Unmanned Aerial Vehicle Fleet Mission Planning Subject to Changing Weather Conditions

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UNMANNED AERIAL VEHICLE FLEET MISSION PLANNING

SUBJECT TO CHANGING WEATHER CONDITIONS

BY
AMILA THIBBOTUWAWA

DISSERTATION SUBMITTED 2019

AALBORG UNIVERSITY
DENMARK

UNMANNED AERIAL VEHICLE FLEET MISSION PLANNING

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by

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AALBORG UNIVERSITY
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Dissertation submitted October 2019.

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His research interests include operations research, supply chain optimization and logistics. He is keen on various other areas of supply chain engineering including supply chain decision making and lean manufacturing.

ABSTRACT

Emerging demands for autonomous delivery and logistics operations have driven researchers to investigate Unmanned Aerial Vehicles (UAVs) as an enabling technology. The 3D flexible utilization of airspace, promogulated by UAVs, are a potential game changer in solving the urban air mobility challenge by allowing to reshape transportation and logistics in the future. UAVs have become the frontiers for areas such as defense, search and rescue, agriculture, manufacturing, environmental surveillance and especially in materials distribution. Materials distribution using a fleet of UAVs was the inspiration for this study as companies are focusing to use large UAVs to distribute materials to industrial customers such as delivering materials to the windmill farms in Denmark for the maintenance activities of windmills. The deployment of UAV systems requires minimum physical modifications to the existing infrastructure and are a faster, more cost-effective sustainable alternative for existing traditional delivery modes of transportation.

To cater to this rising demand of utilizing large UAVs to execute operations, in particular material deliveries, in outdoor environments and specifically to address the technology gaps found in industry and research, this thesis report presents the novel problem of UAV fleet mission planning subject to changing weather conditions. Such problems and the solution to these is of great interest to companies like *Airbus Defence & Space*, and other major aerospace system providers. From literature, it is easily established that there is a lack of contributions reported on this topic with regard to fleet mission planning for large UAVs operating in outdoor environments, while taking into account energy consumption behavior of the UAVs due to the influence of weather (wind speed and wind direction) during operations. This thesis report proposes a declarative model for the UAV fleet mission planning problem which enables the decision support for UAV fleet mission planning considering the characteristics of UAV fleet, characteristics of the weather conditions, characteristics of the network and customer locations. Furthermore, this thesis report provides a solution approach for the hitherto unformulated UAV fleet mission planning problem considering both energy consumption constraints and the impact of weather conditions and uncertainty, while ensuring collision free routing of the UAVs. The novelty of this research is especially found in the following contributions:

- A mapping of the current-state of research in terms of a comprehensive literature review.
- A formulation which presents the UAV fleet mission planning problem in changing weather conditions.
- A declarative model to present the UAV fleet mission planning problem in changing weather conditions which provides inputs for decision support in UAV fleet mission planning.

- An extensive of the performance of the declarative model and a study of formulations and solution methodologies which can be used as a prototype for decision support system of UAV fleet mission planning.

The thesis report and the appended papers provide the overview of these contributions, of which the main ones are briefly highlighted here. Paper A provides a published general overview of the current-state and contributions in the domain of the UAV routing. Paper B and Paper C presents the different conditions influencing the non-linear energy consumption of which are unique to UAVs and analyze how those factors affect the routing of UAVs in UAV fleet mission planning. Paper D presents the novel problem of UAV fleet mission planning in changing weather conditions. Paper E presents a declarative model for the problem of UAV fleet mission planning in changing weather conditions. Paper F proposes a method based on a decomposition solution approach to solve the problem of UAV fleet mission planning in changing weather conditions which provides inputs for decision support of UAV fleet mission planning. Paper L presents a declarative model, implemented in the IBM ILOG environment that allows designing routes of UAVs that guarantee the maximum level of customer demand satisfaction for various weather conditions. Certain assumptions considered in the declarative model such as soft delivery time windows and the homogenous fleet of UAVs could be excluded and, tested with real-world simulations in further research. Furthermore, open problems such as, the problem of heterogeneous UAV fleet mission planning with customer time windows could be focused as future research domains.

Furthermore, included in this PhD thesis is a proposal for a UAV fleet planning decision support system enabling to prototype alternative mission proposals for execution. The implementation of the proposed solution approach as a decision support system enables one to determine whether is it possible to find a fleet mission plan for a given fleet of UAVs guaranteeing assumed delivery amounts to a given set of customers in a given time horizon and evaluates different scenarios of UAV fleet mission planning. Investigations on potential approaches and an offline-based system are carried out to ensure that only missions suitable to be sent to approval from Air Traffic Control are accepted and the results of the study can be directly implemented as a technical tool in decision support systems of aerospace companies.

DANSK RESUME

Trends og stigende fokus på systemer til autonome logistik og leverance har drevet forskere til at undersøge ubemandede flyvende platforme (Unmanned Aerial Vehicles), UAVer, som en mulig løsning på disse udfordringer. Muligheden for på en fleksibel måde at udnytte de tre dimensioner luftrummet giver, fremfor de to som er mulige ved jordbaseret transport, er en potentiel revolutionerende nytænkende tilgang til at løse de udfordringer verdens i stigende grad tungt trafikkerede urbaniserede miljøer står overfor. UAV teknologien skaber nye fronter og muligheder indenfor så diverse emner som: forsvar, beredskab, landbrug, produktion, miljøovervågning og især materialetransport. Materialetransport ved brug af UAVer er inspirationen til det arbejde som præsenteres i denne afhandling. Fordelen ved brugen af UAVer til denne slags formål, er, at det kræver minimale fysiske ændringer til eksisterende infrastruktur, UAVer er hurtige, kosteffektive under de rette vilkår og bæredygtige sammenlignet med alternative transportmuligheder.

For at imødekomme det stigende brug af UAVer er der et behov for at udvikle nye metoder til at planlægge missioner for flåder af UAVer. Sagens natur gør, at disse metoder skal være i stand til at tage vejrforhold i betragtning, noget som især de store internationale aktører indenfor feltet, såsom Airbus Defence & Space, er interesserede i. Fra litteraturen er det nemt at etablere, at der er en udpræget mangel på bidrag relatereret til planlægning af missioner for flåder af store UAVer i udendørs miljøer, som tager højde for energiforbrug, vejrforhold og disses indflydelse på eksekveringen af missionerne. I denne afhandling foreslås en deklarativ model til flådemissionsplanlægning, som understøtter beslutningsstøtte ifbm.

flådemissionsplanlægning, samt tager højde for UAV flådens karakteristika, vejrforhold, netværket og kundelokationer. Ydermere rapporteres der i denne afhandling en løsning på det hidtil uløste problem om planlægning af missioner for UAV flåder, under hensynstagen til energiforbrugsbegrænsninger og vejrforholds og disses usikkerhed indflydelse på mulighederne for at planlægge og eksekvere en mission. Samtidigt er løsningen struktureret på en sådan måde at resultatet er konfliktfri planer og ruter til multiple UAVers missioner i begrænset luftrum.

Hovedbidragene i denne forskning kan opsummeres til i overordnede punkter at være:

- En kortlægning af den nuværende forskning i form af et omfattende litteraturstudie.
- En formulering af problemet, som præsenterer planlægning af missioner for UAV flåder under skiftende og usikre vejrforhold.
- En deklarativ model, der kan fungerer som input til et beslutningsstøttesystem til planlægning af missioner for UAV flåder under usikre vejrforhold.

- Et omfattende studie af den deklarative models performance, samt et studie af potentielle problemformuleringer og løsningsstrategier, der kan fungere som prototyper på et beslutningsstøttesystem.

  Alle disse bidrag er udviklet på en måde, som understøtte de krav til sikker eksekvering af lufttrafik luftfartsmyndigheder må forventes at have.

ACKNOWLEDGEMENTS

First and foremost, I want to express my sincerest gratitude to my supervisor Assoc. Prof. Peter Nielsen, for supporting and guiding me throughout my PhD project. Thank you for always trusting me and showing an immensely positive attitude toward my work and giving me the freedom to pursue whichever path my research took me. Thank you for introducing me to the network of excellent researchers that have driven my desire to pursue a scientific career. Beyond your role as my supervisor, I have enjoyed your company, and I hope our collaboration will continue in future.

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ABBREVIATIONS

AGV	Automated Guided Vehicle
CL	Customer Cluster
COP	Constraint Optimization Problem
DFS	Depth-First Search
DSS	Decision Support System
FTW	Flying Time Window
STW	Sub-mission Time Window
UAM	Urban Air Mobility
UAV	Unmanned Aerial Vehicle
VRP	Vehicle Routing Problem
VRPTW	Vehicle Routing Problem with Time Windows
WUV	Weather Utility Value
Cn	Number of customers visited by a UAV per route
ep	The empty weight of a UAV
G	The graph which represents the transportation network
H	The time period
K	The size of the fleet of UAVs
w	The time spent for take-offs and landings of UAVs
P_{max}	The maximum energy capacity of a UAV
Q	The maximum loading capacity of a UAV

CHAPTER 1. INTRODUCTION

1.1 INTRODUCTION AND MOTIVATION

Over the past decade, Unmanned Aerial Vehicles (UAVs) have become increasingly popular and have been developed as a part of the solution to such challenges as urban mobility, disaster relief efforts, mapping of forest fires, etc. UAV technology is viable and applicable in such diverse areas such as defense, search and rescue, agriculture, manufacturing, and environmental surveillance (Bolton and Katok 2004; Avellar et al. 2015; Khosiawan and Nielsen 2016; Barrientos et al. 2011). Following recent advancements in UAV technology large companies such as Airbus (Airbus 2019), Amazon (Ben Popper 2016), DHL (Bonn 2017) and Federal Express (Wang et al. 2016), have begun to investigate the viability of incorporating UAV-based solutions and invest in including UAVs into their commercial services. A critical challenge to achieve effective and efficient exploitation of UAV technology for these purposes is to have in place a coordination and monitoring system for the UAVs' operations. For UAV-based activities, it is important to route and schedule operations in a safe, collision-free and time-efficient manner (Khosiawan and Nielsen 2016; Xiang et al. 2016).

UAVs show high potential for delivery logistics, as it is faster, cost effective (Bocewicz et al. 2018; Dorling et al. 2016) and potentially more sustainable than traditional delivery modes such as land and sea transportation. Urban Air Mobility (UAM) is a new dimension to technological developments, where it will reshape transportation and logistics in future. The concept of UAM is proposed by introducing next-generation Vertical take-off and landing (VTOL) capable UAVs as a mode of transport service (Jeff and Goel 2016; Airbus 2019), where it covers the different levels of abstraction including fleet level, platform level and the element level of logistics systems (Figure 1). UAVs and UAM systems will provide various novel UAVs-related operations to the airspace above metropolitan areas and all across the globe. These systems are expected to revolutionize the transportation infrastructure, in particular in dense urban areas or hard to reach rural areas.

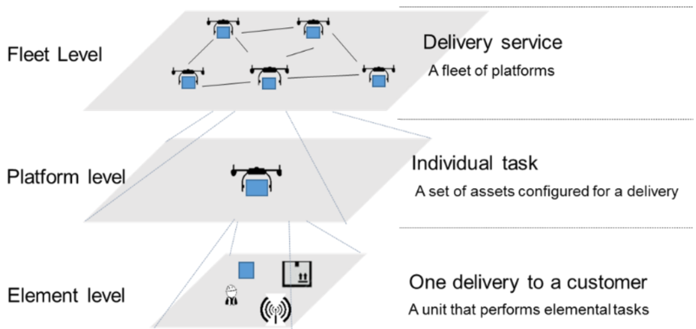


Figure 1. Overall hierarchical representation of UAM (Paper **F**).

Pilot projects are scheduled to be commenced in cities such as Dubai, Singapore, Los Angeles and Dallas in the early 2020s (Holger Lipowsky et al. 2018), with technological advancements and it is predicted that by the late 2020s UAV technology will spread cost effective services to major metropolitan areas around the globe (Holger Lipowsky et al. 2018; Airbus 2019). UAM will be useful for solving the urban mobility problem in general (urban traffic pollution and congestion) where the increasing two-dimensional capacity in transport networks will not be able to address existing traffic situation. As there is a global challenge of reducing emissions due to the reasons such as idling motor vehicles causing serious pollution and contribute strongly to issues with living in dense urban areas, UAM will be a potential strategy to support sustainable transportation.

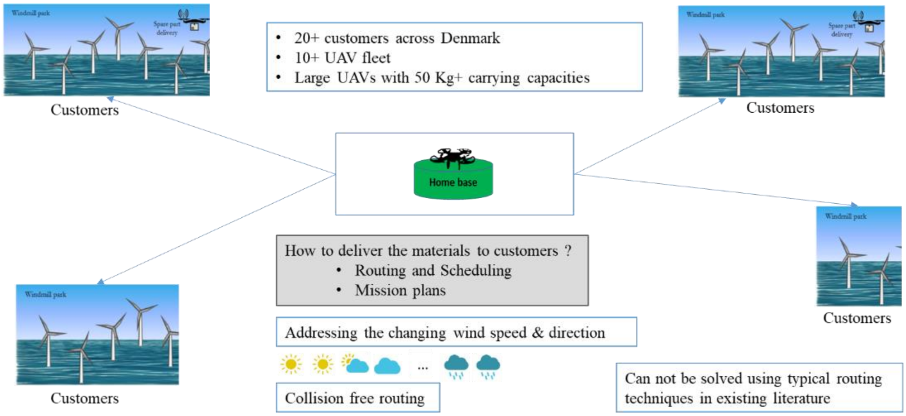


Figure 2. Graphical representation of real-world industry requirement that inspired the study.

The project Operational Reliability Management System (ORMS) is the initial motivation for this PhD project (Figure 2). The project is a joint research initiative between *Airbus Defence & Space* and the Department of Materials and Production of Aalborg University. The objective of this project is to create mission plans for a fleet of UAVs performing material delivery operations. It therefore should generate schedules and routes for a fleet of UAVs at which defined tasks such as material deliveries have to be performed by particular fleet of UAVs.

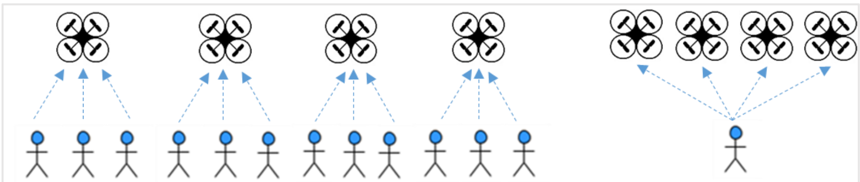


Figure 3. Transitioning from teams of operators managing a single UAV to a single operator managing multiple UAVs.

As UAVs flight and navigation tasks are increasingly automated to gain economies-of-scale and speed of operations and support the large scale operations envisioned in UAM, UAV mission planning and execution is transitioning from teams of operators managing a single UAV to a single operator managing multiple UAVs (Figure 3). Enhancement in the autonomy of UAVs will change the operating personals role to one of control supervision where the operator will be primarily handling the high-level mission management in contrast to low-level manual flight control. Due to this reduction in tasks requiring direct human control, a UAV operator will become able to supervise and divide attention across a fleet of UAVs (Cummings and Brzezinski 2010). The increasing degree of autonomy and automation creates a continuous push for faster, smarter and safer methods for managing complex UAV operations. Such systems will naturally require the development of advanced prediction, routing and scheduling methods and implementation of various systems to support decision makers in handling the complexity of operations.

Rising expectations for UAV technology to solve a number of societal challenges (e.g. UAM) requires the creation of seamless flow, while practical constraints such as weather conditions and energy consumption make the problem highly complex and potentially intractable. UAV technologies, on one hand, give the potential for more flexible transfer of goods between locations, while on the other hand, they generate new problem types related to the organization and maintenance of the planned routes and schedules. UAVs mission planning is essential in any operation of UAV fleets. To support autonomous operations UAV fleets, fleet mission planning must be enabled. UAV fleet mission planning problems are an extension of the well-known Vehicle Routing Problem (VRP), but with the added complexity of three dimensional operations and combined routing and scheduling (Zhen et al. 2019). While the classical VRP is well-studied, the methods and approaches found within this domain are still very much applicable for the advancement of new technology in the area of UAV operations (Chandran and Raghavan 2008). Typically the mission planning for UAVs must consider constraints on UAV range (dependent on UAV characteristics and weather conditions), airspace regulations and restrictions as well as congestion (collision avoidance, safety distance, etc.) and UAV characteristics (air speed, maximum payload, energy capacity, physical dimensions, etc.) (Thibbotuwawa et al. 2019).

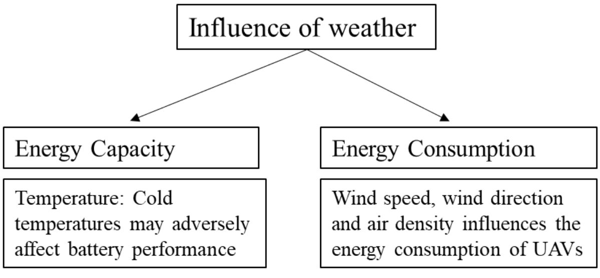


Figure 4. Influence of weather in energy capacity and energy consumption.

