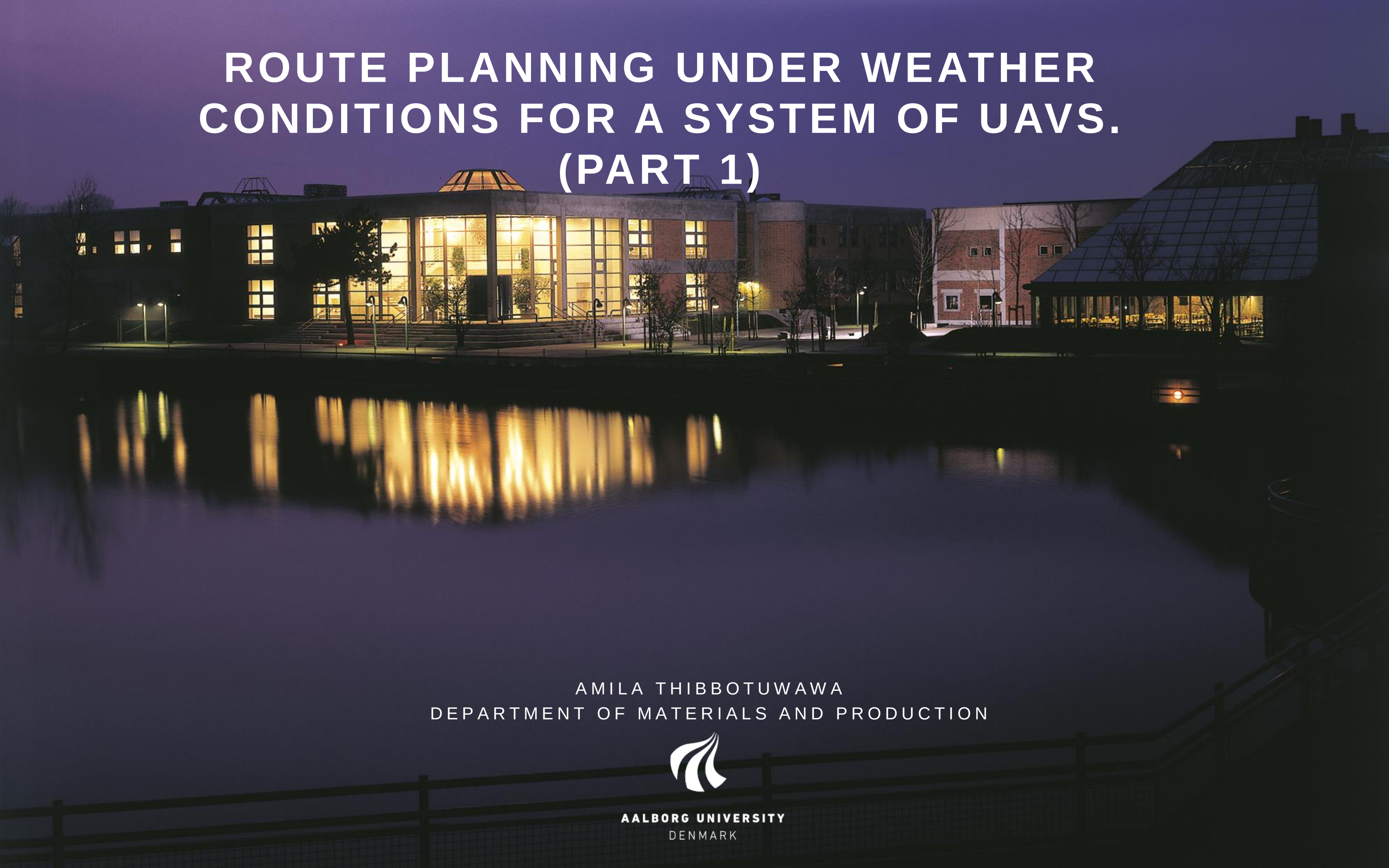

ROUTE PLANNING UNDER WEATHER CONDITIONS FOR A SYSTEM OF UAVS. (PART 1)

AMILA THIBBOTUWAWA
DEPARTMENT OF MATERIALS AND PRODUCTION

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Outline

- Introduction
- Important factors to consider in deriving energy consumption of UAVs
- Energy consumption models for UAVs
- Relationship of factors affecting UAV energy consumption
- Analysis of factors affecting UAV energy consumption
- Illustrative example
- Conclusion

Introduction: Motivation

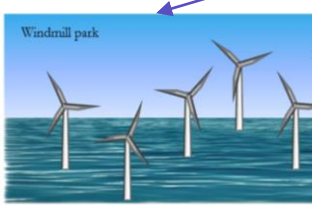
Experience: Real world industry problem

Customers

Customers

- 400+ customers
- 20+ UAV fleet
- Large UAVs with 100 Kg+ carrying capacities

Customers



Customers

How to deliver the materials to customers ?
- Routing
- Scheduling

Collision free routing

Changing wind speed & direction

Can not be solved using typical routing techniques in existing literature

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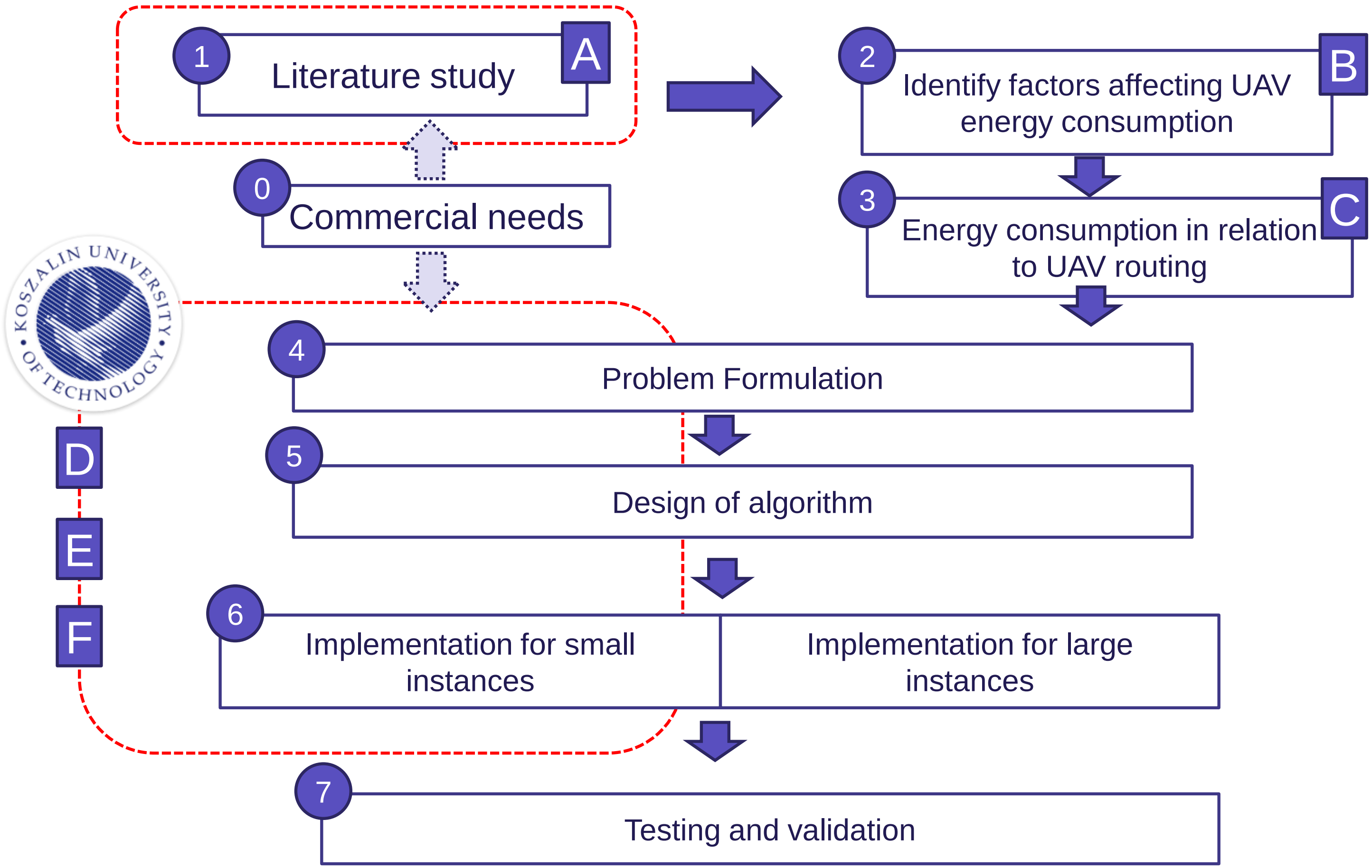

