AMBULANCE DRONES IN THE NETHERLANDS:
A VISION + CONCEPT DESIGN FOR 2035.

APPENDIX

APPENDIX A

Interview Eduard van Belle, Ambulance station Delft

Interview ambulance station Delft
Friday 9-4-2021
Interview and tour with Eduard van Belle, ambulance station manager Delft.

Eduard has over 30 years of experience within medical healthcare. He started working in the hospital and eventually worked as an ambulance nurse, before taking on his role as manager of the ambulance station in Delft around a decade ago. He invited me to have a one on one interview and a tour of the ambulance vehicle. The interview was recorded and the interpretations of his answers are listed below. Note that this is not a literal transcription, but rather a concise summary of his answers.

Ambulance layout

1. What equipment is inside an ambulance?
As described in 1.5.3 based on literature research, there are no significant differences in the equipment of this ambulance.

Is this according to protocol, or are there also items that you have added in yourself?
Inside the cases for medication they have made holders for different kinds of medication bottles with their on site 3D printer.

2. Does all equipment have to be modular?
Most items can be taken out, aside from the obvious things such as the stretcher and the medicine cases. Even the patient monitor can be removed, which is a rather heavy piece of equipment of around 15 kg. Eduard mentioned these monitors are 11 years old and they are looking into new monitors that are lighter. Things that are fixed in place are the drip machine and breathing equipment. The breathing equipment built inside the ambulance is rarely used as they often use the manual breather device, which they can take with them to the patient.

3. What is the reasoning behind the placement of the equipment inside the ambulance?
Large items that are predominantly used at the site of the incident are placed so that they can be reached from outside of the ambulance. This makes access a lot easier, quicker and more comfortable. Equipment and medication that is needed during transport is all within the reach from the nurse's seat. The nurse can check all the vital signs of the patient using the monitor and can check or add medical records using the notebook.

4. How is the stretcher taken out of the ambulance?
The stretcher is electrically powered and can roll itself in and out of the ambulance, saving the team a lot of effort as the stretcher is one of the heaviest pieces of equipment in the vehicle.

5. Are there things that could be improved, but are impossible due to lack of space?
Not really, a lot of problems have been addressed over the years. Also given that most of the work needs to be done seated while on the move, a compact setup within arm's reach is more beneficial than a lot of open space. Eduard also stipulated that they work in cooperation with the manufacturer of the vehicles to design them to the specifications and wishes of the ambulance staff.

6. Why are the driver cabin and the rear cabin separated from each other?
This has to do with hygiene most of all, as the rear is designed to be sterile and easily cleanable. This is not possible for the driver cabin.

Preparations

7. Which preparations are made at the beginning of the day?
Ambulance staff are provided with inventory lists which determine what equipment has to be present inside the ambulance, so that they can check this. At the end of their shift they always prepare the vehicle for the next day, so usually they are ready to go in the morning after a short backup check to be sure everything is in order. When they are ready to be deployed they notify the control room, using their personal ID codes so that the control room knows exactly which driver and nurse are on their shift.

8. Which preparations are made in between calls?
Cleaning and preparing the ambulance is usually done by separate staff at the hospital whilst the ambulance staff is transferring the patient into the hospital. So when they return to their station the ambulance is already deployable. When they have time between calls they try to do some relaxing activities or some training to keep their medical skills on point.

9. Are the driver and nurse responsible for all the preparations or do they have staff helping them?
At the ambulance station the driver and nurse do the preparations themselves. The driver checks the driver cabin and some mechanical things, whilst the nurse checks the loading area. In most cases they help each other with these task. On top of these regular preparations, currently external cleaning companies are there to help sterilising the ambulances after every call, which is mandatory due to COVID-19.

10. Can it happen that a call comes in right after returning from the previous call?
Yes, that certainly happens.

How do you manage to prepare in time?
This is not usually an issue since the ambulance arrives back from the hospital clean and prepared. Theoretically, an ambulance could go out on another call without any preparations, as it is equipped to perform two emergency responses.

11. How is the ambulance cleaned
And how is it done during COVID-19 times?
There are special wash boxes for ambulances which are used to rigorous cleaning, in case the ambulance is really dirty inside. Next to that there is a cleaning protocol in place during the COVID-19 pandemic which means the vehicles need to be sterilised after each call. For this the cleaners use alcohol in spray bottles and wipes.

Departure
12. When a call comes in, how quickly are you able to depart, on average?
On average within 50 seconds the ambulance drives out of the gate at the station in Delft. They really optimise everything to decrease this time as far as possible. Eduard mentioned that they even installed a door next to the coffee machine that leads straight into the garage, saving them many seconds. Another testament to time savings is that the control room even looks at the ambulance that is parked closest to the exit and prioritises that one over the others parked next to it.

Are there cases in which departure is delayed and if so, for what reasons?
Sometimes it is so busy that an ambulance is still at the hospital while receiving their next call. Then they will first deliver their current patient and then respond to the next call, which creates a delay.

13. How many times a day do you receive a call and does it vary?
On average 6 times a day.
Yes, sometimes it can go up to 10 times a day and very incidentally there are no calls, but this only happens at night.