In outdoor UAV mission planning, as shown in Figure 4, it is necessary to address changes in weather conditions that influence energy consumption and energy capacity of UAVs (Kinney et al. 2005; Yu and Lin 2015). These weather conditions can potentially strongly influence the solution strategy for the UAV mission planning, especially with regards to the wind in the form of both wind direction and speed that impacts the energy consumption either through head or tail wind influences (Tseng et al. 2017).

The challenge is to close the gap between the real-world application needs and the existing technologies. To enable large scale UAM, several key gaps and challenges must be managed. The current-state of research to address these gaps is fragmented and existing studies fall short of providing a unified answer to all the challenges. This PhD project aims to close several of the larger gaps and act as a significant step towards achieving autonomous UAVs based UAM.

Specifically, this research addresses the current gap in state-of-the-art mission planning for a UAV fleet, by taking into account the changing weather (wind speed and directions) conditions and generating alternative robust mission plans. Furthermore, the aim of the research is to propose solutions of collision-free mission plans for a fleet of UAVs providing the maximum satisfaction of all given customers' orders in a manner that enables decision support for an operator of a UAV fleet.

In other words, this research answers the following question: Is it possible to find a fleet mission plan using the given fleet size to deliver the required amount of deliveries to customers within a given time period with the given weather forecast, while ensuring collision avoidance between the UAVs (Paper **F**)? Furthermore, there are other relevant related questions that can be answered such as:

- Is it possible to determine the fleet mission plan for a given UAV fleet, which delivers the maximum demanded volumes to all the customers within a time period under the given weather conditions?
- What is the appropriate fleet size needed to deliver with a certain service level under the given forecasted weather conditions?
- What are the system parameters (describing the network, UAV fleet, weather conditions) that guarantee to deliver the required amount of material to the customers (Paper **F**)?

Answers to these questions are used in a Decision Support System (DSS) to make the decisions regarding utilizing a given UAV fleet size in delivering a required amount of demands to the customers with in a time period. Furthermore, answering these questions enables the mission planner in obtaining the fleet mission plans that can be conveyed to aviation authorities to get the approval for execution.

1.2 RESEARCH QUESTIONS

The research questions are formulated concerning the following objectives, which hypothetically give the corresponding answers to the motivation of the study mentioned in section 1.1.

- Review the state-of-the-art of UAV fleet missions planning in an outdoor environment and the challenges beyond.
- Identify the gap in the existing literature to address the energy consumption of UAVs in outdoor environments.
- Identify and formulate the problem (constraints, parameters and decision variables) of UAV fleet mission planning problem in outdoor environments considering changing weather conditions and ensuring collision avoidance. This study has not considered the mission risk assessment as the study focuses on offline mission creation where the mission plans are created ensuring collision avoidance between the UAVs in the UAV fleet. However, the mission risk factors with regards to loss of control of the UAVs and fault handling mechanisms are not considered.

To ensure that these objectives are addressed in a structured manner following research questions are composed.

RQ1 What is the current-state of UAV fleet mission planning in the existing literature and what are the gaps?

RQ2 What are the conditions influencing the UAV fleet mission planning, which are unique to UAVs?

RQ3 What are the factors, which affect the energy consumption of UAVs, and how do those factors affect the energy consumption of UAVs?

RQ4 Is it possible to solve the UAV fleet mission planning problem for a fleet of UAVs delivering materials to maximize the customer demand satisfaction ensuring collision avoidance and considering the behavior of energy consumption of UAVs?

- ***RQ1*** is answered by contributions found in Paper **A**.
- ***RQ2*** is answered by contributions found in Paper **B**.
- ***RQ3*** is answered by contributions found in Paper **C**.
- ***RQ4*** is answered by contributions found in Papers **D**, **E**, **F**, **G** and **L**.

A description of the papers and the link between the papers is presented in section 1.5.

1.3 RESEARCH METHODOLOGY

To address the research questions, a research methodology is needed. The purpose of the methodology is to guide the creation of knowledge in a structured manner. The methodology has two main purposes. The first is to ensure that the studied topic is tackled in an appropriate manner, where the knowledge creation method matches the topic, so that the problem under consideration provides a strong link to the solution to the problem. The second aspect the methodology should address is to ensure internal coherence in the work (Checkland 2000). Specifically, the research questions are answered in a structured and similar manner, thereby ensuring that the answers to one question can be used to build upon for answering the next question. Without this internal coherence, it is difficult to utilize the knowledge created in subsequent steps. In this sense, the research methodology serves to ensure coherence between the research problem and solutions.

As this research study is related to a real-world implication of a material distribution system using a fleet of UAVs, a research methodology was chosen which was adopted based on the work done by Checkland, Ulrich, Coghlan and Brydon-Miller (Ulrich 1988; Coghlan and Brydon-Miller 2014; Checkland 2000). The research methodology shown in Figure 5 explains systems thinking in relation to real-world context and it consists of seven stages. Each stage of the research methodology is explained below.

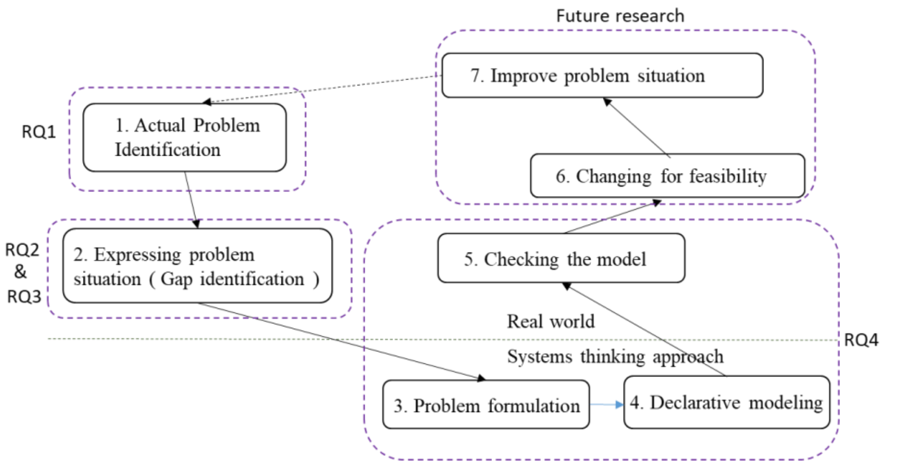


Figure 5. Research methodology.

Stage 1 is focused on the emergence of the problem and the state-of-the-art related to the problem. Stage 2 is related to the gap identification in state-of-art to address the problem. This stage expresses the problem situation in terms of bridging the gaps for real-world implications. Stage 3 recommends systemic thinking about the situation of the problem. Problem formulation with defining the relevant systems are stated in this stage. Aspects are identified that might offer insight into the problem situation and to fill or reduce the gap in current-state to solve the problem. Stage 4 elaborates on problem definitions by coming up with models that could describe the actions of the solution strategies. In stage 5, the conceptual models, which are the results of systemic thinking about the real-world, are transferred into the real-world and compared to the problem situation expressed in stage 2. In stage 6, the feasibility of the solutions are evaluated in the context of the problem situation and changes are made to obtain desired outputs. Stage 7 seeks to explore possible ways of improving the problem situation with regards to the enhancement of the technology.

The proposed research methodology matches with the RQs as Stage 1 is related to ***RQ1*** and Stage 2 relates to ***RQ2*** and ***RQ3***, while Stage 3, Stage 4 and Stage 5 cover ***RQ4***. Stage 6 and Stage 7 are related with the future studies where the outputs of the research should be checked for feasibility in terms of real-world implications and improving the problem situation. The problem formulation and the declarative modeling approach presented in this report are capable of reducing the gap between the real-world applications and this research methodology supports in bridging the gap in the current-state to solve the problem of UAV fleet mission planning subject to weather conditions (Paper **F**).

1.4 STRUCTURE OF THE THESIS

This thesis consists of two distinct parts. The first part of the thesis presents the research results achieved through the PhD study in a comprehensive manner. This part is structured as follows. First, a literature study (Chapter 2) is presented. This is followed by the problem of UAV mission planning with experiments and results (Chapter 3 and Chapter 4) where the problems are described, a mathematical model is formulated and solution approaches are developed (often in the form of heuristic algorithms) to solve the problem. Furthermore, results from computational experiments are presented to demonstrate the performance of the proposed approach. Finally, concluding remarks and a discussion of future works into the research area are presented (Chapter 5). The second part of the thesis is a collection of papers submitted and published as a part of the research.

1.5 PUBLICATIONS AND SUBMISSIONS DURING PHD STUDY

The papers published and submitted during the PhD period including the main contributions are presented in the following Table 1.

Table 1. Papers published and submitted during the PhD.

Paper	Reference
A	Thibbotuwawa A. & Nielsen P. **Unmanned Aerial Vehicle Routing Problems: A literature review**. Submitted to the journal of Logistics Research (Under review – second revision).

B	Thibbotuwawa A., Nielsen P., Zbigniew B., Bocewicz G. (2019) **Energy Consumption in Unmanned Aerial Vehicles: A Review of Energy Consumption Models and Their Relation to the UAV Routing**. In: Świątek J., Borzemski L., Wilimowska Z. (eds) Information Systems Architecture and Technology: Proceedings of 39th International Conference on Information Systems Architecture and Technology – ISAT 2018. ISAT 2018. Advances in Intelligent Systems and Computing. Springer.
C	Thibbotuwawa A., Nielsen P., Zbigniew B., Bocewicz G. (2019) **Factors Affecting Energy Consumption of Unmanned Aerial Vehicles: An Analysis of How Energy Consumption Changes in Relation to UAV Routing**. In: Świątek J., Borzemski L., Wilimowska Z. (eds) Information Systems Architecture and Technology: Proceedings of 39th International Conference on Information Systems Architecture and Technology – ISAT 2018. ISAT 2018. Advances in Intelligent Systems and Computing. Springer.
D	Thibbotuwawa A., Nielsen P., Bocewicz G., Banaszak Z. (2020**) UAV Fleet Mission Planning Subject to Weather Fore-Cast and Energy Consumption Constraints.** In: Szewczyk R., Zieliński C., Kaliczyńska M. (eds) Automation 2019. AUTOMATION 2019. Advances in Intelligent Systems and Computing. Springer
E	Thibbotuwawa A., Bocewicz G., Nielsen P., Banaszak Z. (2020) **Planning deliveries with UAV routing under weather forecast and energy consumption constraints.** In: IFAC-PapersOnLine. Elsevier.
F	Thibbotuwawa A., Bocewicz G., Nielsen P., Banaszak Z. **A solution approach for UAV fleet mission planning in changing weather conditions.** Applied Sciences.
G	Thibbotuwawa A., Bocewicz G., Nielsen P., Banaszak Z. (2020) **UAV mission planning subject to weather forecast constraints.** In: Rodríguez S. et al. (eds) Distributed Computing and Artificial Intelligence, Special Sessions, 16th International Conference. DCAI 2019. Advances in Intelligent Systems and Computing. Springer. An extended version of this paper is invited to be submitted for a special issue of the journal of Sensors.
H	Bocewicz G., Nielsen P., Banaszak Z., Thibbotuwawa A. (2019) **Routing and Scheduling of Unmanned Aerial Vehicles Subject to Cyclic Production Flow Constraints.** In: Rodríguez S. et al. (eds) Distributed Computing and Artificial Intelligence, Special Sessions, 15th International Conference. DCAI 2018. Advances in Intelligent Systems and Computing. Springer.
I	Bocewicz G., Nielsen P., Banaszak Z., Thibbotuwawa A. (2019) **A Declarative Modelling Framework for Routing of Multiple UAVs in a System with Mobile Battery Swapping Stations**. In: Burduk A., Chlebus E., Nowakowski T., Tubis A. (eds) Intelligent Systems in

	Production Engineering and Maintenance. ISPEM 2018. Advances in Intelligent Systems and Computing. Springer.
J	Bocewicz G., Nielsen P., Banaszak Z., Thibbotuwawa A. (2018) **Deployment of Battery Swapping Stations for Unmanned Aerial Vehicles Subject to Cyclic Production Flow Constraints.** In: Damaševičius R., Vasiljevienė G. (eds) Information and Software Technologies. ICIST 2018. Communications in Computer and Information Science. Springer.
K	Kłosowski, G., Gola, A., & Thibbotuwawa, A. (2018). **Computational Intelligence in Control of AGV Multimodal Systems.** In: IFAC-PapersOnLine. Elsevier.
L	Radzki G., Thibbotuwawa A., Bocewicz G. (2019) **UAVs flight routes optimization in changing weather conditions – constraint programming approach,** Applied Computer Science.

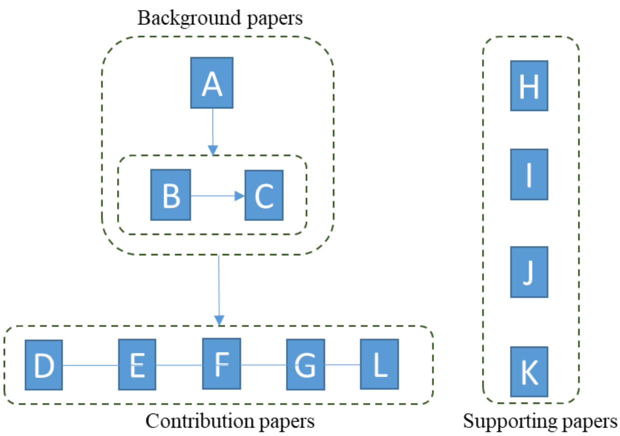


Figure 6. The link between the papers.

Figure 6 shows the overall positioning and link of the appended papers in the thesis. Paper **A** covers the literature study. Research gaps found in relation to non-linear energy consumption models and their relationships to UAV routing, which were obtained in **Paper A** were addressed in Paper **B** and **C**. Paper **A**, **B** and **C** provide the foundation to clearly identify the research gaps in current-state UAV fleet mission planning under changing weather conditions which is formulated and presented in Paper **D**. A declarative model of the problem presented in Paper **D** is elaborated in Paper **E**, **F**, **G** and **L**. With the distinction between the four contributions that:

- Paper **F** focuses on determining UAV fleet mission plans providing the maximum customer delivery satisfaction.

- Paper **E** determines a sequence of sub-missions that ensures delivery to customers, satisfying the requested amount of demands.
- Paper **G** presents a Constraint Optimization Problem (COP) approach to solve the problem which is solved in a constraint-programming environment (IBM ILOG). This paper which was selected as a best paper from 16th International Conference Distributed Computing and Artificial Intelligence. An extended version of this paper is invited to be submitted for a special issue of the journal of Sensors.
- Paper **L** determines solutions to the Vehicle Routing Problem with Time Windows (VRPTW) formulation of the problem.

The additional supporting papers, which were written during the time of the PhD study are presented in Paper **H**, **I**, **J** and **K**. These papers are related to explore various aspects of the routing and scheduling of UAVs and serve as an inspiration to address the problem focused on this research. Paper **H**, **I** and **J** address various related aspects of production systems in which material handling operations are carried out by a fleet of UAVs. Paper **K** focuses on in-plant transportation control with Automated Guided Vehicles (AGVs).

The research objectives for each of the papers from A to K are presented in the Table 2.

Table 2. Overview of the objectives of the appended papers.

Paper	Objectives
A	-Provide an overview of the current-state and contributions to the area of the UAV routing and a general categorization of the VRP followed by a UAV routing classification based on the analysis of existing literature. -Analyze the existing research contributions and identify the gaps in the current- state to address the specific nature of the routing of UAVs in outdoor environment, these are critical in UAV fleet mission planning.
B	-Identify the factors affecting the energy consumption of UAVs during execution of missions and examines the general characteristics of the energy consumption, as these are critical constraining factors in UAV routing. -Provide an overview of the current-state of and contributions to the area of UAV energy consumption followed by a general categorization of the factors affecting UAV energy consumptions
C	-Analyze the different parameters that influence the energy consumption of the UAV routing through an example scenario of a single UAV multiple delivery mission, and based on the analysis, present the relationships between UAV energy consumption and the influencing parameters.

D	-Present a declarative framework enabling to state a model aimed at the analysis of the relationships between the structure of a given UAVs driven supply network and its behavior resulting in a sequence of sub-missions following a required delivery. -Provide an illustrative example of an approach leading to sufficient conditions guaranteeing solutions existence for a solvable class of UAV driven mission planning problems.
E	-Propose a depth-first search strategy to cope with the problem of multi-trip UAV fleet mission planning with the objective to get a sequence of sub-missions that ensures delivery to customers satisfying the requested amount and demands within a given time period. -Provide a methodology, which offers solutions to questions related to the multistage mission planning that could be applied to solve problems such as: minimizing energy consumption and conducting the mission in the shortest possible time.
F	-Present a decision support driven declarative decomposed solution approach to solve the problem of UAV fleet mission planning under changing weather conditions for a fleet of multi-trip UAVs considering factors such as UAVs specifications, weather dependencies, collision avoidance and addressing non-linear energy consumption behavior of UAVs. The proposed model supports the selection of the UAV mission planning scenarios subject to variations on different configurations of the UAV system and changing weather conditions. -Provide solution methodologies to assists fleet mission planners in aerospace companies to select and evaluate different mission scenarios, for which fleet mission plans are obtained for a given fleet of UAVs, while guaranteeing delivery according to customer requirements in a given time horizon.
G	-Present a solution for the UAV fleet mission planning problem as a sequence of sub-missions, which are created through a constraint optimization approach that will ensure delivery of requested amounts of goods to customers, satisfying their demands within a given time period under the given weather forecast constraints. -Establish the relationships between the decision variables such as wind speed and direction, battery capacity and payload weight using computational experiments, which allow assessing alternative strategies of UAV mission planning.
H	-Present solutions for a production system in which material handling operations are carried out by a fleet of UAVs, which will reduce to a minimum UAV downtime and the takt time of the cyclic production flow in which operations are performed by the UAVs.