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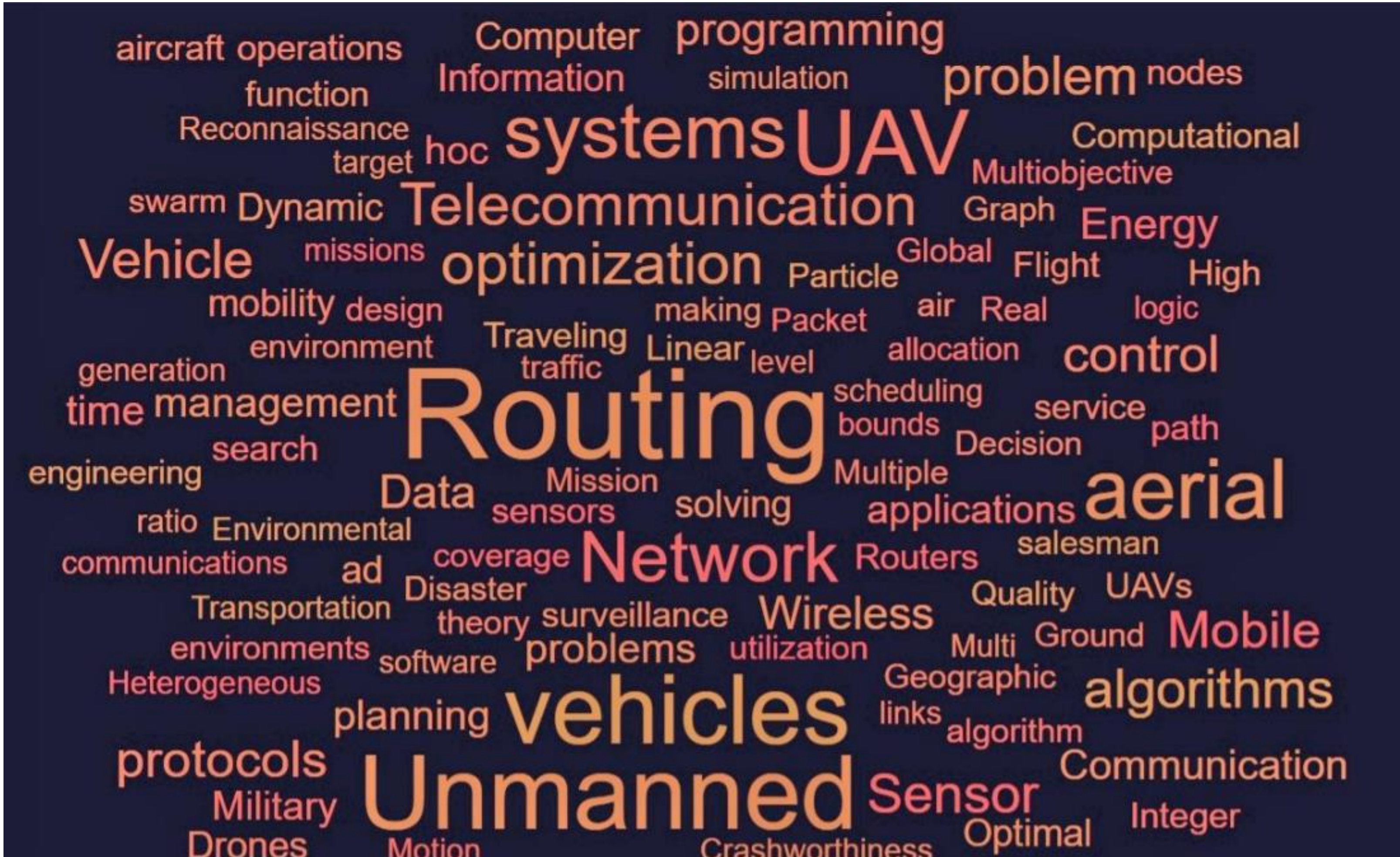
aircraft operations
Computer
programming
function
Information
simulation
problem
nodes
Reconnaissance
target
hoc
systems
UAV
Computational
Multiobjective
swarm
Dynamic
Telecommunication
Graph
Energy
Vehicle
missions
optimization
Particle
Global
Flight
High
mobility
design
making
Packet
air
Real
logic
environment
Traveling
traffic
Linear
level
allocation
control
generation
time
management
Routing
scheduling
bounds
service
path
search
Decision
engineering
Data
Mission
Multiple
aerial
ratio
Environmental
sensors
solving
applications
communications
ad
coverage
Network
Routers
salesman
Disaster
Quality
UAVs
Transportation
theory
surveillance
Wireless
environments
software
problems
utilization
Multi
Ground
Mobile
Heterogeneous
Geographic
algorithms
planning
vehicles
links
algorithm
protocols
Unmanned
Sensor
Communication
Military
Integer
Optimal
Drones
Motion
Crashworthiness

Literature Study & Questions Answers

1.1 What are the existing route optimization implementations for land based transportation and maritime transportation, which are published in existing literature?

- Linier approximations of Fuel
- (Horizontal travel) 2D in contrast to UAV fly on 3D (Vertical & Horizontal)

1.2 What is the current state of UAV routing in existing literature and what are the gaps?

- Current state of research has not considered the weather factors and ignores the impact of weather on performance
- Assumed unlimited fuel capacities
- No studies done for large scale UAVs

1.3 What are the stochastic conditions influencing the routing, which are unique to UAVs?

- Weather conditions(Wind speed & direction , Temperature, Air density)

Publications A

Unmanned Aerial Vehicle Routing Problems: A literature review

Amila Thibbotuwawa[1] and Peter Nielsen[1]