On the way
14. If the ambulance gets stuck or is involved in an accident, how is this handled?
Another ambulance is sent out to pick up the patient from the ambulance that is stranded or was involved in an accident and will check the wellbeing of the other ambulance staff in case of an accident.

15. Do patients get distressed from the bumpy ride and if so, how are they comforted?
Sometimes, of course the nurse will do their best to calm the patient. Patients with spinal injuries or other injuries that need to be stabilised are put in a vacuum mattress to keep them completely fixed during the bumpy ride.

16. Are friends/relatives of the patient allowed to drive along in the ambulance?
Before COVID-19 they actually preferred someone to accompany the patient to the hospital, but at the moment this is not allowed.

17. What kind of navigation system do you use?
The navigation system they use is called City-NAV and is specially developed for the ambulances. When the control room gets a call the navigation system automatically plots a route and attaches patient data to it as well, which the ambulance staff can view on their screen. During the drive the data is updated based on new information, which they will get notified of on their navigation screen. The maps of the navigation system are incredibly up to date and ambulances are supplied with updated maps through a WIFI point at the station which uploads it automatically to the navigation system upon arrival. Also they employ a scout who scans the region for changes in traffic situations. For example when there is an event and certain roads are blocked or when a street or pathway has become temporarily obstructed.

Is there ever any difficulty with navigation because the destination is difficult to reach?
Rarely. Really only because of traffic jams, although they will still be able to slowly move through them as well.

18. Can the driver and the nurse communicate with one another during the drive to the hospital?
They can, the window between driver cabin and loading area can be opened. They can also contact each other using their portophone system, for which the driver has a special button on the steering wheel.

On site
19. How does the driver assist the nurse at the place of the incident?
Mostly with carrying items from the ambulance to the patient and the driver also assists with treatments. Next to that the driver deals with bystanders, trying to comfort them or keep them away from getting too close.

20. How do you transport patients from difficult to reach places with the stretcher?
The stretcher cannot really be taken up stairs as it is quite heavy, so they have to transport the patient to the stretcher. In some cases windows or walls are demolished in order to access the patient. Any sacrifice is made to save the patient.

21. Are there ever cases of vandalism or robbery of items in the ambulance by bystanders?
Very rarely, mostly negligible. There is a lot of media attention for aggression towards ambulance staff, but in practice this seldomly occurs.

22. Do bystanders ever hamper the ambulance staff's work or meddle with their way of treating the patient?
Usually this only happens out of concern for the patient. Ambulance staff will also call on the help of bystanders often, because they can use their assistance.

General questions
23. How long is a shift?
Each shift is 8 hours. Every 24 hours is divided into multiple overlapping shifts, to avoid periods of time in between shifts when no staff is available because they are finishing or just starting their shift.

24. How long does an ambulance van last?
Five years, this is determined by the lease contract that they have with their supplier. The supplier then sells these phased out ambulances, mostly to other countries.
In case an ambulance breaks down at the station they have a backup vehicle prepared. Another department that is responsible for the repairs will service the defective ambulance.

25. How long does the equipment last?
This differs, depending on the reliability of the equipment. One very reliable piece of equipment is the patient monitor which has been in use for 11 years.

If equipment breaks during the call, how is this handled?
If it is a vital piece of equipment another ambulance is sent to take over the task. The staff of the defective ambulance will still proceed treating the patient to the best of their abilities in the meantime.

26. How is the ambulance network organised?
The main objective is to always maintain a 15 minute response time coverage on every ambulance station. This means that if a station gets a call and their last ambulance needs be deployed, an ambulance from another station is immediately send to the dormant station to maintain 15 minute coverage in that area. The control room is responsible for organising the distribution of ambulances among all the stations within their region. In the region Haaglanden, which the station in Delft is part of, the average response time is 10 minutes. According to protocol they should respond to 97% of cases within 15 minutes, but they cannot reach this during the COVID-19 pandemic due to more preparation. Right know they respond within 15 minutes in 90% of calls.

Project related
27. In the future automated ambulance drones may not need a pilot, so is the assistance of the pilot crucial to the nurse or could they potentially work alone?
According to Eduard's estimation a nurse could potentially work individually especially as equipment is expected to be optimised and automated further in the future.

28. Could very fast response times make some equipment unnecessary because the patient is at the hospital so quickly that treatments can be started there?
Doubtful, because the most basic necessary equipment is also by far the heaviest equipment (stretcher, monitor, various stabilising devices). There is no doubt that a lot of small items can potentially left out, so there is room for optimisation but not significantly. This has to do with the fact that most of the equipment is also necessary for treating the patient at the place of the incident, which is what makes their chances of survival much greater. To put it plainly, you cannot simply put someone with heart complications in an empty cabin and fly them to the hospital, even if it only takes 5 minutes. It is the immediate care in the first seconds that makes the biggest difference.

29. Are there documents explaining how ambulances are constructed?
Eduard could not provide these. He did explain that ambulance vehicles weigh around 3500kg which requires ambulances drivers to have a truck license to be allowed to drive them. This weight may give some insight into the added weight of the equipment onto the empty weight of a Mercedes-Benz van.