	-Present a declarative model of the analyzed case, which allows to view the problem as a constraint satisfaction problem and to solve it in the Oz mozart constraint programming environment.
I	-Present a flow production system with concurrently executed supply chains providing material handling/transportation services to a given set of workstations by a fleet of UAVs are considered, where the workstations have to be serviced within preset time windows and can be shared by different supply chains. The batteries on-board the UAVs are replaced at mobile battery swapping stations. -Present a solution to the problem of routing UAVs and mobile battery swapping stations fleets, through determining the routes travelled by the UAVs servicing the workstations and the routes travelled by the mobile battery swapping stations servicing the battery swapping points, such that the total length of these routes is minimized.
J	-Focus the problems of split delivery-vehicle routing problem with time windows and deployment of battery swapping depots. -Determine the number of UAVs and the routes they fly to serve all the workstations periodically, within a given takt time, without violating constraints imposed by the due time, pickup/delivery operations and collision-free movement of UAVs. -Present a declarative model which allows viewing the problem under consideration as a constraint satisfaction problem. The problem is solved in the Oz Mozart programming environment.
K	-Present a model for the problem of in-plant transportation control with AGVs. The controlling part is performed with the use of software constituting a hybrid information system employing fuzzy logic and genetic algorithms. -Present an approach of segmentation of workspace into zones and switching stations to resolve the problem of multimodality in transportation and potential collisions between AGVs.
L	-Formulate the UAV fleet mission planning problem as an extension of the VRPTW and formulated as a COP. -Propose a declarative model (implemented in the IBM ILOG environment) which allows to design routes of UAVs that guarantee the maximum level of customer demand satisfaction for various weather conditions. -Present computational experiments illustrating the impact of weather conditions on route determination.

CHAPTER 2. LITERATURE STUDY

As it is important to identify gaps between real-world requirements to perform mission planning for a fleet of UAVs, the current-state of research into this domain should be deeply studied. In the following, the nature the gaps are elaborated and details leading to the research questions addressed in this PhD thesis, which are presented addressing ***RQ1*** ***RQ2*** and ***RQ3***.

2.1 SURVEY OF LITERATURE

The problems of material delivery mission planning for UAV fleets have gained significant attention in research in recent years (AbdAllah et al. 2017; Bekhti et al. 2017; Thibbotuwawa et al. 2019). UAV mission planning can be treated as an extension of the VRP (Dorling et al. 2016) and belongs to the class of planning problems (AbdAllah et al. 2017; Kambhampati and Davis 1986).

UAV routing relates to a fleet of UAVs that has to visit a set of nodes to deliver demands and it solves the question of: what is the set of routes for a fleet of UAVs to traverse in order to deliver to a given set of customer demands which satisfy the energy capacity constraints of UAVs (Paper **F**)? The UAV fleet mission planning problem relates to the creation of collision-free mission plans, which consists of routes and schedules for a fleet of UAVs to deliver a set of customer demands. The UAV fleet mission planning problem solves the question of: what are the fleet mission plans of a fleet of UAVs to deliver a given set of customer demands?

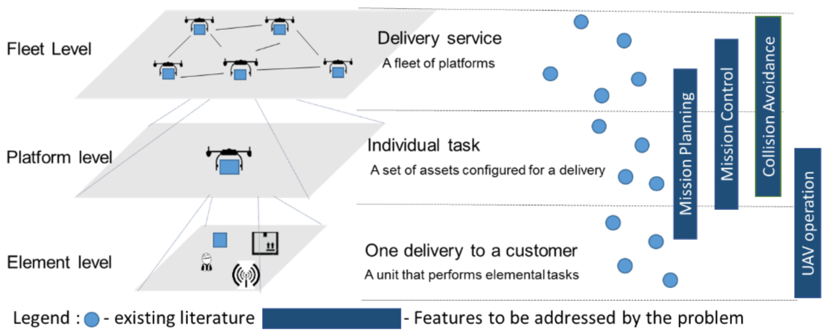


Figure 7. Overall hierarchical representation of the system related to the UAV fleet mission planning problem (Paper **F**).

Unlike the traditional routing problems, the fleet mission planning problem addresses different decision layers in the system architecture. This includes the fleet level where the fleet is managed to provide delivery services using the UAV fleet and the platform level where it focuses on the individual functioning of the UAVs (Paper **F**). The current-state of research is fragmented as shown in the layers illustrated in Figure 7 and neglects that different types of decisions are addressed at different abstraction levels. For this reason, comprehensive studies covering all the three layers are seldom found in the literature. To address this gap, the research presented in this thesis cover both fleet and platform level decisions as shown in Figure 7. Mission planning consists of finding a sequence of waypoints that connects the start to the destination waypoint which differs from trajectory planning where the solution path is expressed in terms of the degrees of freedom of the vehicle (LaValle 2006; Paper **F**). While mission control addresses the updating of such missions during execution, due to e.g. changes in environment (weather).

Limited research has been published in the area of UAV routing in 3-D environments (Guerriero et al. 2014; Sundar et al. 2016; Goerzen et al 2010). In general the accomplishments in the field are focused on UAV routing for transporting materials and surveillance (Dorling et al. 2016) without considering the changing conditions in weather and non-linear energy consumption (Wang et al. 2016). In general vehicle routing problems, the standard objective function is typically minimizing time spent on achieving goals. In contrast, several individual objective functions can be used in UAV routing such as reducing individual UAV costs, enhancing its profit, increasing safety in operations, reducing lead time, and increasing the load capacity of the entire system (Coelho et al. 2017; Enright et al. 2015; Paper **F**). Furthermore, the problem can be seen as an extended case of the vehicle routing and scheduling problem, where the UAV fleet mission planning problem is NP-hard (Dorling et al. 2016; Paper **E;** Paper **F**). This problem differs from the traditional time dependent VRP as it must address both the fleet management as well as the individual vehicle management as shown in Figure 2. In contrast to the typical routing problems in existing literature due to various influencing parameters and constrains unique to UAVs, the decision criteria in UAV fleet mission planning shows a complex behavior.

From literature one can identify the decision criteria in UAV mission planning and that these include numerous parameters and constraints. Specifically we note that the decision space comprises of the following aspects:

- Routing and scheduling in 3D environment (Khosiawan et al. 2016).
- Changing weather conditions (Wind speed, wind direction, air density) (Thibbotuwawa et al. 2019).
- UAVs specifications (Cho et al. 2015).
- Energy consumption affected by weather conditions (Thibbotuwawa et al. 2019).
- Carrying payload of UAVs (Dorling et al. 2016).
- Collision avoidance with respect to:
    - Moving objects (including other UAVs) (Khosiawan et al. 2018).
    - Fixed objects (Khosiawan et al. 2016).

Together, these elements emphasize the potential intractability of mission planning as it is highly challenging to develop models considering all these influencing aspects simultaneously (Paper **F**).

2.1.1 Collision avoidance strategies

Concerning collision avoidance, solutions differ with fixed obstacles vs moving flying obstacles and single obstacle vs many obstacles (Paper **F**). As the solution space becomes large, prevention of collisions can be achieved by heuristics that guarantee collision free mission planning. However, these come at the cost of higher quality solutions as the solutions require covering both fleet level and individual flight planning of each UAV (Figure 7). In the context of mission planning, w.r.t. fleet and platform level, collision avoidance constraints should be considered. In platform level, constraints related to individual UAV such as payload constraints and energy constraints should be focused which are important for the routing of each UAV. Current-state methods for UAV mission planning have predominantly focused on finding paths that satisfy vehicle dynamics assuming linear fuel consumption (Rathbun et al. 2010; Yang and Kapila 2002). A number of the existing models have put less emphasis on the majority of the physical properties particularly related to UAVs. As a consequence the problem has been reduced in complexity to a VRPTW, which includes a large number of targets and UAVs (Pohl and Lamont 2008; Adbelhafiz et al. 2010; Tian et. al 2006; Weinstein and Schumacher 2007). The existing approaches fall into the categories of offline mission planning and online mission control.

Table 3. Strategies to avoid collisions in different contexts.

	Moving obstacles	Fixed obstacles
Predicting/offline planning	Mission organizing satisfying collision avoidance constraints (Hall and Anderson 2011).	Planning the missions avoiding the fixed obstacles (Su et al.2009).
Reacting/online planning	Detection by sensors (Geyer et al. 2008), Avoiding using collision avoidance constraints (Belkadi et al. 2017).	Detection by sensors (Zhan et al. 2014).
Free space	Detection by sensors (Geyer et al. 2008).	Detection by sensors (Geyer, et al. 2008).
Dedicated corridors	Mission organizing satisfying collision avoidance constraints (Belkadi et al. 2017).	Mission organizing satisfying collision avoidance constraints (Thibbotuwawa et al. 2020).

Collision avoidance is seldom considered in UAV routing literature. In mission planning, studies have assumed that the UAVs can detect obstacles to avoid collisions (Belkadi et al. 2017). Collision avoidance consists of two aspects; the physical avoidance of objects that are detected by sensors near the UAV during its flight and that the routes of the UAVs are planned such that all known obstacles (e.g. routes of other UAVs) are avoided in the plan. The majority of recent studies regarding routing problems in communication networks do not explicitly avoid collisions between UAVs during the routing (Paper **F**). Rather it is assumed that recent advances in collision avoidance technology allows most small UAVs to sense the air traffic and alter flight altitudes or turn in order to avoid collision (Shetty et al. 2008; Paper **F**). Collision avoidance can be conducted by predicting potential collisions in offline planning, whereas in online control it is achieved by reacting to potential collisions. In most of the reactive planning systems, collisions are avoided using the detection of sensors, where the UAVs in the system communicate via wireless networks (Geyer et al. 2008). In addition, the approaches to collision avoidance differ when the fleet of UAVs are flying in free space vs dedicated corridors (Paper **F**). Table 3 illustrates some of the common strategies pursued in literature.

2.1.2 Constraining factors particular to UAVs and UAV fleet mission planning

UAVs are subject to a number of constraints, some are typical and often addressed in VRP or related problems (e.g. energy constraints). However, there are a number of aspects that necessitates to treat the problem in a manner separate from the traditional transportation problems. UAVs are limited by loading capacity as well as flight duration, which is related to the energy capacity. These constraints are typically addressed in transportation problems. However, UAVs have the additional complexity that the flight duration depends on the payload carried which requires these characteristics to be taken into consideration in UAV mission planning (Song et al. 2018, Maza and Ollero 2007). A number of contributions have proposed to divide the whole mission area taking into account UAVs relative capabilities and to cluster the subsequent smaller areas to reduce the problem size (Habib et al. 2013; X. F. Liu et al. 2014; Xu et al. 2001; Sung and Nielsen 2019). Figure 8 illustrates the relationships between different factors linked to energy consumption of UAVs. Weather in various forms is critical for energy consumption, as it affects the travel speed of the UAV, and the temperature in the atmosphere affects the energy capacity (Dorling et al. 2016; Paper **F**) of batteries used in UAVs. Air density affects the energy consumption, but that is a function of humidity, air pressure and temperature. Cold temperatures may adversely affect battery performance until the batteries warm up (Dorling et al. 2016).

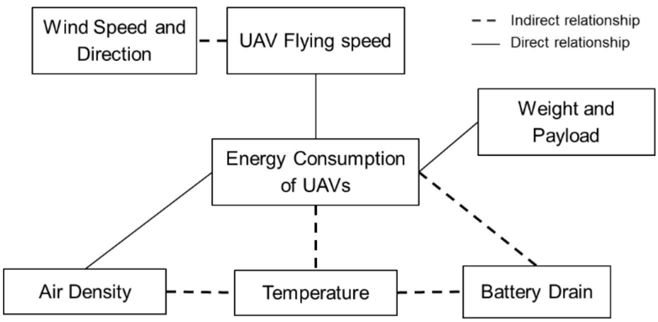


Figure 8. Factors that affect energy consumption of UAVs (Paper **B**).

The current-state of research has yet to consider weather factors and assume the weather has a negligible impact on performance (Guerriero et al. 2014; Habib et al. 2013; Sundar and Rathinam 2014). Rarely has research focused on considering wind conditions on energy consumption while simultaneously using that information in planning the missions of UAVs (Rubio and Kragelund 2003; Nguyen and Tsz-Chiu 2017; Dorling et al. 2016), with the work of being the few contributions currently found. Certain studies have assumed constant wind speed and wind direction (Rubio and Kragelund 2003) and used linear approximations for energy consumption (Dorling et al. 2016; Paper **F**).

2.1.3 Summary of current-state of literature

Existing work does not adequately address the requirements for UAV fleet mission planning considering organizing delivery networks to deliver customer demands during a time period with changing weather with the goal of maximizing the customer demand satisfaction before the end of time period. Literature status with the gaps in terms of addressing the problem studied in this thesis are further discussed in detail in Paper **A** and the research gaps found in relation to non-linear energy consumption models and their relationships to UAV routing were addressed in Papers **B** and **C**. For the class of UAVs considered in this research linear approximations are not reasonable as the weight of the UAV is larger than the UAVs used in existing research (Paper **F**). In existing research considered weight of UAVs are less than 4 Kgs whereas in this study considered weight is more than 40 Kgs and the models used in existing literature are not reasonable when the weight of UAVs increases (Dorling et al. 2016). Hence, the non-linear models proposed in Paper **B** are used to calculate energy consumption considering weather conditions and carrying payload in this research. This research focuses on mission planning of UAVs, where the collisions with known obstacles are addressed in advance and missions are planned ensuring collision avoidance (between the UAVs). Furthermore, in this research, customers are clustered and for each cluster a set of feasible UAV fleet routings and accompanying schedules taking into account the weather conditions imposing the energy consumption constraints are calculated (Papers **E** and **F**).

CHAPTER 3. UAV FLEET MISSION PLANNING

In this chapter, the general form of the overall decision problem addressed in the thesis is presented. The problem of UAV fleet mission planning is presented and the solution approach is proposed where it answers ***RQ4***.

3.1 PROBLEM DESCRIPTION

The identification of goals and criteria related to the UAV fleet mission planning problem form the foundation of determining what constitutes a satisfactory outcome of the planning process. Based on the overall goal, one should identify the criteria associated while keeping in mind that those criteria should be satisfied during the solution process. A criterion can be associated with available resources, time period within which the mission needs to be completed, etc. The problem addressed in this research concerns that a set of customers are to be served during a time period subject to changing weather conditions by a fleet of UAVs (Paper **F**). In general, the problem focused is presented as follows:

Given: Weather forecast data, network data, Customer demand data, UAV specifications.
Focus question: Is it possible to create a fleet mission plan, which consists of routes and schedules that provide the maximum customer demand satisfaction?

The goal is to maximize the customer demand satisfaction, such that each customer is serviced before the end of the time period while respecting the energy consumption constraints and ensuring conflict and collision-free routes. The output should provide a sequence of sub-missions as illustrated in Figure 13, which maximizes customer demand satisfaction for all customers.

3.1.1 Understanding the context of the problem

In order to better understand the problem, objective function, decision variables and constraints should be identified based on the specifications. The objective function formulated using variables reflects a goal and criteria that relates to the perceived quality of a given mission plan. The decision variables represent the state of the overall system ensuring the achievement of the desired outcome. The objective function is then maximized or minimized by determining the decision variables subject to a set of constraints representing operational conditions and restrictions that must be respected during mission execution. Thus, it is important to know in which context the problem is tackled (requirements, desired outcomes, etc.).

The overall representations of the proposed structure to understand the nature of the problem addressed in this thesis w.r.t. the overall goal, criteria, objectives, constraints, decisions and outcome are illustrated in Figure 9. The illustration in Figure 9, shows how some decisions, within the red border, are critical for achieving the overall goal of the decisions and outcomes shown as central (denoted by the red border). The decisions shown as supporting in green border implies to the supporting decisions, which reduces the complexity of the problem.