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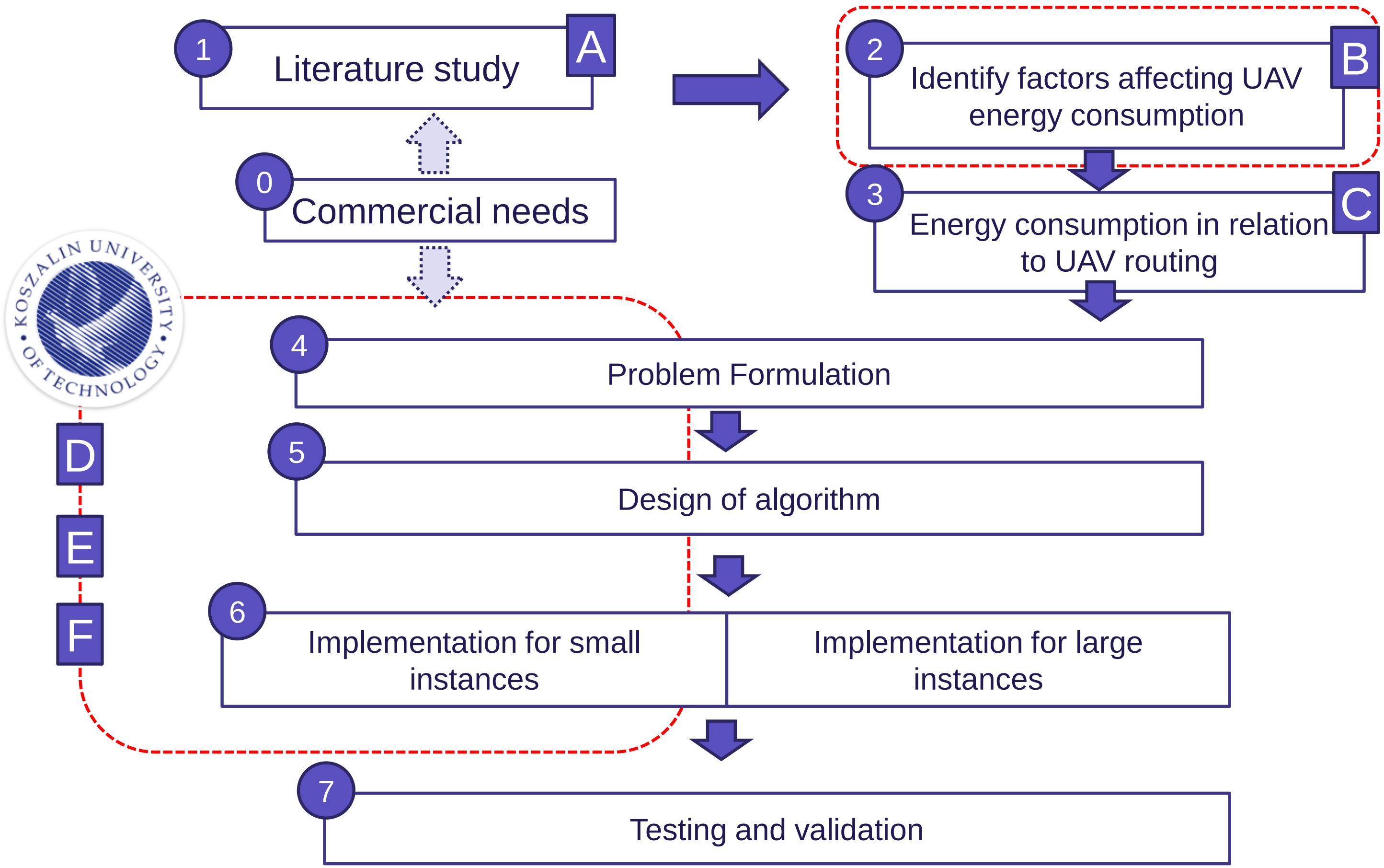
Abstract. Unmanned Aerial Vehicles (UAV) routing is, in general, a topic that is transitioning from an emerging topic to a growing research area. This transition has revealed a need to classify different types of research and examine the general characteristics of the research area. This research aims to assist in identifying the main topics addressed and emerging research streams, provides the first published overview of the current state and contributions to the area of the UAV routing problem (UAVRP) and a general categorization of the Vehicle Routing Problem (VRP) followed by a UAVRP classification based on the analysis of UAVRP current status. To achieve this, an analysis of the existing research contributions promulgated in this domain is conducted. This analysis is used to identify the current state of UAVRP and the gaps in the current state to address the specific nature of the UAVRP.

- Journal Paper
- Journal : Logistics Research
- Status : Under Review



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2

Research Questions

2.1 What are the important factors that affect energy consumption of UAVs ?

2.2 What is the relationship between the factors affecting UAV energy consumption ?

2.3 What is the current state models for addressing the fuel consumption of UAVs and How can we calculate the fuel consumption of UAVs considering the factors?

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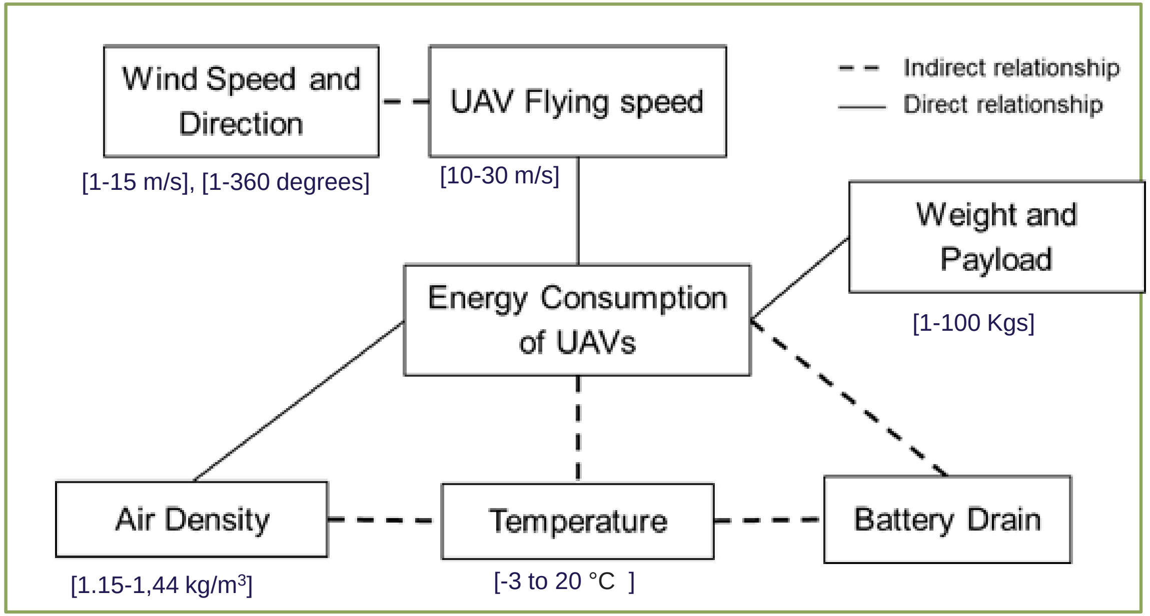
2 Important factors affecting UAV energy consumption and their relationship

1
2



Flying with the wind could reduce/increase energy consumption

Maximum flight distance could be constrained by
- Take-off gross weight
- Fuel weight and payload .

