable the means to complete the objectives of each combination of the Blue kill and live chain phases as intended.

The DMCDA model as a whole describes the air combat scenario and its progression as expected, i.e., there are no major bugs or anomalies in the model and its solution procedure. The operation of the solution procedure requires a sensible amount of time and effort from the DM. That is, the solution procedure takes under ten seconds of runtime per time step. In addition, the DM is able to use the fast forward functionality of the GUI to reduce the decision making burden.

An approach, which aims to help to produce chained and state-dependent TTPs with the kill and live chains describing the taskwork of pilots, has not been yet introduced in the existing literature. Previously, feedback from the air combat state has been applied in air combat models that are not utilized in the context of TTP development. The kill and live chain representations have been used in the development of TTPs for describing the taskwork of pilots, but separately from analytical tools.

Future research topics for the development of chained and state-dependent TTPs include considering more complex air combat scenarios than one versus one. A sensible expansion of the complexity of the air combat scenario is four versus four. In addition, the accuracy of the DMCDA model in terms of, e.g., the precision of maneuvering and the amount of decision alternatives, can be improved. The use of existing sophisticated models for, e.g., aircraft and their systems is a way to improve the accuracy of the DMCDA model. The MDH approach could also be used in the combat training of pilots as follows. The pilot trainees could fly a virtual and constructive simulator where the approach is operated simultaneously. With the simultaneous use of the approach, the decision suggestions of the solution procedure can be provided for the trainee during training. The decisions of the trainee and the suggestions can be reviewed and compared after the flight with the flight instructor. On the other hand, they can also be reviewed during the flight by pausing the simulation. By the application of the MDH approach, the need for memorizing written TTPs could potentially by decreased.

To summarize, the demonstrative use of the MDH approach illustrated that it can be successfully used to develop chained and state-dependent TTPs. Such TTPs consider the current air combat state that changes unpredictably in air combat. Traditionally developed TTPs contain predefined actions to address the assumption of the behavior of the threat and therefore fail to adapt when the assumption is incorrect. New TTPs introduced in this thesis, thus, match the challenges that arise in modern air combat. The MDH approach, accompanied by the GUI, is an adequate tool for the planning of air combat TTPs. In the future, it could also offer new practices for the combat training of pilots.

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