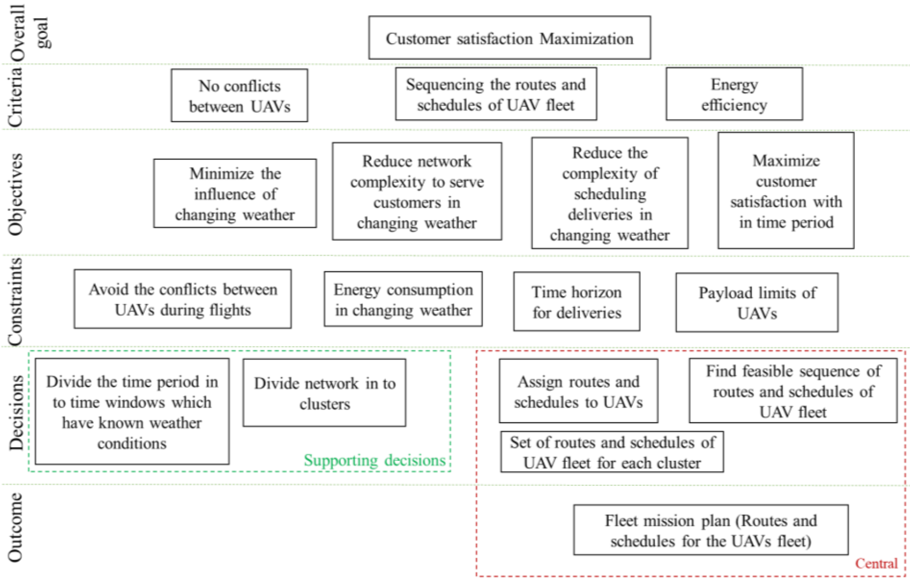


Figure 9. Overview description of the problem.

There are several potential approaches based on the literature to address the considered problem as mentioned below.

- Developing a new hybrid meta-heuristic able to solve the problem (Duan et al. 2010; Khosiawan et al. 2018; Zhang et al. 2016) .
- Multi agent approach to solve the problem (Casbeer and Holsapple 2011; Tso et al. 1999; Chen et al. 2013).
- Developing a COP approach (Paper **L).**
- Decomposition based heuristic approach (Paper **E** and **F**).

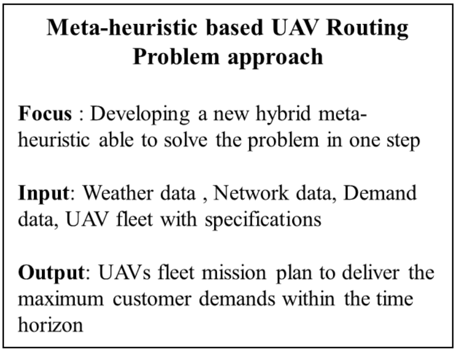


Figure 10. Meta-heuristic based approach to solve the problem.

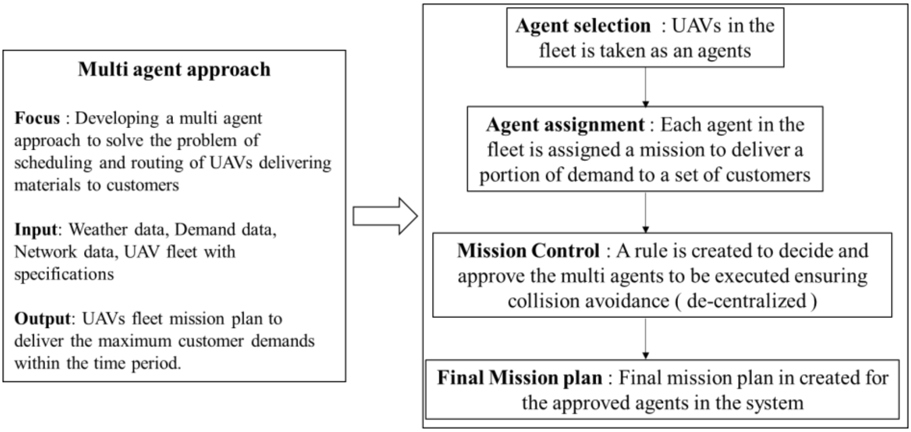


Figure 11. Multi agent approach to solve the problem.

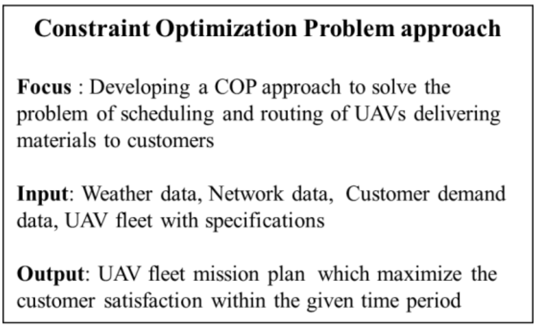


Figure 12. COP based approach to solve the problem.

Figure 10 represents a meta-heuristic approach to solve the problem in a UAV routing problem approach, concerning the problem focused in this study with its input and output. Figure 10 illustrates how the implementation of a dedicated search strategy implemented in the form of a hybrid meta-heuristic would be used to address the problem. In that context, one hybrid meta-heuristic needs to be formulated combining all the aspects of UAV fleet mission planning together but such approaches are better in finding solutions for only specific instances as they have less flexibility and adaptability (Khosiawan et al. 2018). Thus, extensive parameter tuning is required in meta-heuristics. Furthermore, adaptation to changes in the problem specifications potentially require the development of a completely new solution approach. Due to the complexity and interdependency of the influencing parameters involved in this research study that includes UAV specifications, network complexity and weather complexity which affect the energy consumption of UAVs, such hybrid meta-heuristic approaches are not able to provide solutions for the large scale problems (Duan et al. 2010; Zhang et al. 2016). Such solution approaches are found broadly in literature and have been applied to various topics and problems over the last decade (Duan et al. 2010; Khosiawan et al. 2018; Zhang et al. 2016).

Figure 11 illustrates an approach where a multi agent approach is used to tackle the problem. In that context each UAV in the fleet is considered as an individual agent and the agents are assigned separately to deliver materials to customers. The collision avoidance is ensured between the agents through a control rule determining which agent to be executed in a given time. In such an approach the agents need to communicate to each other to address mission control issues but the UAVs used in this problem are not capable of this. Such multi agent approaches lack of potential solution quality when the relations between tasks, resources and weather conditions is as complex as it is in the problem focused in this study. These approaches provide sub-optimal results and are neither able to guarantee high quality solutions to the considered problem when the number of agents increases nor supports UAV fleet mission prototyping (Casbeer and Holsapple 2011; Tso et al. 1999; Chen et al. 2013).

Among these potential approaches to address the problem considered in this research, Figure 12 illustrates a COP approach to solve the problem and this approach is presented in detail in Paper **G**. The problem is formulated as an extension of VRPTW and solved in a COP approach in Paper **L**. The results obtained from the presented COP approaches have limitations in generating solutions for large instances. As these COP based approaches, multi agent approaches and hybrid meta-heuristic approaches are not able to guarantee results with regards to the highly complex and interdependent aspects of UAV fleet mission planning, a decomposition based heuristic approach was proposed in this research. Decomposed approaches are better in terms of scaling and successful in providing solutions considering highly complex and interdependent aspects of UAV fleet mission planning (Paper **F**). Furthermore, as far as the decomposition is utilized, the solution approaches to the individual sub-problems can be replaced with alternative solution strategies. This ensures the interdependency between the sub-problems is maintained, but that the fundamental approach remains the same. A decomposition approach is therefore considered to be more flexible in terms of changes to problem specifications than e.g. developing a dedicated meta-heuristic. The proposed decomposed approach is presented in section 3.5.

3.2 ASSUMPTIONS

To facilitate the formulation of the problem, with the goal and criteria as stated as above in Figure 9, some assumptions are necessary. The aim of the work presented in this thesis is to reduce the number and scope of the assumptions as much as possible. At the same time assumptions are introduced in such a manner that they have the least possible impact on the quality of solutions in terms of ensuring a real-life implementation will achieve the goals in as faithful a manner as possible. To limit the assumptions we must first define a few features.

First, we define that there is such a term as a Sub-mission Time Window (STW) and that any STW can be subdivided into Flying Time Windows (FTWs). In defining the FTWs, the length of the time used in flying of UAVs considering the maximum energy limit and maximum carrying payload (Papers **E** and **F**). We also define that customer demand satisfaction is the portion of demand volume delivered to a customer by the fleet of UAVs from the total demand volume of that customer in a given time period. With these in mind we can state some necessary constraints related to four different areas (Papers **E** and **F**).

Weather related assumptions:

- A weather forecast is known in advance with sufficient accuracy to specific so called STWs, in which constant weather conditions, such as speed and direction of wind exists. For this purpose, we define a STW as a time period for which a constant wind direction and a range of wind speed can be given.
- The minimum and maximum ranges of wind speed for each STW is known in advance from the weather forecast and the wind direction can be considered constant in a given STW **.**

UAV related assumptions:

- The UAVs within the fleet are homogenous. This specifically means that each UAV:
  - Has the same energy capacity and consumption behavior.
  - Spends the same time for take-offs and landings.
  - Has sufficient energy capacity to travel directly to the farthest customer in the network and come back directly to the depot in worst acceptable weather conditions .
- At the start of each new STW the energy level for any UAV is assumed to be the maximum energy capacity.
- Each UAV can fly only one complete mission during a FTW. This can be extended for reusability of UAVs within the same FTW and recharging stations should be introduced at the depot with time taken for recharging. Thus, missions should be created considering recharging of UAVs and time taken to recharge.

Customer and demand related assumptions:

- A similar type of material is delivered to customers in different amounts [Kgs] and the material is stackable.
- Customers can accept deliveries at any time during the time period.
- Maximizing the customer demand satisfaction is equivalent to all customers receiving the maximum demand volume.

Operations and network related assumptions:

- Network data is given, including the location of each customers, base and flying corridors.
- Customers in the network can be divided into different clusters in order to reduce the complexity of the network.
- UAV starts and finishes its traveling route of a within a given FTW.
- More than one UAV can start to fly from the base at the same time. UAVs do not conflict with each other during takeoff as long as they are not traversing the same arc at the same time.

3.3 DECLARATIVE MODEL

For deriving a decision support driven model to address the UAV fleet mission planning problem a declarative model is proposed in Papers **E** and **F**. The mathematical formulation of the declarative model of UAV fleet mission planning in changing weather conditions employs the following symbols (Paper **F**). The main formula are referred in numbers ((1) to (11)) and the equations which explains the main formulas are referred in letters ((a) to (k)).

Sets and sequences

$G = (N, E)$	The graph representing the transportation network
$N = \{0 \ldots a\}$	The set of nodes representing the base (node 0) and customer locations of nodes
$E = \{\{i, j\} \mid i, j \in N, i \neq j\}$	The set of edges defined between each pair of nodes
$CL_{m,l} = \left(N_{m,l}, E_{m,l}\right)$	The subgraph of G representing m^{th} cluster in l^{th} flying time window; $\sigma(l)$ - number of clusters in l^{th} flying time window
$N_{m,l}$	The set of nodes in the m^{th} cluster in the l^{th} flying time window, $N_{m,l} \subseteq N$
$E_{m,l}$	The set of edges in m^{th} cluster in the l^{th} flying time window, $E_{m,l} \subseteq E$

Parameters

UAV Technical Parameters

Q	The maximum loading capacity of a UAV [Kg]
ep	The empty payload of a UAV [Kg]
$vg_{i,j}$	The ground speed of a UAV from node i to j [m/s]
$\vartheta_{i,j}$	The angle of the vector of ground speed $vg_{i,j}$ [degrees]
$va_{i,j}^{l}$	The airspeed of a UAV from node i to j in the l^{th} flying time window
$\overline{va_{i,j}^{l}}$	The maximum range of $va_{i,j}^{l}$
$\underline{va_{i,j}^{l}}$	The minimum range of $va_{i,j}^{l}$
P_{max}	The maximum energy capacity of each UAV [J] in the fleet of UAVs
$P_{i,j}^{k}$	The amount of energy consumed per time unit from node i to j by k^{th} UAV [J/s]
w	The time spent for take-offs and landings of UAVs
K	The size of the fleet of UAVs

Network Parameters

$d_{i,j}$	The travel distance from node i to j [m]
$t_{i,j}$	The travel time from node i to j [s]
D_i	The demand at node $i \in N_0 = N \setminus \{0\}$[Kg]
$b_{\{i,j\};\{\alpha,\beta\}}$	The binary variable of crossing edges

$$b_{\{i,j\};\{\alpha,\beta\}} = \begin{cases} 1 & \text{when an edge } \{i,j\} \text{ and } \{\alpha,\beta\} \text{ is utilized} \\ 0 & \text{otherwise} \end{cases}$$

Environmental Parameters

H	The time period $H = [0, t_{max}]$
STW_T	The Sub-mission time window T: $STW_T = [STWS_T, STWE_T]$, $STWS_T$ / $STWE_T$ is a start/end time of STW_T
FTW_l	The flying time window l: $FTW_l = [FTWS_l, FTWE_l]$, $FTWS_l$/$FTWE_l$ is the start time of FTW_l
Φ	The number of Flying time windows
vw_l	The Wind Speed in the l^{th} flying time window
$\overline{vw_l}$	The Maximum range of vw_l

$\underline{vw_l}$	The Minimum range of vw_l
θ_l	The Wind direction in the l^{th} flying time window
WUV	WUV= α (the standard deviation of the wind directions) + β (the standard deviation the wind speeds)
α, β	The Weighted parameters corresponding to wind speed and wind direction
g	Gravitational acceleration [m/s^2]

Variables

Decision Variables

$x_{i,j}^k$	The binary variable used to indicate if k^{th} UAV travels from node i to node j $x_{i,j}^k = \begin{cases} 1 & \text{if } k^{th} \text{ UAV travels along from node } i \text{ to node } j \\ 0 & \text{otherwise} \end{cases}$
y_i^k	The time that k^{th} UAV arrives at the node i
s_0^k	The time that k^{th} UAV starts to fly from node 0
c_i^k	The payload weight amount delivered to node i by k^{th} UAV
$f_{i,j}^k$	The payload weight carried by a UAV from node i to j by k^{th} UAV

Output Variables

$S_{n,m,l}$	The n^{th} sub-mission in the m^{th} cluster in the l^{th} flying time window, $S_{n,m,l}$ = ($R_{n,m,l}, P_{n,m,l}, C_{n,m,l}$) ; $\psi(m,l)$ – the number of sub-missions in the m^{th} cluster in the l^{th} flying time window
$C_{n,m,l}$	The customer demand satisfaction levels of n^{th} sub-mission in m^{th} cluster in the l^{th} flying time window
$Ro_{r,m,l}$	The r^{th} route in the m^{th} cluster in the l^{th} flying time window, where each route consists of a sequence of nodes (starts from the base , visits one or more customer nodes and returns to the base)
$Pl_{r,m,l}$	The schedule of the r^{th} route in the m^{th} cluster in the l^{th} flying time window, where each schedule consists of a sequence of times where the nodes in a corresponding route is reached
$CS_{r,m,l}$	The customer demand satisfaction levels of the r^{th} *route* in the m^{th} cluster in the l^{th} flying time window
$R_{n,m,l}$	The routes of the n^{th} sub-mission in the m^{th} cluster in the l^{th} flying time window. $R_{n,m,l}$ consists of a set of routes ($Ro_{r,m,l}$)
$P_{n,m,l}$	The schedules of n^{th} sub-mission in m^{th} cluster in the l^{th} flying time window $P_{n,m,l}$ consists of a set of schedules ($Pl_{r,m,l}$)
$RL_{s,m,l}$	The s^{th} scenario in the m^{th} cluster in the l^{th} flying time window, $RL_{s,m,l} = \left(Ro_{r,m,l}, Pl_{r,m,l}, CS_{r,m,l}\right)$; ¥ (m,l) – the number of scenarios in the m^{th} cluster in the l^{th} flying time window

$Cs_{i,n,m,l}$ The customer demand satisfaction level of the i^{th} node of the n^{th} sub-mission in the m^{th} cluster in the l^{th} flying time window

Constraints

Arrival time at nodes

The relationship between the binary decision variable of $x_{i,j}^{k}$ and the decision variable of y_i^k.

$$(x_{i,j}^{k} = 1) \Rightarrow (\, y_j^k = y_i^k + t_{i,j} + w) \quad , \qquad \forall\{i,j\} \in E, \forall k \in K. \quad (1)$$

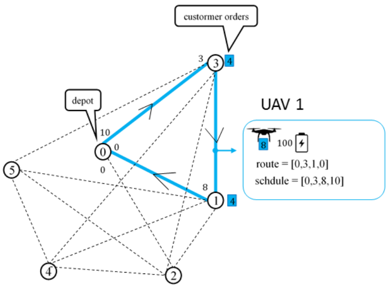
If UAV k is flying from node i to node j in a given FTW then the arrival time y_j^k to node j is equal to the sum of travel time $t_{i,j}$ between node i to j, time spent for take up landing w and the arrival time y_i^k to node i (1).