Cold temperatures may adversely affect battery performance

Different Weather → Different Energy Consumption → Different routes/schedules

Strongly influence the solution strategy for the UAV routing problem

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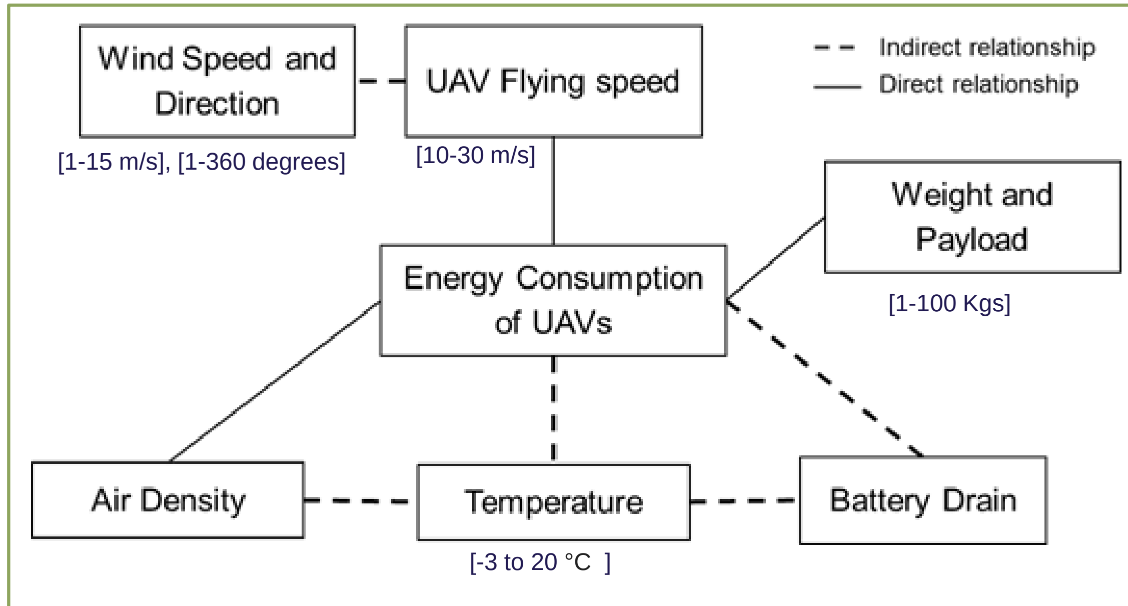
Analysis of the factors affect UAV energy consumption

$$P_T = \frac{1}{2} C_D A D v^3 + \frac{W^2}{D b^2 v}$$

P_T	Power needed for flight
C_D	Aerodynamic drag coefficient
A	Front facing area of the UAV
W	Total weight of the UAV
D	Density of the air
b	Width of UAV
v	Relative speed of the UAV

$$p^* = \frac{T^{\frac{3}{2}}}{\sqrt{2D\varsigma}}$$

p^*	Power needed for take-off and landing
T	Thrust T = W g
ς	Facing area of the UAV is in m^2



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Publications B

Energy Consumption in Unmanned Aerial Vehicles: A Review of Energy Consumption Models and Their Relation to the UAV Routing

Amila Thibbotuwawa[1(✉)], Peter Nielsen[1], Banaszak Zbigniew[1], and Grzegorz Bocewicz[2]

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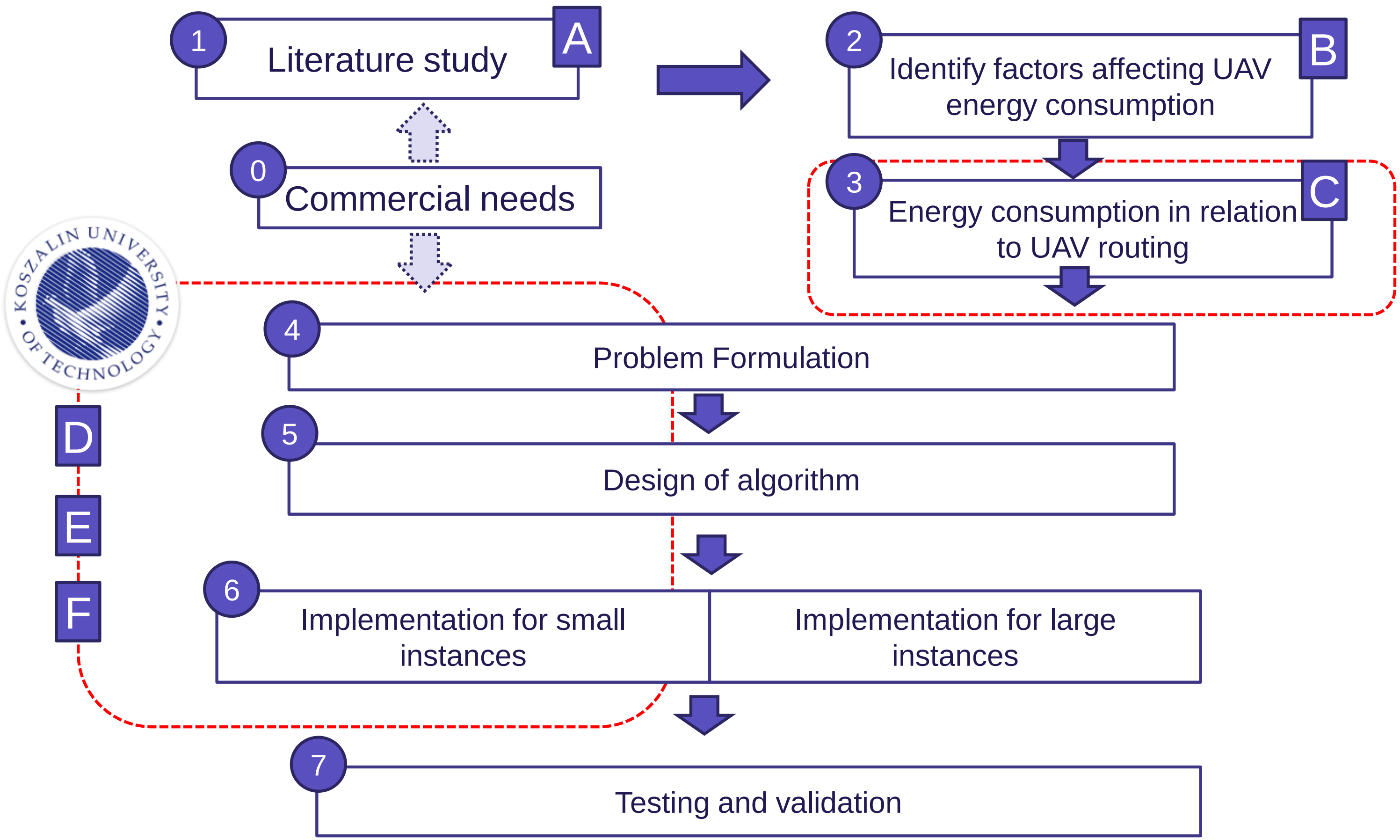
{amila,peter}@mp.aau.dk, Z.Banaszak@wz.pw.edu.pl
[2] Faculty of Electronics and Computer Science, Koszalin University of Technology, Koszalin, Poland
bocewicz@ie.tu.koszalin.pl

Abstract. The topic of unmanned aerial vehicle (UAV) routing is transitioning from an emerging topic to a growing research area with UAVs being used for inspection or even material transport as part of multi-modal networks. The nature of the problem has revealed a need to identify the factors affecting the energy consumption of UAVs during execution of missions and examine the general characteristics of the consumption, as these are critical constraining factors in UAV routing. This paper presents the unique characteristics that influence the energy consumption of UAV routing and the current state of research on the topic. This paper provides the first 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.

- Conference Paper
- Conference : ISAT 2018
- Status : Published



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Questions

- We want to find answers to following questions ;
  1. How does the factors found on step 2 affect the energy consumption of UAVs?
  2. How does energy consumption changes in relation to UAV routing?