Example 1: If the utilized UAV is $k = 1$ on Figure 13 then formula (1) for each edges from route (blue arrows) is shown in (a), (b) and (c) assuming that $s_0^k = 0$.

$$(x_{0,3}^{1} = 1) \Rightarrow (\, y_3^1 = s_0^k + 2 + 1) = 3. \qquad (a)$$

$$(x_{3,1}^{1} = 1) \Rightarrow (\, y_1^1 = y_3^1 + 4 + 1) = 8. \qquad (b)$$

$$(x_{1,0}^{1} = 1) \Rightarrow (\, y_0^1 = y_1^1 + 1 + 1) = 10. \qquad (c)$$



x_{ij}^k		j					
		0	1	2	3	4	5
i	0	0	0	0	1	0	0
	1	1	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	1	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0

y_j^k	j					
	0	1	2	3	4	5
Time	10	8	—	3	—	—

t_{ij}		j					
		0	1	2	3	4	5
i	0	—	1	8	2	7	1
	1	1	—	2	4	5	3
	2	8	2	—	8	2	6
	3	2	4	8	—	8	7
	4	7	5	2	8	—	2
	5	1	3	6	7	2	—

w=1

Legend : : UAV : Battery of UAV

Figure 13. Illustration of example 1.

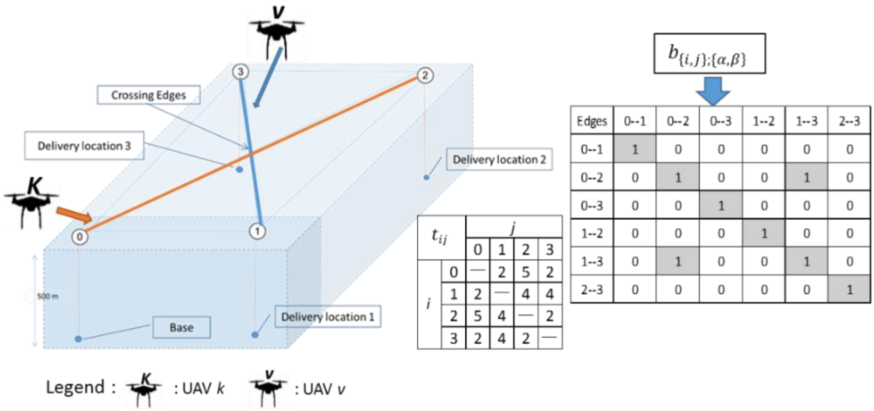
Collision avoidance

As the UAV fleet mission planning should ensure collision avoidance, Paper **E** proposes collision avoidance constraints to ensure that no more than one UAV can occupy at an edge in the network at the same time. This includes the blocking edges corresponding to which is utilized by UAV k and UAV v. The blocking edges $(b_{\{i,j\};\{\alpha,\beta\}} = 1)$ should not be utilized at the same time when they are occupied by the UAVs ($x^k_{i,j} = 1$ and $x^v_{\alpha,\beta} = 1$). Thus, in collision avoidance, it provides the decision to fly the UAV with higher priority before the UAV with lower priority. If UAV k has higher priority than UAV v then:

$$\begin{cases} \left(b_{\{i,j\};\{\boldsymbol{\alpha},\boldsymbol{\beta}\}} = 1\right) \wedge \left(x^k_{i,j} = 1\right) \wedge \left(x^v_{\boldsymbol{\alpha},\boldsymbol{\beta}} = 1\right) \Rightarrow (y^k_j \leq y^v_{\boldsymbol{\alpha}}) \\ \left(b_{\{i,j\};\{\boldsymbol{\alpha},\boldsymbol{\beta}\}} = 1\right) \wedge \left(x^k_{i,j} = 1\right) \wedge \left(x^v_{\boldsymbol{\beta},\boldsymbol{\alpha}} = 1\right) \Rightarrow (y^k_j \leq y^v_{\boldsymbol{\beta}}) \\ \left(b_{\{i,j\};\{\boldsymbol{\alpha},\boldsymbol{\beta}\}} = 1\right) \wedge \left(x^k_{j,i} = 1\right) \wedge \left(x^v_{\boldsymbol{\beta},\boldsymbol{\alpha}} = 1\right) \Rightarrow (y^k_i \leq y^v_{\boldsymbol{\beta}}) \\ \left(b_{\{i,j\};\{\boldsymbol{\alpha},\boldsymbol{\beta}\}} = 1\right) \wedge \left(x^k_{j,i} = 1\right) \wedge \left(x^v_{\boldsymbol{\alpha},\boldsymbol{\beta}} = 1\right) \Rightarrow (y^k_i \leq y^v_{\boldsymbol{\alpha}}) \end{cases} \quad \begin{matrix} k = 1 \ldots K \\ v = 1 \ldots K, \end{matrix} \qquad (2)$$

Example 2: If UAV k has a higher priority than UAV v (Figure 14) then formula (2) ensures utilizing the edges of 0-2 (orange line) and 1-3 (blue line) ensuring collision avoidance (e).

$$\left(b_{\{0,2\};\{3,1\}} = 1\right) \wedge \left(x^k_{0,2} = 1\right) \wedge \left(x^v_{3,1} = 1\right) \Rightarrow (y^k_2 \leq y^v_3). \qquad (e)$$



t_{ij}		j			
		0	1	2	3
i	0	—	2	5	2
	1	2	—	4	4
	2	5	4	—	2
	3	2	4	2	—

Edges	0--1	0--2	0--3	1--2	1--3	2--3
0--1	1	0	0	0	0	0
0--2	0	1	0	0	1	0
0--3	0	0	1	0	0	0
1--2	0	0	0	1	0	0
1--3	0	1	0	0	1	0
2--3	0	0	0	0	0	1

Figure 14. Illustration of example 2.

Capacity

The demand assigned to a UAV should not exceed its capacity, which leads to the following formulation:

$$\sum_{i \in N_{m,l}} \sum_{j \in N_{m,l}} x^k_{i,j} c^k_j \leqslant Q \qquad , \qquad k = 1 \ldots K. \quad (3)$$

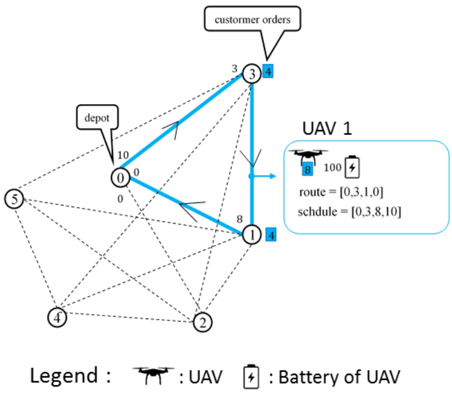
The sum of all the carried weights c_j^k by UAV k should not exceed the maximum carrying payload Q. Furthermore, the sum of all carried weights delivered to a customer should not exceed the demand of each customer (4).

Example 3: In the route (blue lines) shown in Figure 15, customers receive 4 Kgs of material ($c_3^1 = 4$, $c_1^1 = 4$) by UAV no. 1 which has a maximum loading capacity of 10 Kgs (Q=10). UAV 1 returns to the depot with empty payload (c_0^1=0). This is shown in (*f*) and (*g*) using formula (3).

$$x_{0,3}^1 c_3^1 + x_{3,1}^1 c_1^1 + x_{1,0}^1 c_0^1 \leqslant Q. \qquad (f)$$

$$1 * 4 + 1 * 4 + 1 * 0 \leqslant 10. \qquad (g)$$

$$\sum_{k \in K} \sum_{i \in N} \sum_{j \in N} x_{i,j}^k c_j^k \leqslant D_i \qquad , \qquad i \in N_0 = N \setminus \{0\}. \quad (4)$$



x_{ij}^1		j					
		0	1	2	3	4	5
i	0	0	0	0	1	0	0
	1	1	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	1	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0

Figure 15. Illustration of example 3.

Flow of UAVs

When a UAV arrives at a node, the UAV must depart from that particular node.

$$\sum_{j \in N_{m,l}} x_{i,j}^k - \sum_{j \in N_{m,l}} x_{j,i}^k = 0 \qquad , \qquad k = 1 \dots K, \forall i \in N_0 = N_{m,l} \cup \{0\}. \; (5)$$

The sum of all the occupied edges which enter node i ($\sum_{j \in N_{m,l}} x_{j,i}^k$) should be equal to the sum of all the edges, which depart from node i ($\sum_{j \in N_{m,l}} x_{i,j}^k$).

Example 4: In the route illustrated in Figure 15, the sum of all the occupied edges which go to node 1 should equal the sum of all the edges which departs from node 1. This is shown in (h) and (i) using formula (5).

$$(x_{1,0}^1 + x_{1,2}^1 + x_{1,3}^1 + x_{1,4}^1 + x_{1,5}^1) - (x_{0,1}^1 + x_{2,1}^1 + x_{3,1}^1 + x_{4,1}^1 + x_{5,1}^1) = 0. \, (h)$$

$$(1+\ 0+0+\ 0+0)-(0+\ 0+1+\ 0+0)=0. \qquad (i)$$

Start and end of routes

Each UAV that departs from the depot (Node 0) should return to the depot.

$$(x_{i,j}^{k}>0)\Rightarrow\ (\sum_{i\in N_{m,l}}\ x_{0,i}^{k}=\sum_{i\in N_{m,l}}\ x_{i,0}^{k}=1) \qquad , \qquad k=1\dots K. \qquad (6)$$

Constraint (6) ensures that each UAV departs from the depot (Node 0) and returns to the depot. The sum of all the edges which start from node 0 as well as the sum of all the edges which returns to node zero should be equal to one.

Example 5: By using the example 3 in Figure 15, (5) is checked in (*j*) and (*k*).

$$(x_{3,1}^{1}>0)\Rightarrow(x_{0,1}^{1}+x_{0,2}^{1}+x_{0,3}^{1}+\ x_{0,4}^{1}+x_{0,5}^{1})=(x_{1,0}^{1}+x_{2,0}^{1}+x_{3,0}^{1}+x_{4,0}^{1}+x_{5,0}^{1})=1. \, (j)$$

$$(0+\ 0+1+\ 0+0)=(1+\ 0+0+\ 0+0)=1\,. \qquad (k)$$

Energy

Each UAV has a maximum energy capacity of P_{max} and in flight it is not possible to consume more than the max energy capacity (Paper **E**).

$$\sum_{i\in N_{m,l}}\ \sum_{j\in N_{m,l}}\ x_{i,j}^{k}\,P_{i,j}^{k}\,t_{i,j}\leqslant P_{max} \qquad , \qquad k=1\dots K. \qquad (7)$$

The energy constraint (7) defines that the energy consumed by the k^{th} UAV should be less than or equal to the maximum energy capacity of the UAV. To calculate the energy consumption of the UAVs considered in this research, energy consumption equations introduced in Paper **B** were used. The energy consumption of the UAVs as following.

$$P_{i,j}^{k}=\frac{1}{2}C_{D}AD(va_{i,j}^{l})^{3}+\frac{\left((ep+\ f_{i,j}^{k})g\right)^{2}}{Db^{2}va_{i,j}^{l}}\,, \qquad (8)$$

where C_D is the aerodynamic drag coefficient, A is the front facing area, ep is the empty weight of the UAV, D is the density of air, b is the width of UAV and g is gravitational acceleration (Paper **F**). The air speed of a UAV $va_{i,j}^{l}$ is defined in the following equations and an example for calculation of $va_{i,j}^{l}$ (considering $vg_{0,4}$=20 m/s) is shown in Figure 16.

$$\overline{va_{i,j}^{l}}=\sqrt{\left(vg_{i,j}\cos\vartheta_{i,j}-\underline{vw_{l}}\cos\theta_{l}\right)^{2}+\left(vg_{i,j}\sin\vartheta_{i,j}-\underline{vw_{l}}\sin\theta_{l}\right)^{2}}\,. \qquad (9a)$$

$$\underline{va}_{i,j}^{l} = \sqrt{\left(vg_{i,j}\cos\vartheta_{i,j} - \overline{vw_l}\cos\theta_l\right)^2 + \left(vg_{i,j}\sin\vartheta_{i,j} - \overline{vw_l}\sin\theta_l\right)^2}\,. \qquad (9b)$$

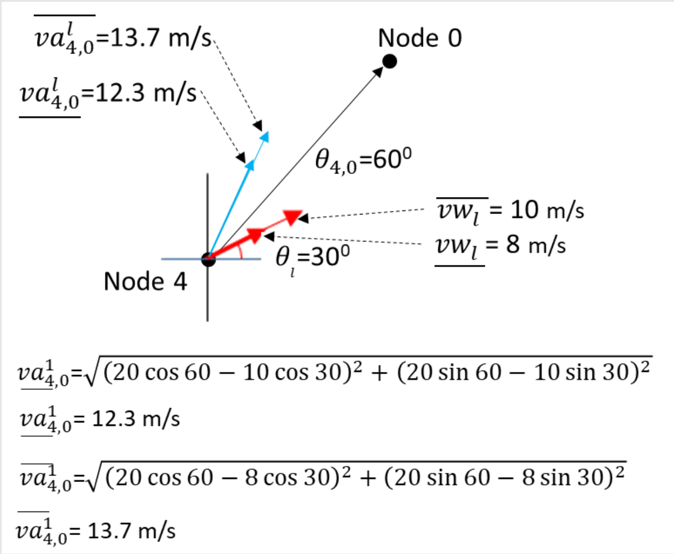


Figure 16. Example of calculation of UAV $va_{i,j}^{l}$.

The objective function

The objective is to maximize the customer demand satisfaction levels for all the customers (10), where $Cs_{i,n,m,l}$ is calculated as a percentage using (11) as presented in Paper **F**.

$$\text{maximize:} \quad \min_{i\,\in\,N_0} \left\{\sum_{i\in N} \sum_{n=1}^{\psi(m,l)} \sum_{m=1}^{\sigma(l)} \sum_{l=1}^{\Phi} \frac{1}{a} Cs_{i,n,m,l}\right\}. \qquad (10)$$

$$Cs_{i,n,m,l} = \frac{\sum_{k\in K} c_i^k}{D_i}. \qquad (11)$$

The solution approach considered in the study is illustrated in Figure 17. A set of customers located at different points in a delivery distribution network are to be serviced by a fleet of UAVs during a specified time period that contains changing weather conditions.

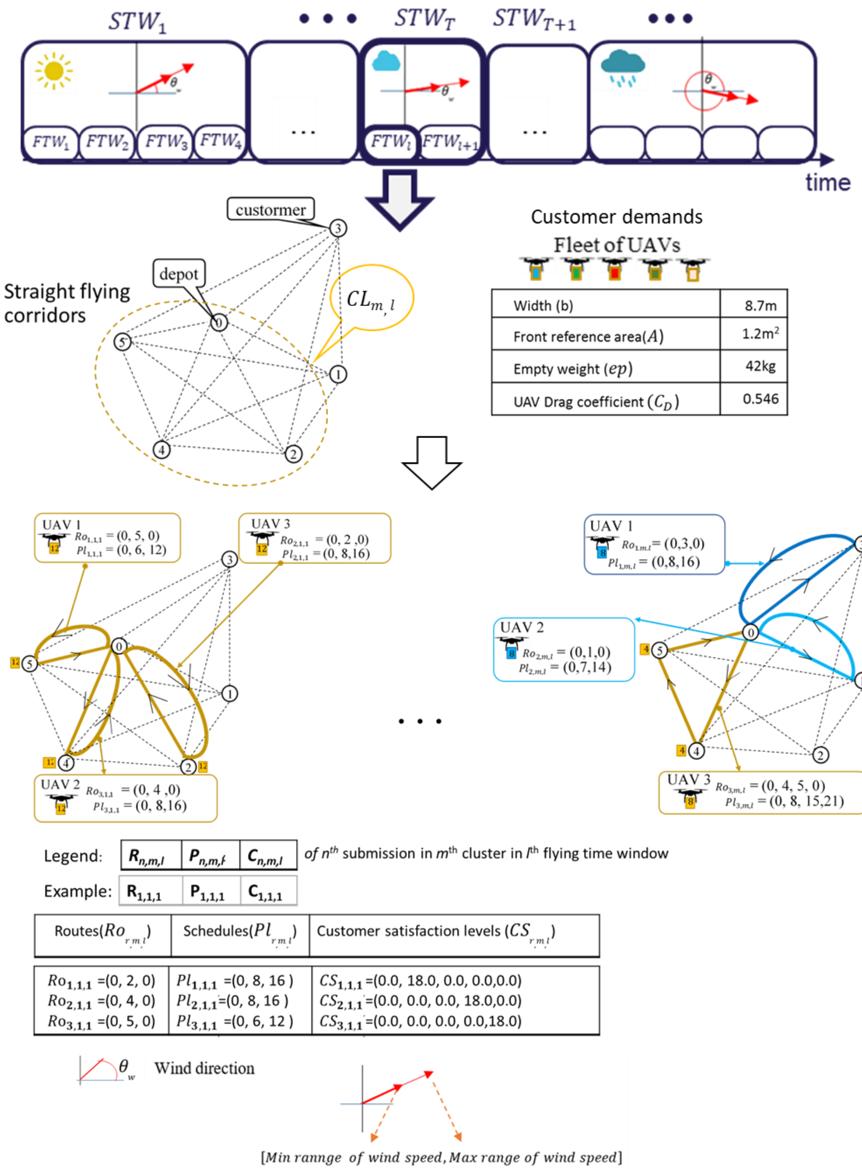


Figure 17. The problem modeling illustration (Paper **F**).