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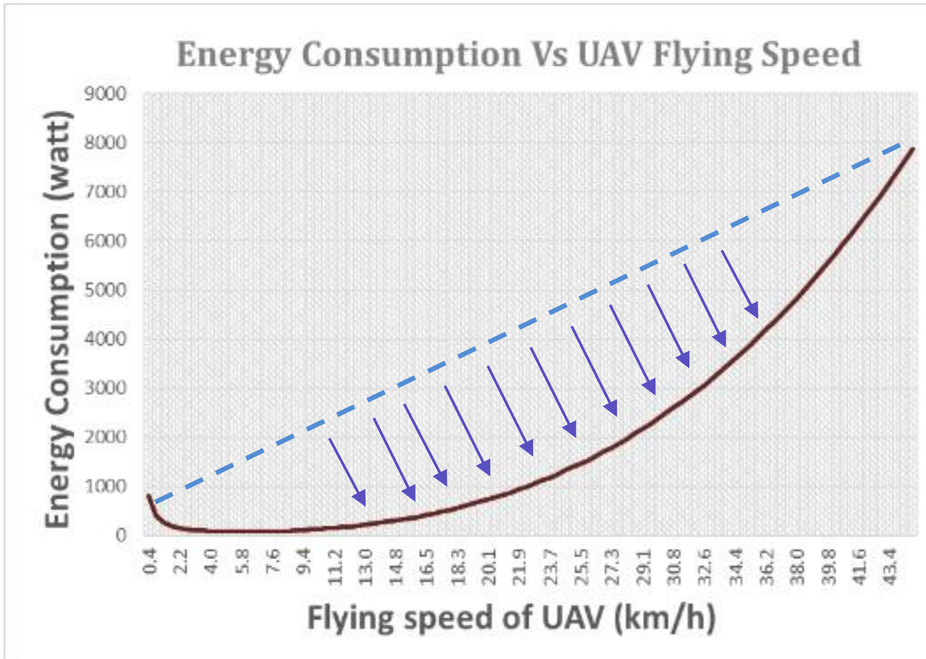
UAV power consumption and UAV flying speed



UAV energy consumption Vs UAV flying speed

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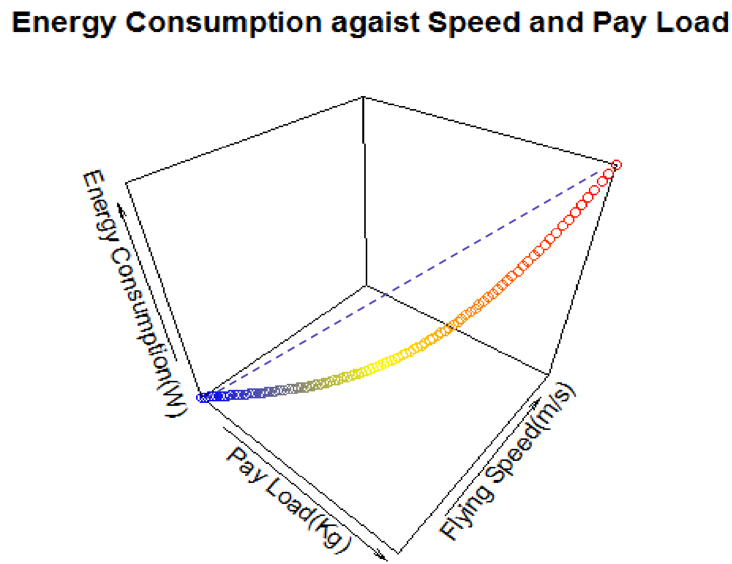
UAV Power Consumption against two changing parameters



Energy consumption against speed and payload

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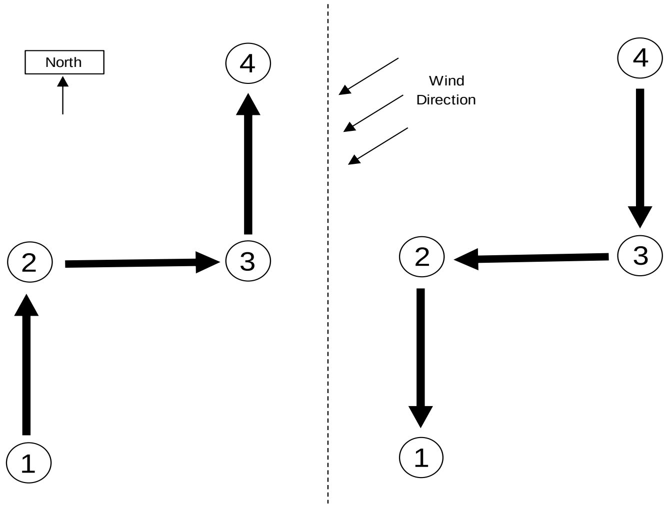
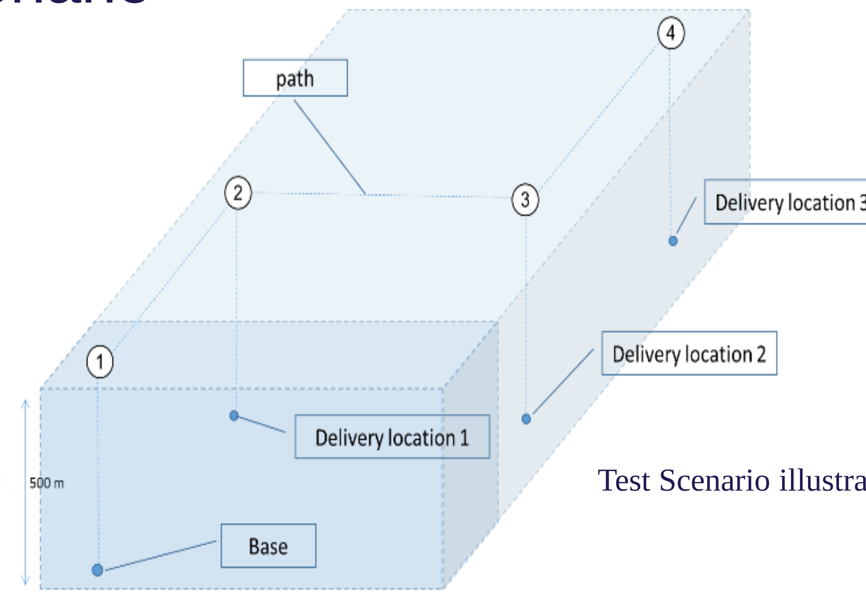
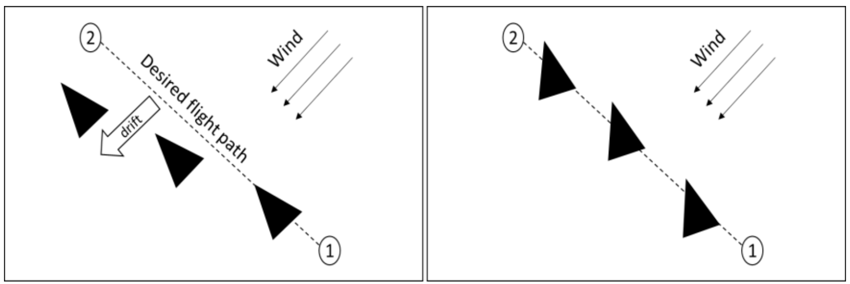
Scenario analysis : Test scenario

Test Scenario diagram





Test Scenario illustration 2.5D



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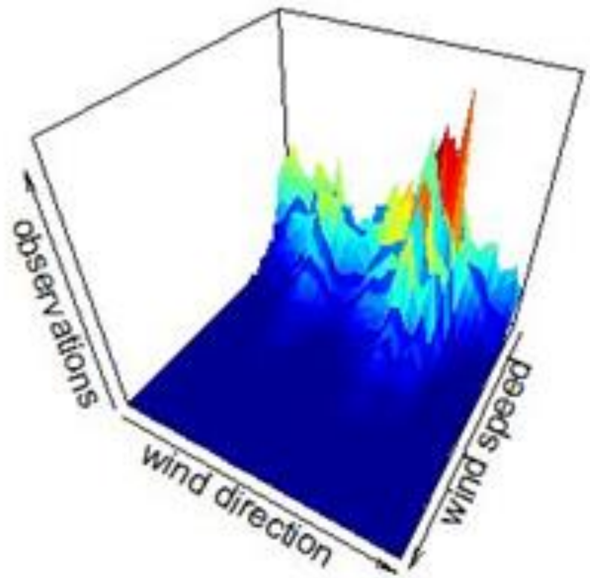
UAV specifications

Width	8.7m
Front reference area	1.2m^2
Top reference area	7.5m^2
Empty weight	57.5kg
Maximum takeoff weight	120 kg
UAV Drag coefficient	0.546

Scenario analysis: **Weather data**



Weather data

- Weather data was taken based on the actual weather data of Denmark from January 1st of 2006 to December 31st of 2016.
- Figure 6 shows the distribution of weather data over the time of 10 years
- Based on the data we selected most occurred wind speed range and for the scenario, analysis and we did the analysis for all the possible wind directions.

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Assumptions

- UAVs fly between locations at a constant speed in a constant altitude.
- We assume a simple flight path, such that the UAV first ascends vertically to a desired altitude, and then travels in a straight path, and descends vertically in the location *i,* which has a demand *Di.*
- Wind speed and direction is constant during the mission execution
- Demand at each location can be fully satisfied by the UAV and that the demand at a location is not higher than the carrying capacity.
- We assume that the UAV has sufficient energy capacity to complete the mission.
- We assume for practical reasons that in a UAV trip all parameters will remain constant on a given arc. Payload and speed may change from one arc to another

Results of the analysis

- We observed how the energy consumption changes with respect to inbound vs outbound travels and level flight vs take-off and landing.
- Experiments are carried out, with regards to the scenario explained for different flying speeds, different carrying payloads and changing wind speeds and directions.

Results of the analysis : Changing wind speed

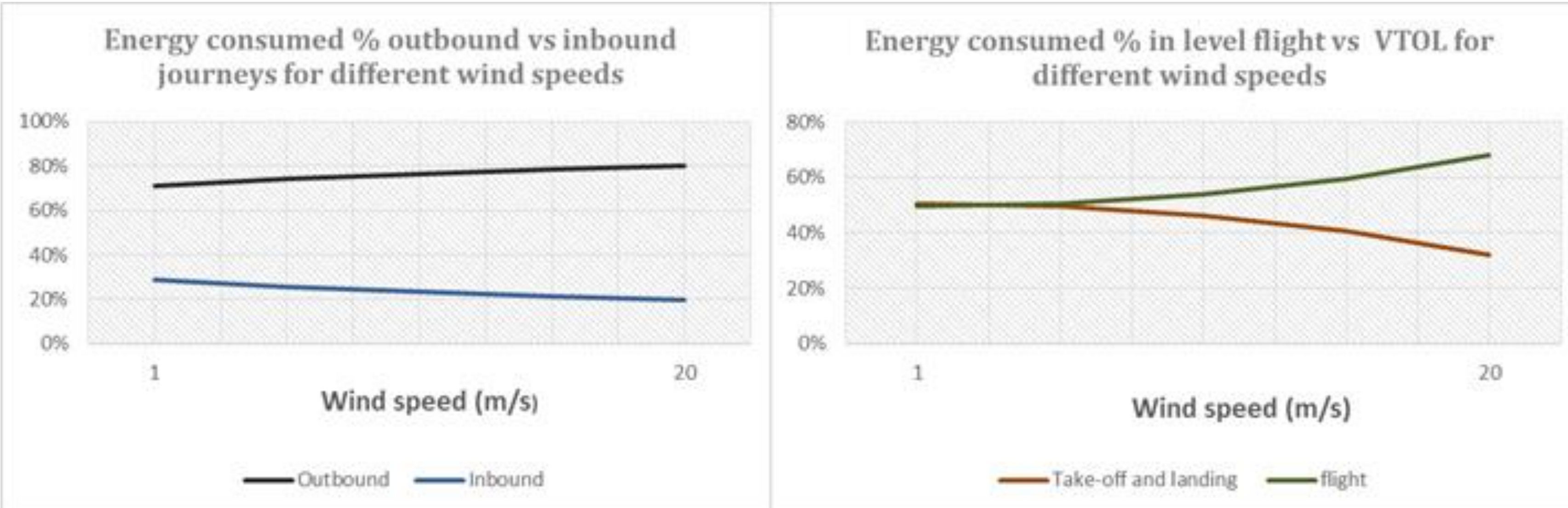
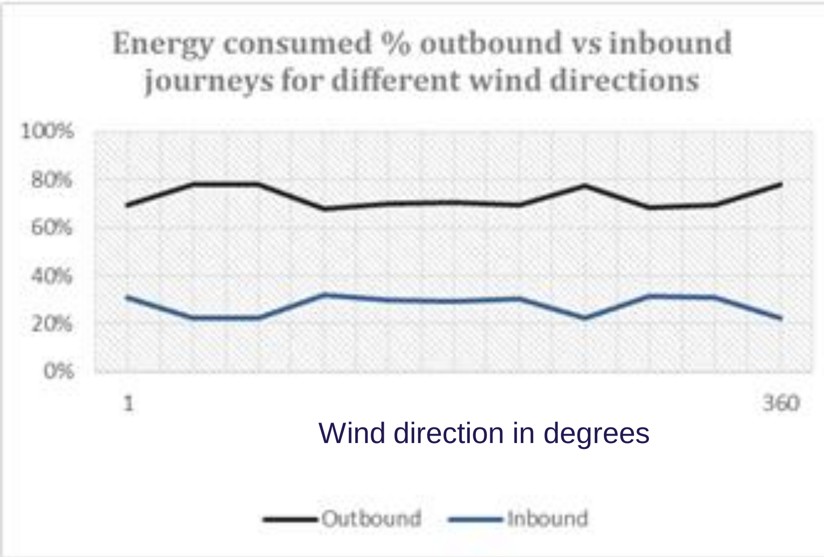


Fig. 9. Energy consumed percentage in outbound vs inbound trips and Level flight vs VTOL for different wind speeds

Results of the analysis : Changing wind direction



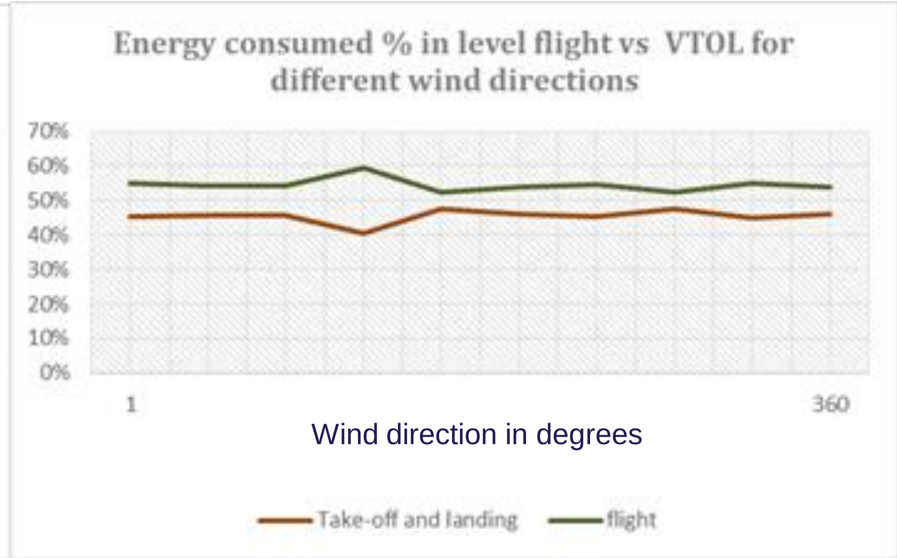


Fig. 10. Energy consumed percentage in outbound vs inbound trips and Level flight vs VTOL for different wind directions