Figure 17 illustrates the time period as a sequence of STWs, which consists of different weather conditions. Each STW consists of a range of wind speed and a given wind direction so that in creation of routes and schedules for the UAV fleet, the weather data of each STW are considered. The specifications of the UAVs, customer demands, network data with flying corridors and customer locations and weather data are given as input data. A solution strategy should be used to create a final mission plan which consists of a sequence of sub-missions with corresponding routes and schedules (blue and orange lines) for the UAV fleet as shown in the latter part of Figure 17.

3.4 PROBLEM FORMULATION

As mentioned in the literature review, there are still no effective solutions, which allow to plan (route and schedule) UAV missions under the changing weather conditions. In order to find a solution for the problem following guiding question to facilitate the main problem should be considered (Papers **E** and **F**).

Is it possible to create a fleet mission plan which consists of a sequence of sub-missions $S_{n,m,l} = (R_{n,m,l}, P_{n,m,l}, C_{n,m,l})$ (determined by decision variables x_{ij}^k, $y_i^k, c_i^k, f_{i,j}^k$) of a given UAV fleet which maximize customer demand satisfaction ($Cs_{i,n,m,l}$) considering weather conditions and all defined constraints within the given time period (H) ?

Problem statement

The problem's nature gives that a set of geographically dispersed customers should be served by a fleet of UAVs charged from a central charging depot within a clearly defined time period, while taking into account that changing weather conditions occur. The goal is to maximize the demand satisfaction, such that each customer is reached with the maximum demand before the end of the time period, while obeying all hard constraints.

3.5 DECOMPOSITION APPROACH

A decomposition approach is proposed to solve the problem. It is inspired by the work completed by Cheng and Wang (2009), who solve the VRPTW using a decomposition technique. Cheng and Wang (2009) results show that problem decomposition provides better solution quality than directly solving the problem in one step (Cheng and Wang 2009). Accordingly, a general decomposed approach consisting of four sub-problems is proposed to overcome the potential poor solution quality found in the one step approach. This decomposition is presented in Paper **E** and explained in detail in Paper **F**.

3.5.1 Determine the Sub-mission Time Windows

In order to reduce the complexity of the weather conditions in the main problem, the first considered sub-problem assumes that a given time period with changing weather conditions can be divided into several STWs as proposed in Papers **E** and **F**. As proposed in Paper **F**, the STWs consist of similar weather conditions from the start of STW to the end of STW. The goal is to determine the size of STWs and create a sequence of STWs, such that each window consists of a range of wind speed and a wind direction. The weather forecast data is used to determine the size of STWs (Papers **E** and **F**). The minimum and maximum ranges of wind speed for each STW are known in advance and the wind direction is assumed to be constant within a given

STW. Subsequently, the STWs can be further subdivided into FTWs. The intention is to determine the length of FTWs to match needs for the sub-missions of each UAV, matching energy and payload carrying constraints. These sub-missions in their entirety comprise the complete mission plan for the UAV fleet. The results from solving this sub-problem provide a sequence of STWs where each STW is further sub-divided into FTWs.

3.5.2 Determine the clusters of customers

In order to address the complexity of the network and the customer demand requirements in the main problem, the second considered sub-problem defines that it is reasonable to group a given set of customers at different points into Customer Clusters (CLs) as proposed in Paper **E** and **F**. The aim is to create clusters such that customers can receive either the entirety of their demand or fraction of this within a given FTW. The results of this sub-problem provide a set of alternative clusters of customers for each FTW.

3.5.3 Create a possible set of sub-missions

In order to reduce the complexity in the scheduling and routing of UAVs, the third considered sub-problem assumes that a given set of customers in a cluster will be served during a given FTW. As proposed in Paper **E**, each FTW consist of a set of sub-missions, such that each sub-mission consists of routes with schedules of the UAVs delivering materials to the customers. The goal is to create a set of sub-missions for each cluster, in such a manner that the customers are reached with a portion of the demands during each FTW. The results of this sub-problem provide a set of possible feasible sub-missions for a cluster in a given FTW.

3.5.4 Find sequences of sub-mission deliveries, which gives the maximum customers satisfaction

In order to reduce the complexity in the main problem, the fourth considered sub-problem defines that the combined UAV fleet mission plan consists of a sequence of sub-missions as presented in Papers **E** and **F**. The goal is to find admissible missions, such that the sum of the sub-missions' deliveries provide the maximum customer demand satisfaction. As a secondary objective it is possible to determine the admissible solutions which minimizes total travel time. The results obtained through solving this sub-problem provides a sequence of sub-missions that together constitute the UAV fleet mission plan (Papers **E** and **F**).

3.5.5 Interdependency between the sub-problems

Figure 18 illustrates the relationships between the sub-problems based on the influences from the outputs of each sub-problem. The interdependencies between the sub-problems, illustrated in Figure 18, are as defined below (Papers **E** and **F**).

A set of selected clusters of customers in the network are considered to plan the delivery missions for each STW. For each customer cluster, a set of feasible collision-free UAV routes and accompanying schedules are created. The creation of sub-missions is influenced by the nature of weather condition in each STW. The sequence of sub-missions from each FTW provides a full mission plan. The created feasible sub-missions are combined in a sequence to identify the sequence which provides the maximum demand satisfaction (Paper **F**). An interdependency analysis substantiates that sub-problem 3, is the most captious problem as all the remaining sub-problems are linked to it.

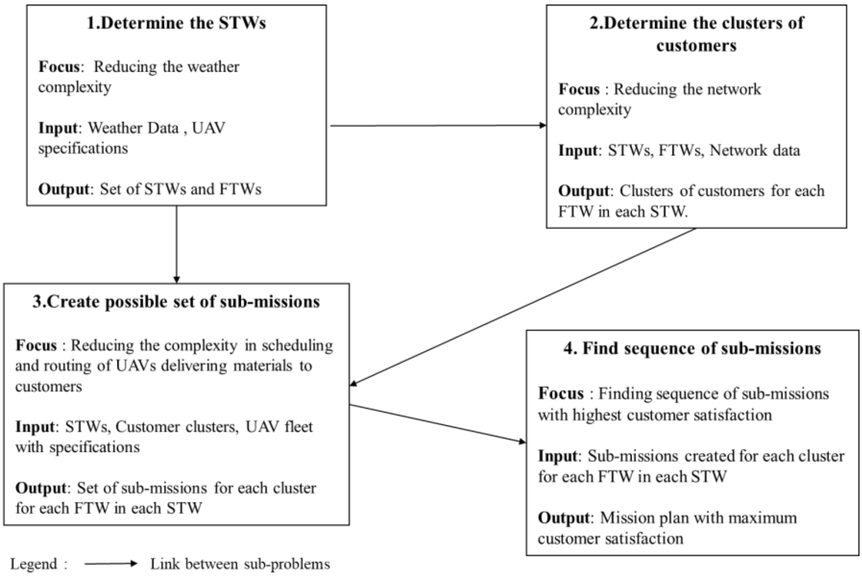


Figure 18. Interdependency between the decomposed sub-problems (Papers **F**).

CHAPTER 4. SOLUTION APPROACH

In this chapter, the solution approach and the results of the problem in the thesis are presented which address the ***RQ4***.

4.1 SOLUTION APPROACH

In order to solve the main problem by addressing the decomposed sub-problems stated in section 2 and depending on the link between the sub-problems a sequential approach is proposed in Papers **E** and **F** as following.

4.1.1 The method to determine the sub-mission time windows

Given: *Data about weather forecast (wind direction and wind speed) in the time period* $[0, t_{max}]$.

Question: *How many STWs should be created in the time period* $[0, t_{max}]$ *and how many FTWs should be extracted in each STW?*

By using the weather forecast data, the possible length of STWs are determined by using the following steps as proposed in Paper **F**. The method mentioned in Paper **F** creates a sequence of STWs where the whole planning period is divided into STWs. A similar concept is proposed in Paper **E**, but in that paper those time windows are defined as weather time windows with the purpose to create sub-missions during a time where there are similar weather conditions. The STWs are divided in FTWs based on the time used in flying the UAVs considering the maximum fuel limit and maximum carrying payload. The method to create the STWs is illustrated in Figure 19.

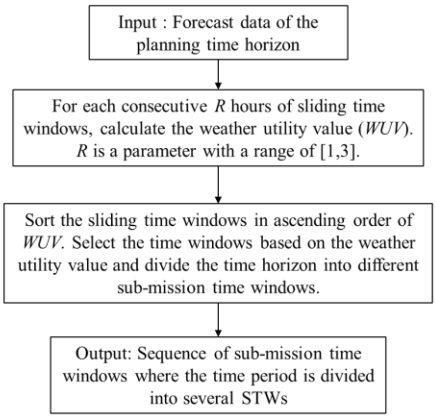


Figure 19. The method to create STWs.

4.1.2 The Method to determine the clusters of customers

The given variables are: $G = (N, E)$, F_l, $vw_l = [\overline{vw_l}, \underline{vw_l}]$, θ_l.

Question: *How to determine clusters of customers* $CL_{m,l} = \left(N_{m,l}, E_{m,l}\right)$ *which should be extracted from the transportation network?*

A method for determining the customer clusters is proposed in Paper **F** based on the geographical location of the customers. Customer clustering can be achieved in several ways such as hierarchical clustering and expectation–maximization clustering and "k-means" clustering. In Paper **F**, the "k-means" clustering algorithm is applied as it is already used in existing literature with competitive results (X. Liu et al. 2013; Mourelo Ferrandez et al. 2016). Euclidian distance between customers are taken as the feature of the clustering algorithm and the clustering algorithm is shown in Figure 20, where the centroid is the data point at the center of each cluster. The determination of the number of clusters are done arbitrarily.

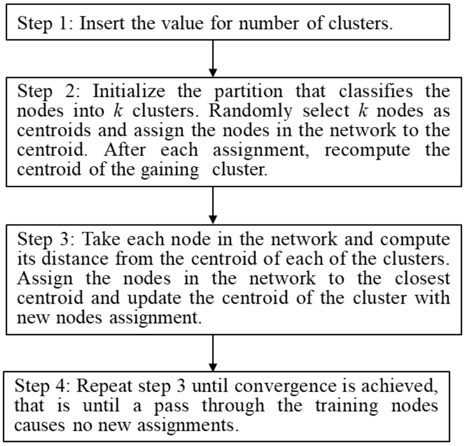


Figure 20. Clustering algorithm.

4.1.3 The method to create a possible set of sub-missions

Given: *l-th flying time window:* F_l, $vw_l = [\overline{vw_l}, \underline{vw_l}]$, θ_l, $CL_{m,l}$, $d_{i,j}$, $vg_{i,j}$, $t_{i,j}$.

Question: *Does there exists a set of admissible sub-missions* $S_{m,l} = \{S_{1,m,l}, \dots, S_{q,m,l}\}$ *which satisfy the energy constraints and ensure collision avoidance?*

The method to create a possible set of sub-missions for a cluster in a given FTW has two stages as explained in Papers **E** and **F**. In the first stage a list of scenarios for the cluster is created and stage two utilizes these scenarios to create sub-missions. This provides a set of sub-missions for each m^{th} cluster in each l^{th} FTW. As the tendency in the business is to be conservative, which means that one rather reduces the solution space in this manner than allows for potential solutions that are going to turn out to be infeasible to execute in real-life.

Stage one: Create possible scenarios ($RL_{s,m,l} = \left(Ro_{r,m,l}, Pl_{r,m,l}, CS_{r,m,l}\right)$) for each cluster in a FTW. As presented in Paper **F** the scenarios consist of Cn customers and each customer receives a portion of materials which is equal to the payload of the UAV divided by Cn. Cn is a parameter with the range of [1, max number of customers in the cluster]. Scenarios are created which have one customer to a maximum number of customers in the cluster as explained in detail in Paper **F**. The desired number of scenarios are given as the input in this method and the method stops when the list of scenarios consists of the desired number of scenarios (Paper **F**).

Stage two: Input for stage two is the list of scenarios and customer demand satisfaction levels determined in stage one for a cluster. The sub-missions for each cluster are created as per the method presented in Paper **F**.

Illustration of the method for first time window

A simple illustration of sub-mission creation within a given FTW for two clusters ($CL_{1,1}$ and $CL_{2,1}$) is selected for demonstrating the method. For $CL_{1,1}$ (Figure 21) sub-mission creation is illustrated in Figures 22 and 23. For $CL_{2,1}$ (Figure 24) sub-mission creation is illustrated in Figures 25 and 26.

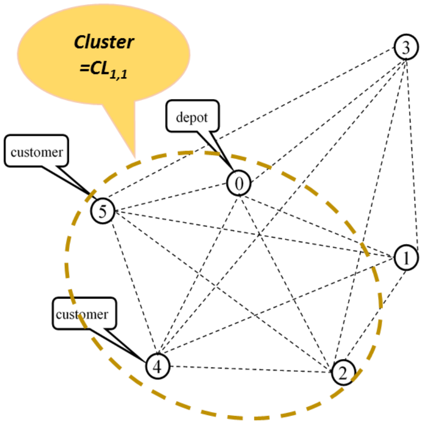


Figure 21. First cluster in first FTW.

Stage one of the sub-mission creation for $CL_{1,1}$ is illustrated as following in Figure 22, taking the stopping criterion of desired number of scenarios equals to 4. This stopping criterion is taken to illustrate the differences in four created scenarios.

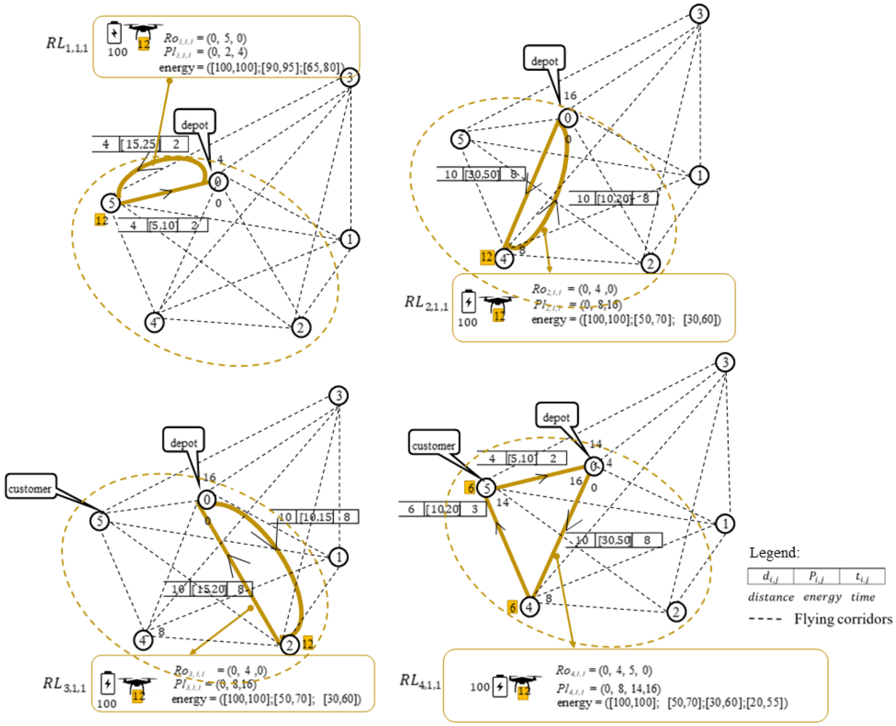


Figure 22. Four scenarios created for the first cluster in first FTW.

Stage two of the sub-mission creation for $CL_{1,1}$ is illustrated as following, taking the stopping criteria of desired sub-missions equals to 2. These stopping criterions are taken to illustrate the differences of two created sub-missions in the solution approach.

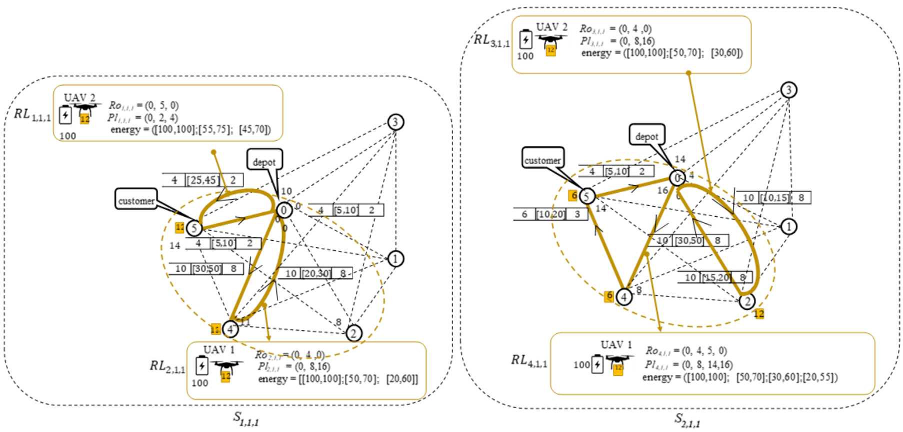


Figure 23. Two sub-missions created for the first cluster in first FTW.

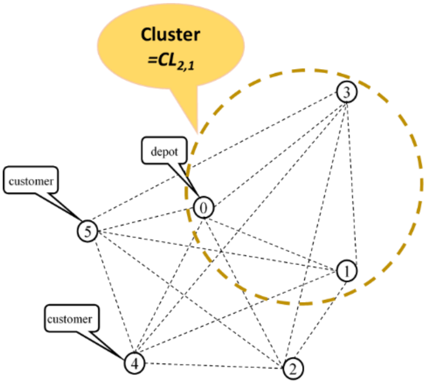


Figure 24. Second cluster in first FTW.

Stage one of the sub-mission creation for $CL_{2,1}$ is illustrated as following, taking the stopping criteria of the desired number of scenarios equals to 4.

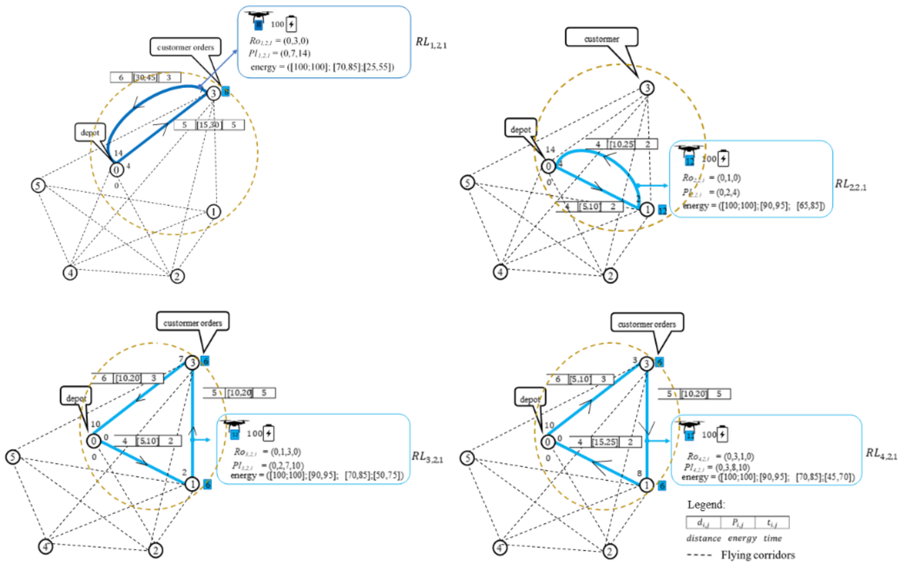


Figure 25. Four scenarios created for the second cluster in first FTW.

Stage two of the sub-mission creation for $CL_{2,1}$ is illustrated as following, taking the stopping criteria of desired sub-missions equals to 2.

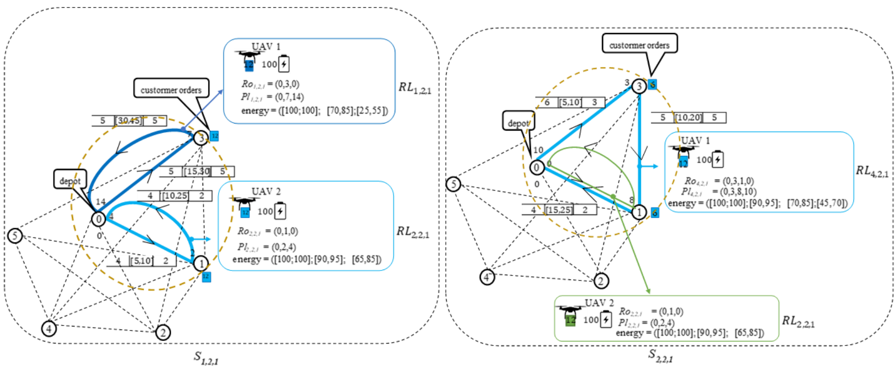


Figure 26. Two sub-missions created for the second cluster in first FTW.

For the first FTW four sub-missions are created as *S1,1,1, S2,1,1, S1,2,1, S2,2,1.*

4.1.4 The method to find sequences of sub-mission deliveries ensuring high demand satisfaction

Given: *a set of FTWs:* FS_l, FE_l, *set of clusters* $CL_{m,l} = (N_{m,l}, E_{m,l})$ and *the set of admissible sub-missions* $S_{m,l} = \{S_{1,m,l}, \ldots, S_{q,m,l}\}$ *for each cluster in each FTW.*

Question: *How to find the sequence of sub-mission deliveries which maximize the customer demand satisfaction?*

The Depth-first search (DFS) algorithm is proposed in Paper **F** to find admissible missions which gives the highest customer demand satisfaction as DFS expands all nodes to the greater depth, it is guaranteed to find an quality solution (Korf 2003).

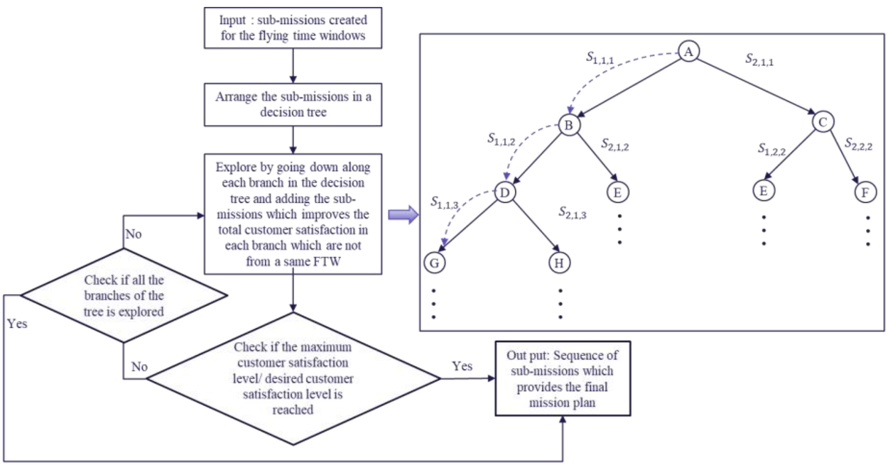


Figure 27. Process to find the sequence of sub-missions, which provides the maximum customer demand satisfaction.

The sub-missions which are created are searched using the DFS to find the sequence of sub-missions which provides the maximum customer demand satisfaction level and Figure 27 shows steps in searching the sequence of sub-missions which provide the final mission plan. All sets of possible sequences of sub-missions are searched in Paper **E** using brute-force search for small instances.

4.2 NUMERICAL EXAMPLES AND COMPARISONS

Several numerical examples with illustrations to explain the solution approach stated in section 4.1 are presented in Papers **D, E** and **F**. This section contains additional experiments not mentioned in the appended papers and expanding on the numerical investigation of both the problem and solution approach. The experiments presented in this section support the answering of ***RQ4*** and in understanding how the various parameters influence the sub-mission creation.

All experiments were performed with a fleet of UAVs having the characteristics listed in Figure 17. The considered STWs consist of different lengths where the STWs are the outputs of sub-problem 1. A description of the input data used for the experiments is shown in Table 4. For each FTW, which falls under an STW, the input parameters for the UAV fleet size, maximum carrying payload, the number of customers per route and the maximum energy of UAV are changed to make the sub-missions while all remaining parameters are kept constant. Weather data is taken from the weather data of Denmark (Danish Meteorological Institute, 2015). All experiments were conducted on a personal computer with 2.7 GHz speed and 8 Gb RAM.

Table 4. Input data for the experiments (Papers **F**).

Input Data	Values
The maximum energy of UAV (P_{max})	12000 (KJ)
UAV fleet size (K)	2,3,4,5
Number of sub-mission time windows	5
Number of clusters per STW (σ)	2,3,4
Number of scenarios per cluster per FTW (¥)	3,4,5
Number of sub-missions per cluster (ψ)	2
Number of customers per route (Cn)	1,2,3,4,5
Ground speed ($vg_{i,j}$)	20 (m/s)
Length of FTW_l	1800,3600,5400,7200,9000 (s)
Maximum loading capacity of UAV (Q)	24 (Kg)
The demand of the customers (D_i)	[80,100] (Kg)
Time period (H)	43200 (s)

By using the input data, sub-missions are created for each cluster for each flying time window. The creation of sub-missions is done by the method proposed in Paper **F**. By using the input data sub-missions are created for each cluster for each flying time window. The obtained results are presented in Papers **E and F**. In addition, several other experiments were conducted which are described in Table 5.

Table 5. Description of the experiments.

Experi- -ment	Description	Description of changing parameters
1	Input parameters of vw_l, θ_l, Cn, K are changed, and all the remaining parameters are kept as constant.	vw_l: [6,13] (m/s) θ_l: [0, 180] (degrees) Cn: (1, 2), K : [2, 6]
2	Input parameters of length of $FTW_l = FTWE_l - FTWS_l$ and P_{max} are changed and all the remaining parameters are kept as constant.	length of FTW_l: (20,40,60,80,100) (mins) P_{max}: (6000,12000) (KJ)
3	Input parameters of K, Q and Cn are changed and all remaining parameters are kept as constant.	K: [2, 6] Q: (12,24) (Kg) Cn: (1,2)

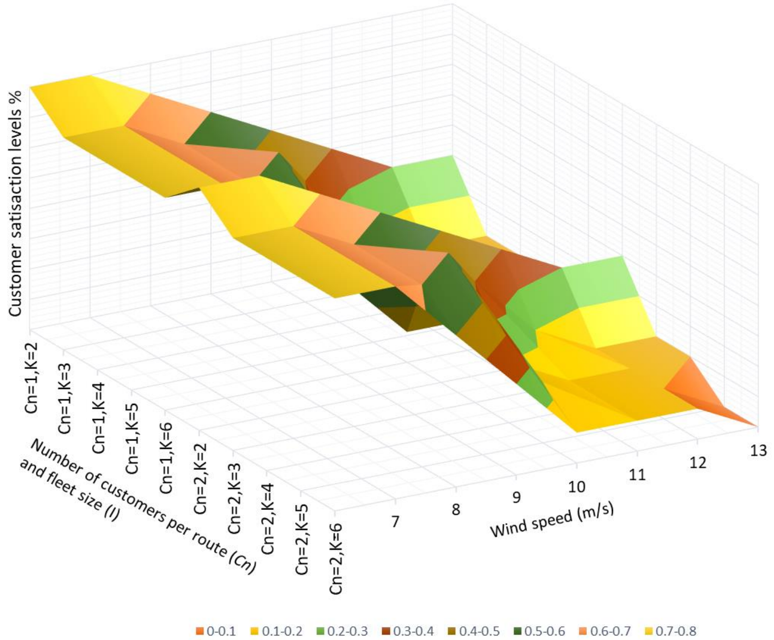


Figure 28. Customer demand satisfaction levels for the sub-missions created at different wind speeds for a wind direction of 30 degrees with different combinations of fleet size and numbers of customers per route (Experiment 1).

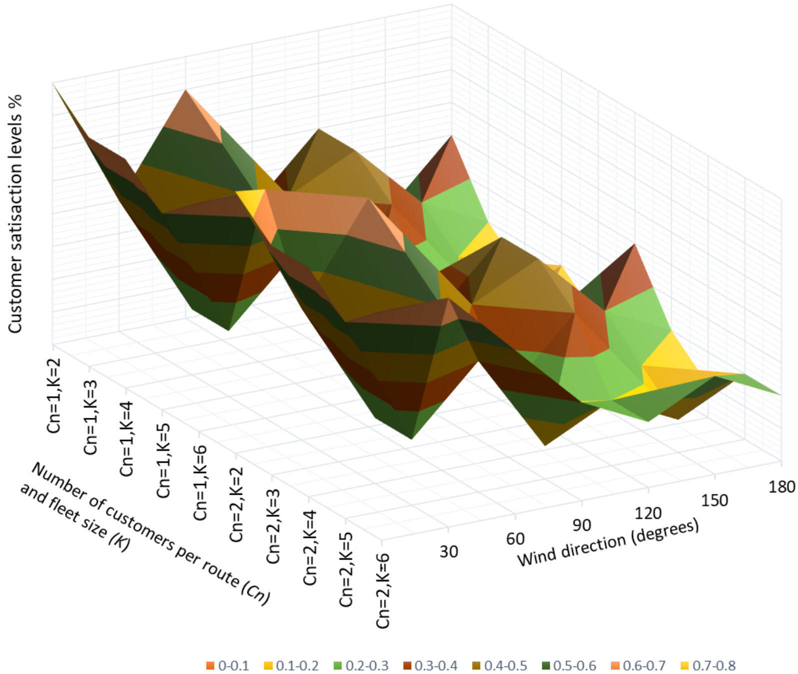


Figure 29. Customer demand satisfaction levels for the sub-missions created for different wind directions and with different combinations of fleet size and numbers of customers per route for a wind speed of 8m/s (Experiment 1).

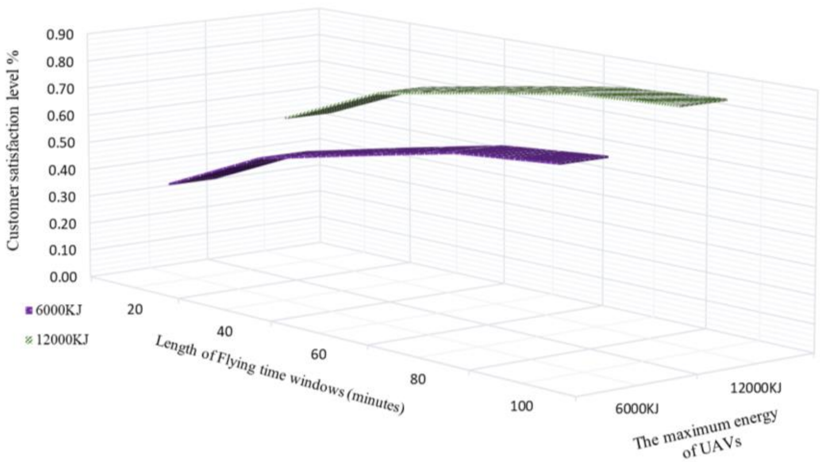


Figure 30. Customer demand satisfaction levels for the sub-missions created for FTWs with different length and with different maximum energy limits of UAVs (Experiment 2).

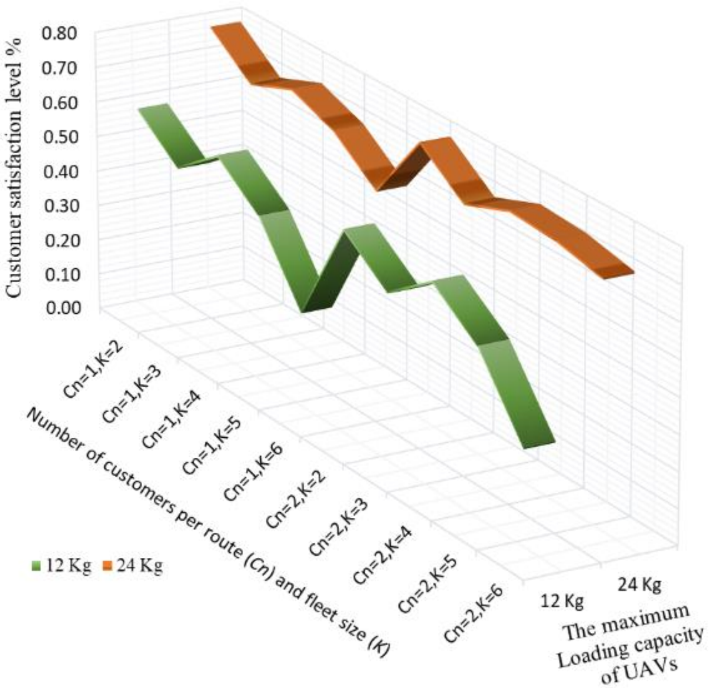


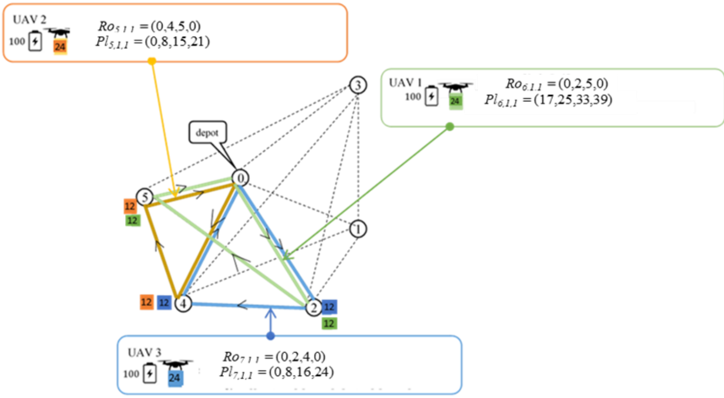
Figure 31. Customer demand satisfaction levels for the sub-missions created for different combinations of fleet size and numbers of customers per route for different maximum loading capacity of UAVs (Experiment 3).