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Answers to questions

3.1 How does the factors found on step 2 affect the energy consumption of UAVs?

- These Factors were analysed using experiments and the relationships and behaviours are identified

3.3 How does energy consumption changes in relation to UAV routing?

- The extended non-linier models for calculating energy consumption helps for better performance in UAV routing compared with linear approximations.
  - Breakdowns of UAVs in air : When linier approximations are used it leads to “out of fuel” situations on air.
  - Reducing the fuel cost: Actual vs Expected error in remaining fuel after finishing a route is reduced by 29%

Publications C

Factors Affecting Energy Consumption of Unmanned Aerial Vehicles: An Analysis of How Energy Consumption Changes in Relation to UAV Routing

Amila Thibbotuwawa[1(✉)], Peter Nielsen[1], Banaszak Zbigniew[1], and Grzegorz Bocewicz[2]

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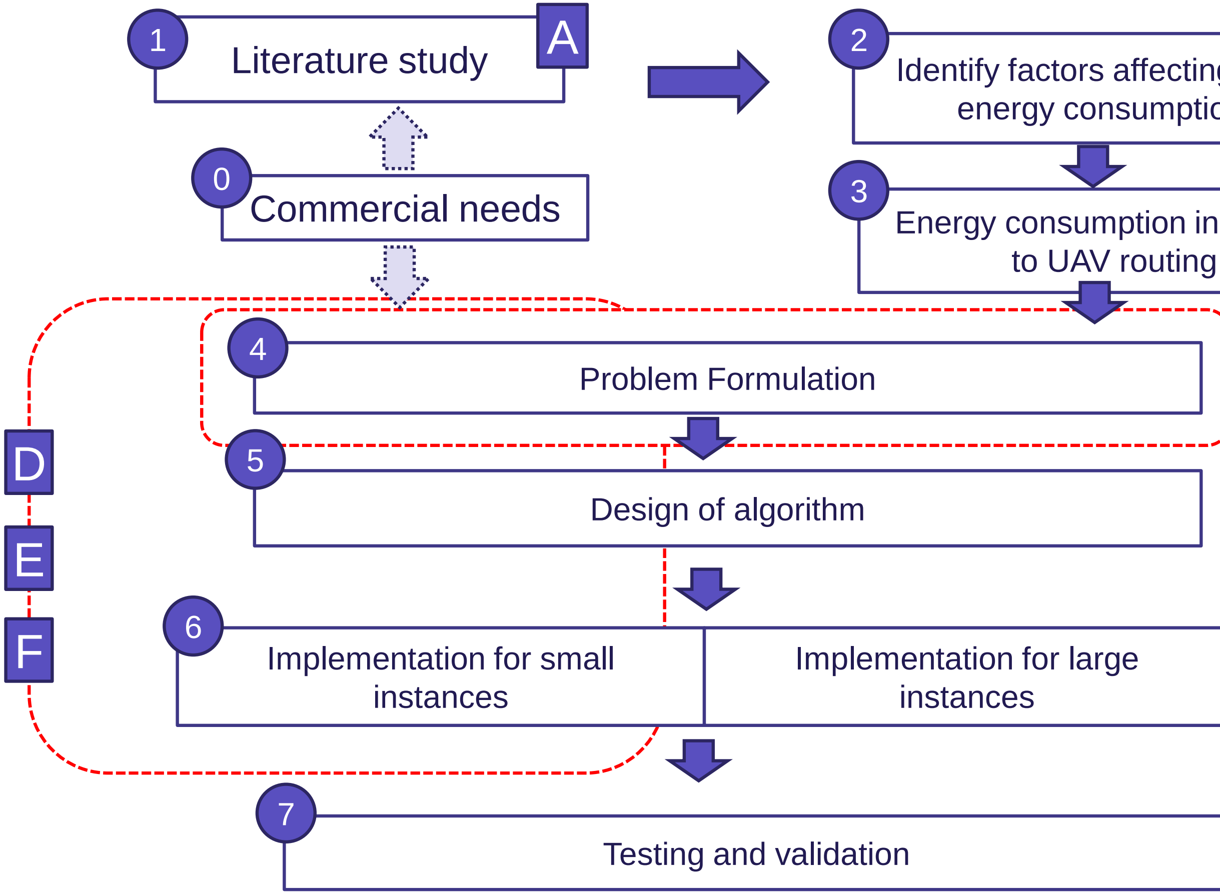
bocewicz@ie.tu.koszalin.pl

Abstract. Unmanned Aerial Vehicles (UAV) routing is transitioning from an emerging topic to a growing research area and one critical aspect of it is the energy consumption of UAVs. This transition induces a need to identify factors, which affects the energy consumption of UAVs and thereby the routing. This paper presents an analysis of different parameters that influence the energy consumption of the UAV Routing Problem. This is achieved by analyzing an example scenario of a single UAV multiple delivery mission, and based on the analysis, relationships between UAV energy consumption and the influencing parameters are shown.

Keywords: Unmanned Aerial Vehicles · UAV routing
Energy consumption of UAVs

- Conference Paper
- Conference : ISAT 2018
- Status : Published



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Publications D

Routing and scheduling of Unmanned Aerial Vehicles subject to cyclic production flow constraints

Bocewicz G.[1], Nielsen P.[2], Banaszak Z.[1], Thibbotuwawa A.[2]

[1] Faculty of Electronics and Computer Science, Koszalin University of Technology, Poland, (bocewicz@ie.tu.koszalin.pl)

[2] Department of Materials and Production, Aalborg University, Denmark, (izabela@mp.aau.dk)

Abstract. Given is a production system in which material handling operations are carried out by a fleet of UAVs. The problem formulated for the considered case of cyclic multi-product batch production flow is a material handling costs problem. To solve this problem, it is necessary to designate the routes and the corresponding schedules for vehicles that make up the given UAV fleet. The goal is to find solutions that will reduce to a minimum UAV downtime and the takt time of the cyclic production flow in which operations are performed by the UAVs. A declarative model of the analyzed case was used, which allowed us to view the problem as a constraint satisfaction problem and to solve it in the Mozart constraint programming environment.

- Conference Paper
- Conference : DCAI 2018
- Status : Published

Publications E

A Declarative Modelling Framework for Routing of Multiple UAVs in a System with Mobile Battery Swapping Stations

Bocewicz G.[1], Nielsen P. [2] Banaszak Z.[1], Thibbotuwawa A.[2]

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(bocewicz@ie.tu.koszalin.pl)
[2]Department of Materials and Production, Aalborg University, Denmark,
(peter;amila@mp.aau.dk)

Abstract. A flow production system with concurrently executed supply chains providing material handling/transportation services to a given set of workstations is considered. The workstations have to be serviced within preset time windows and can be shared by different supply chains. The transportation and material handling operations supporting the flow of products between the workstations are carried out by a fleet of Unmanned Aerial Vehicles (UAVs). The batteries on-board the UAVs are replaced at mobile battery swapping stations (MBSs). The focus of this study is a cyclic steady-state flow of products and transportation means, i.e. a state in whose cycle workstations are serviced periodically, within preset time windows, by the same transportation means travelling the same transportation routes. Under this assumption, UAV batteries are swapped at the some locations of battery replacement depots at moments which are multiples of the cycle under consideration. Similar assumptions are made for the fleet of MBSs. To find a solution to the above problem of routing UAV and MBS fleets, one needs to determine the routes travelled by the UAVs servicing the workstations and the routes travelled by the MBSs servicing the battery swapping points, such that the total length of these routes is minimized.