Depending on the weather forecast, the fleet size and the number of customers per route can be chosen when creating sub-missions (Figure 28 and 29). As the fleet size increases the risk of potential collisions occurring increases and to have possible sub-missions with higher fleet size, larger length of FTW is needed (Figure 30) and UAVs with larger loading capacities are required (Figure 31). From the numerical experiments one is able to infer a number of interesting properties of both the problem and the solution approach. From the experiments it is clear that changes to wind direction significantly affect the creation of sub-missions, which in turn leads to different customer demand satisfaction levels. Thus, it can be noted that the combinations of fleet size, number of customers per route and loading capacity of the UAVs could be decided based on the weather forecast data (Figure 28, 29 and 30). This underlines the importance of including wind speed and direction in mission planning approaches as they severely limit range and carrying capability. As the fleet size is increasing the potential collisions between UAVs are increasing, in small FTWs sub-missions with the higher fleet size are not possible due to the increase of collision avoidance blockage. As the length of the FTWs become shorter, it is challenging to create sub-missions and this influences the quality of the solutions.

This information can be used to decide the fleet size of the sub-missions depending on the available length of FTWs.

K	*Q*	*Cn*	P_{max}	*Total distance*
3	24 Kg	2	6000 KJ	82.2 Km

There is a sub-mission which needs 40 mins length FTW. Within this 40 mins length FTW this sub-mission is passing 82.8 km of traveling distance. Which means in one 40 min length flying time window, this sub-mission is passing only 82.8 Km and delivers 24Kgs to customer 2,4 and 5.



The sub-mission shown above delivers same amount of demand volumes as the sub-mission shown below.

K	*Q*	*Cn*	P_{max}	*Total distance*
3	24 Kg	1	6000 KJ	52.4 Km

There is a sub-mission which needs 20 mins FTW. Within this 20 mins length FTW this sub-mission is passing 52.4 km of traveling distance. Which means in one 20 min length FTW, this sub-mission is passing only 52.4 Km and delivers 24Kgs each to customer 2,4 and 5.

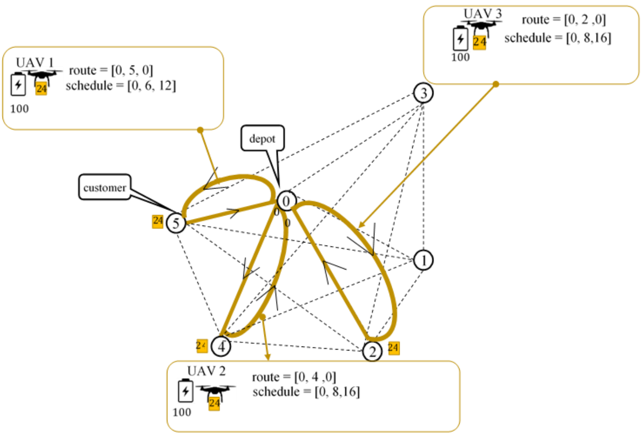


Figure 32. Experiment results showing different sub-missions with *Cn*=2 and *Cn*=1 delivering same demand quantities.

In addition to this, the determination of an appropriate fleet size to satisfy demand quantities can be decided based on the size of FTWs. Shorter FTWs have to be planned with smaller fleet size will result in less blockage due to collision avoidance and as the length of FTWs increases, sub-missions with larger fleet size can be planned. However, this comes with the added difficulty in avoiding collisions as the potential for collisions increases with increasing fleet size. Thus, depending on the length of FTWs which is based on the nature of the weather conditions, different combinations of the of fleet size, number of customers per routes, payload allocations and customer clusters can be chosen to find high quality solutions for the mission planning problem. Furthermore, it is observed that different combinations of sub-missions can lead to exactly the same demand satisfaction with different degrees of total travel distance and total energy consumption (Figure 32). This is an interesting observation, as it implies that there are multiple solutions with the same objective function value, but differing degrees of resource consumption. This supports the approach present in Paper **F**, highlighting the use of the approach for decision support and fleet mission prototyping.

Table 6. Mission planning results behavior with forecast vs. actual weather conditions.

			Actual weather data							
			Wind speed changes in execution				Wind direction changes in execution			
Number of customers (n)	Fleet size(K)	Solution for forecast weather data	1% change from forecast	2% change from forecast	3% change from forecast	4% change from forecast	1% change from forecast	2% change from forecast	3% change from forecast	4% change from forecast
5	2	100.00	100.00	100.00	100.00	99.77	100.00	100.00	100.00	100.00
	3	100.00	100.00	100.00	100.00	99.14	100.00	100.00	100.00	100.00
10	2	99.80	99.80	99.80	99.35	99.31	99.80	99.80	99.80	99.71
	3	100.00	100.00	100.00	100.00	99.13	100.00	100.00	100.00	100.00
	4	100.00	100.00	100.00	100.00	99.82	100.00	100.00	100.00	100.00
15	3	99.22	99.22	99.02	98.81	98.73	99.52	99.52	99.52	99.12
	4	99.43	99.43	99.43	98.43	98.16	99.43	99.43	99.43	99.14
	5	100.00	100.00	100.00	99.83	99.47	100.00	100.00	100.00	100.00
	6	100.00	100.00	100.00	100.00	99.76	100.00	100.00	100.00	100.00

The mission planning results behavior with forecast vs. actual weather conditions are shown in the following Table 6. The actual data have a 4% average deviation from the forecast weather data for 24 hours forecast, and have 3% average deviation from the forecast weather data for 12 hours forecast. The results show that the plans proposed for a 12 hours planning horizon by the model provide acceptable results in execution with real weather data as even for 4% changes it provides results more than 99% of customer demand satisfaction.

4.3 DISCUSSION

As the problem presented in this work is neither previously addressed nor solved in existing literature it is not directly possible to compare with existing methods. Even though several contributions have been completed within UAV fleet mission planning, these contributions have uniformly ignored the impact of weather conditions and only considered relatively small UAVs compared to the UAVs used in this study (Dorling et al. 2016). As the UAVs' specifications highly impact energy consumption, especially for larger UAVs, linear approximations are not justifiable. This contrasts directly with the current-state where primarily linear approximations of energy consumption are considered.

Certain studies have formulated the mission planning problem for a fleet of UAVs as a mixed-integer non-linear programming problem, but approximated the problem as a mixed-integer linear program, and used a solver (Gurobi) to the latter on a set of test instances (Fügenschuh and Müllenstedt 2015). Fügenschuh and Müllenstedt consider energy limitations of UAVs, but has not the effects of weather conditions in deriving the energy consumptions and used linear approximations of the energy consumption of UAVs. A COP approach was used in Paper **G** to solve the problem and limitations that restrict its use to mission planning problems in distribution networks in which the number of customers does not exceed 12 and the number of UAVs in the fleet is not larger than 5. For such problem instances, solutions can be obtained in under 1000 s. This problem is formulated as an extension of the VRPTW and solved using a COP approach and is presented in Paper **L**. The problem was solved in a constraint-programming environment (IBM ILOG) and solutions were obtained. However, such programming environments could provide solutions for networks in which the UAV fleet size is less than or equals to 4, and the number of customers is less than or equals to 8 (Paper **F**).

The UAV fleet size can be given as an input and the maximum customer demand satisfaction level, which can be provided by that fleet size in the given weather conditions can be determined by the model. Furthermore, the presented model can be used by a planner to give a desired customer demand satisfaction level as an input and find the required number of UAVs to accommodate that desired customer demand satisfaction level (Papers **E** and **F**). For instance, if the desired customer demand satisfaction level is 96% then the method can find the mission plans which provides 96% customer demand satisfaction, and the required UAV fleet size to accommodate that desired customer demand satisfaction level for the given weather conditions. In the current method, all the customers have given a similar priority in serving by the fleet of UAVs, but the model can be modified if certain customers should be given higher priority than other customers in receiving the demand volume (Paper **F**).

The outcome of this research can be used as a decision support tool in aerospace companies. Paper **F** discusses in detail on utilizing the proposed method to facilitate mission planners in taking decisions in UAV fleet mission planning. This allows one to answer questions regarding the analysis of the robustness of the UAV fleet mission plan to different influencing parameters of wind speed and direction, UAV fleet size, specifications, payload capacity and energy capacity (Paper **F**). Furthermore, the conducted simulations of this study are provided to aerospace companies, as proposal input for a UAV fleet planning decision support system enabling to prototype alternative mission proposals for execution. Investigations on potential approaches and an offline-based system are carried out to ensure that only missions suitable to be sent to flight approval from Air Traffic Control are accepted and the results of the study will be implemented as a technical tool in decision support systems for aerospace companies (Papers **F**).

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

The focus of this research is presenting a strategy to solve the multi-trip UAV fleet mission planning problem subject to changing weather conditions. This thesis report provides a solution approach for the hitherto unsolved problem considering energy consumption constraints in changing weather conditions and ensuring collision avoidance. The novelty of this research is that it gives the first unified definition of the UAV fleet mission planning problem subject to changing weather conditions and proposing a decomposed approach to solve it. This problem involves managing complex characteristics during the process of mission planning while considering factors such as weather dependencies and collision avoidance. This has to be conducted while addressing the non-linear energy consumption behavior of UAVs, which in turn depends on many factors such as UAV type, weather conditions and payload.

5.1 RESEARCH CONTRIBUTIONS

The scientific contributions of the thesis are as follows:

- Providing a published general overview of the current state and contributions in the domain of UAV routing.
- Identifying the different conditions influencing the non-linear energy consumption of aircrafts and analyzing how those factors affect UAV fleet mission planning.
- Presenting the novel problem of UAV fleet mission planning subject to changing weather conditions.
- Presenting a decision support driven declarative model for the problem of UAV fleet mission planning subject to changing weather conditions.
- Proposing a decision support driven solution strategy based on decomposition solution approach to solve the problem of UAV fleet mission planning subject to changing weather conditions.

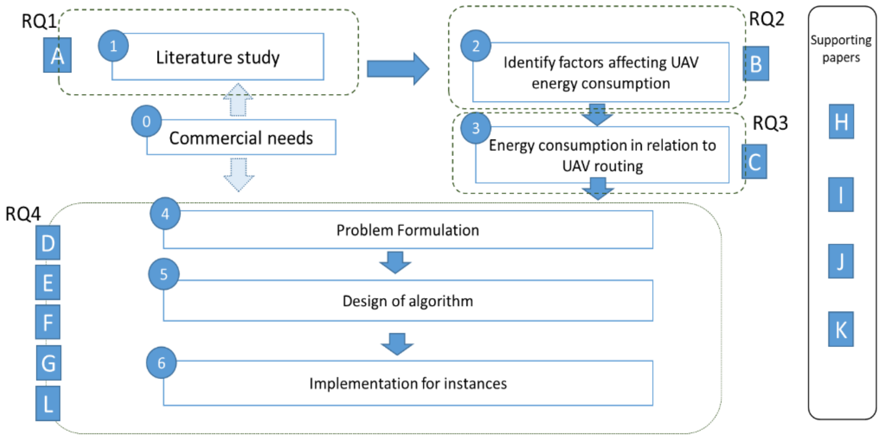


Figure 33. Blue print of the PhD project.

Figure 33 presents the steps of the PhD project with reference to the research questions and publications. Papers **H**, **I**, **J** and **K** are the supporting papers published during the PhD study.

Appended papers in the second part of the thesis has answered the research questions stated in chapter 1 as follows.

RQ1 What is the current state of UAV fleet mission planning in the existing literature and what are the gaps? Addressed in Paper **A**

Paper **A** provides a published overview of the current state and contributions to the area of the UAV routing and a general categorization of the VRP followed by a UAV routing classification based on an extensive analysis of the existing research contributions published in this domain. This analysis is used to identify the gaps in the current state to address the unique nature of the routing of UAVs in outdoor environments in the context of the problem addressed in this study.

RQ2 What are the conditions influencing the UAV fleet mission planning, which are unique to UAVs? Addressed in Paper **B**

Paper **B** identifies the factors affecting the energy consumption of UAVs during execution of missions and examines the general characteristics of the energy consumption. As the energy capacity and consumption are critical constraining factors in UAV routing, Paper **B** provides an overview of the current state of and contributions to the area of energy consumption in UAVs followed by a general categorization of the factors affecting energy consumptions of UAVs which are used in this study.

RQ3 What are the factors, which affect the energy consumption of UAVs, and how do those factors affect the energy consumption of UAVs? Addressed in Paper **C**

Paper **C** presents an analysis related to the parameters that affect the energy consumption of the UAVs through an example scenario of a single UAV multi-delivery mission.

RQ 4 Is it possible to solve the UAV fleet mission planning problem for a fleet of UAVs delivering materials to maximize customer demand satisfaction ensuring collision avoidance and considering the behavior of energy consumption of UAVs? Addressed in Papers **D**, **E**, **F**, **G** and **L**.

Paper **D** presents a method to ensure that at least one feasible solution exists for the considered problem and it leads to the opportunity to find sufficient conditions guaranteeing the existence of at least one feasible solution. Furthermore, in this paper algorithms dedicated to UAV routing and scheduling problems subject to collision avoidance, weather changes and energy consumption constraints are developed.

Paper **E** presents a declarative model aimed at analyzing the relationships of a given UAVs driven supply network and its function in a sequence of sub-missions following the required deliveries. In this paper, an illustrative example is presented with an approach leading to conditions ensuring solutions existence where the permissible size of the distribution network for which such missions can be determined. The proposed model consists of an approach in which a network is decomposed into clusters, which covers a part of the set of all customers serviced by the fleet of UAVs.

Paper **F** proposes a decision support driven solution approach to obtain a sequence of sub-missions that delivers a requested amount of goods to customers, within a given time period under the given weather forecast constraints. Furthermore in the paper computational experiments which allow to assess alternative strategies of UAV fleet mission planning are presented.

Paper **G** provides an offline strategy to solve the problem of the multi-trip UAV fleet mission planning subject to changing weather conditions, while considering energy consumption constraints and collision avoidance of UAVs. When creating the missions, depending on the weather forecast, the fleet size and the number of customers per route can be decided upon.

Paper **L** presents the problem as an extension of the VRPTW and formulates it as a COP. The problem is solved in a constraint-programming environment (IBM ILOG) and solutions are obtained for small problem instances.

Based on the experimental results found in Papers **E**, **F** and **G**, sub-missions having different combinations of fleet size and numbers of customers per route could be used to deliver similar amounts of customer demands. However, depending on the length of FTWs different sub-missions can be chosen to execute the missions. It is observed that the collision avoidance constraint increases the flying time of the sub-missions and if a different network can be used where there is less crossing between flying corridors, then the flying time of sub-missions will be reduced. Hence, the nature of the network influences the results of the creation of sub-missions.

The proposed declarative decomposed solution approach gives a reasonable approach to solve the problem reducing its complexity and leads to acceptable solutions for aerospace companies. The approach could be used as a prototype of a DSS addressing various influencing parameters involved in UAV fleet mission planning.

5.2 FUTURE RESEARCH DIRECTIONS

Future research directions highlighting possible extensions of the presented work will produce a significant step towards autonomous UAV fleet mission planning. The contributions of this research provide a foundation for future researchers to expand on the research directions listed as following. Below are identified four such reasonable directions of future work. All four suggestions focus on extending the problem in terms of adding complexity to match real world needs.

The research presented in this study can be extended to multiple depots with recharging stations as a method of extending the flight distance of UAVs. This would be reasonable to match very large-scale practical implementations of UAV fleets managing deliveries. To complete this extension, customers can be assigned to different depots and each depot could be utilized to supply the materials based on the customer demands. As the network size increases, to cater to a large number of customers, the clusters of customers can be assigned to dedicated depots.

The research presented in this study could also reasonably be extended by adding customer delivery time windows to the problem. This would match with certain existing delivery systems, where goods are promised to be delivered within a given specific time slot. In the current study, the customers need just to be served before the end of the time period. If each customer has specific delivery time windows, the current solution method can be extended as the customers with common time windows can be grouped and the sub-missions can be planned accordingly.

The research presented in this study could be extended by considering two different types of UAV tasks; drop off and pickup. After a UAV completes a delivery, the UAV can either fly back to a depot to complete the next delivery or pick up new material to fly directly to another customer. This breaks with the pickup strategy utilized in the current study, where all materials are picked up centrally at the depot. To accommodate this extension, the current solution strategy should be extended by considering the customer locations as potential depots and the mission creation has to be modified to address pickups and deliveries.

A final potential extension of the research could be to consider a fleet of heterogeneous UAVs rather than the homogenous ones considered in the current research. The advantages of considering a heterogeneous fleet with different types of UAV specifications is that one can match the specifications to customers dependent on the nature of their demand. This influences the mission creation, as the calculation of the energy consumption should be done by taking the specifications of the heterogeneous fleet of UAVs into account and the routes can then be assigned subsequently as in the current approach. Thus, the heuristic method used in mission creation should be modified to be applied for a heterogeneous fleet of UAVs.

These extensions all underline the strength of using a decomposition approach. The extensions can be supported and implemented within the current setup, through modifying sub-problems and the solution strategies to the sub-problems. This underlines the flexibility and scalability of the proposed approach. Furthermore, it underlines how the presented research can be considered as a foundation to build the UAV fleet mission planning systems of the future on.

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