Keywords: Unmanned aerial vehicles, delivery routing problem, declarative modelling, mobile battery swapping station

- Conference Paper
- Conference : ISPEM 2018
- Status : Published

Publications F

Deployment of Battery Swapping Stations for Unmanned Aerial Vehicles Subject to Cyclic Production Flow Constraints

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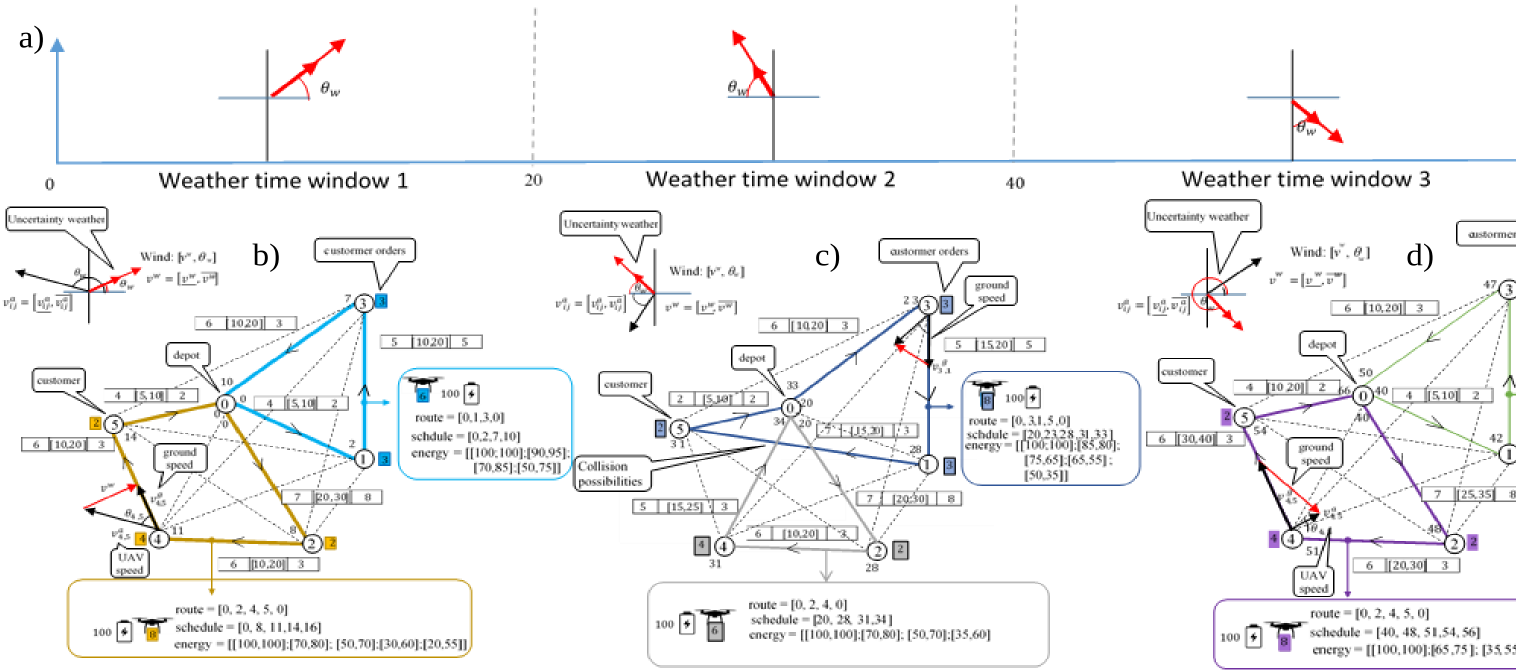
Abstract. Given is a production system in which material handling operations are carried out by a fleet of UAVs. A problem has been formulated for this case of cyclic multi-product batch production flow, which combines the problems of split delivery-vehicle routing with time windows and deployment of battery swapping depots. It is assumed that the times of execution of pickup and delivery operations are known. During these operations, workpieces following different production routes reach and leave workstations cyclically. Given is the number of battery swapping depots and their potential arrangement. Given is also the rate of power consumption by an UAV in hovering mode or flying at a constant speed as well as during take-off and landing. The goal is to find 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. A declarative model of the analysed case allows to view the problem under consideration as a constraint satisfaction problem and solve it in the Oz Mozart programming environment.

Keywords: Unmanned aerial vehicles · Battery swapping · Routing problem

- Conference Paper
- Conference : ICIST 2018
- Status : Published

Example problem

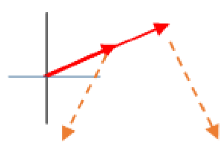


Legend

$d_{i,j}$	$P_{i,j}$	$t_{i,j}$
distance	*energy*	*time*

- - - - - Flying corridors

θ_w Wind direction



$v^w = [\underline{v^w}, \overline{v^w}]$: *Wind Speed* = [*Min rannge of* v^w, *Max range of* v^w]

$v^a_{ij} = [\underline{v^a_{ij}}, \overline{v^a_{ij}}]$: UAV air speed = [*Min rannge of* v^a_{ij}, *Max rannge of* v^a_{ij}]

v^g_{ij} UAV ground speed

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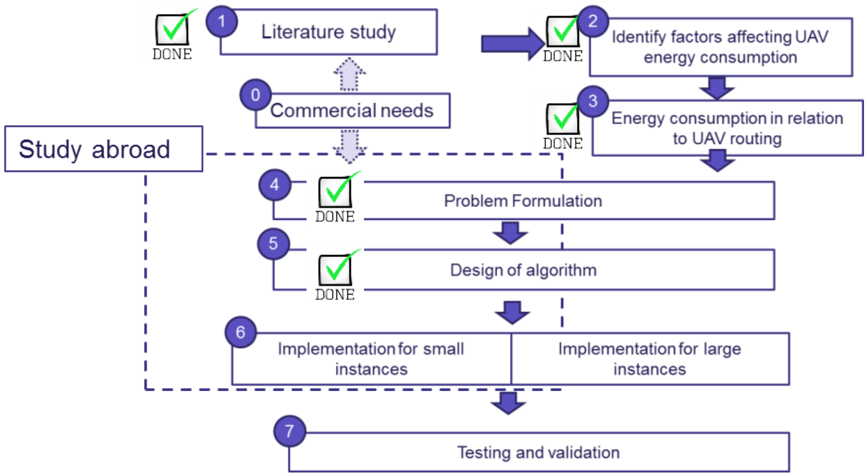
Conclusion

- Up to Now
  - Step 1,2 and 3
  - PhD courses
  - Journal article
  - Conference proceedings
  - Study abroad started
- Future work
  - Step 4-7



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Conclusion

- Focuses on analyzing the energy consumption of UAVs, which is non-linear and dependent on weather, speed, direction, and payload.
- The paper analyses an example scenario of a single UAV multiple delivery mission, and based on the analysis, relationships between UAV energy consumption and the influencing parameters are presented.
- The results of the analysis shows that the energy consumption has a non-linear relationship with the parameters of flying speed and payload.
  - It shows that in higher-flying speeds, linear approximations are possible.
- In lower flying speeds and higher carrying payloads, the UAV consumes more energy for take-off and landing compared level flight, which is the vice versa in higher-flying speeds and lower carrying payloads.
- Results tells that changes wind direction can significantly affect the energy consumption of a UAV.
- Future research

Thank You

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