30. If ambulance drones would replace a large part of regular ambulance vehicles in the future, would the ambulance sector be accepting such an innovation?
Eduard sees it is as an inevitable development of which it is more the question when it will happen than if. As far as the general opinion within his sector for this kind of solution he could not provide a direct answer.

APPENDIX B

Take-off and landing infrastructure Scenarios

SCENARIO 1: AMBULANCE DRONE REPLACES ALL A1-TYPE AMBULANCES

Ambulance network and response times

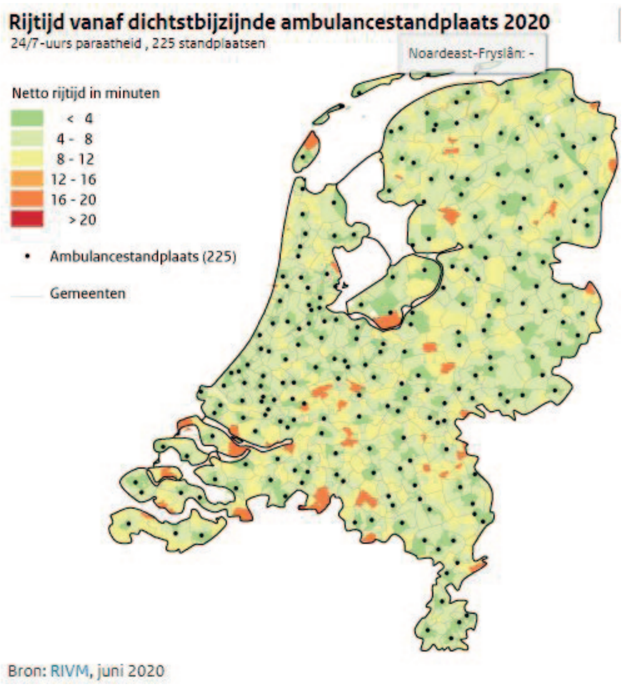


Figure 1: ambulance stations and the response times in their respective areas.

The Dutch government provides detailed documentation of all ambulance stations in the Netherlands. Figure 1 shows all the ambulance stations and the response times in their respective areas. This is a very useful map as it tells a lot about the distribution and density of the network. In combination with figure 2, which shows the amount of A1 responses per 1000 citizens for each RAV, we can start to understand which areas of the country experience the highest pressure on the ambulance system. Clearly, the urbanised provinces of Noord-Holland and Zuid-Holland are busier, which is also reflected in the density of ambulance stations. Surprisingly the provinces of Groningen and Limburg also experience a relatively high amount of A1 responses.

In total there are 225 ambulance stations distributed at different distances from each other. A quick investigation on google maps tells us that the distance between ambulance stations ranges from as low as 1 kilometres up to 20 kilometres. This makes sense, as there is an evident correlation between the inter-station distance and the population density. Stations that are close to each other are always within densely populated areas. This also correlates with the 15 minute limit for response times, as ambulance vehicles in urban areas will take more time to cover the same distance compared to those in rural areas due to traffic congestion and lower speed limits. In short, the range of ambulances is smaller in urban areas than in rural areas.

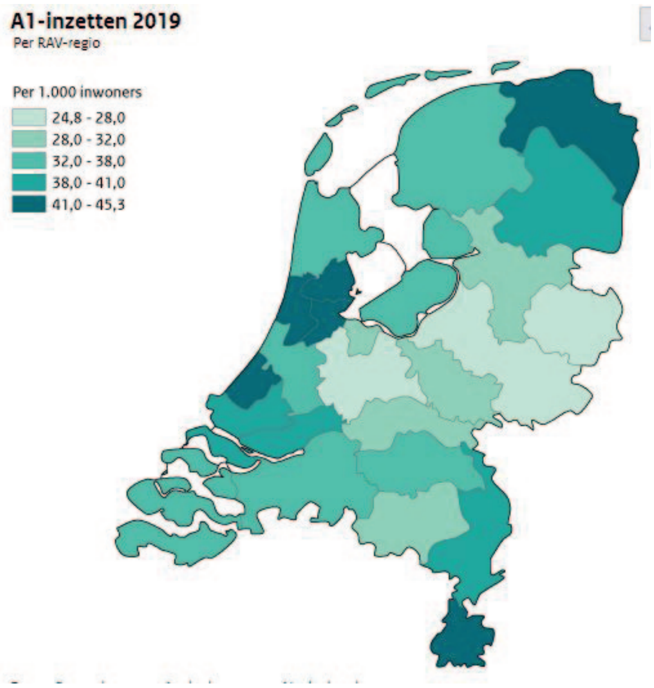


Figure 2: amount of A1 responses per 1000 citizens for each RAV

In the case of ambulance drones the correlation between population density and range is barely existent as they are not limited by traffic. This means vertiports could hypothetically be distributed much more evenly across the country. If an ambulance drone travels at an average speed of 100 km/h and needs to stay within the maximum response time of 15 minutes, it means it can cover a range of 25 kilometres. As the range is dependent on the speed, it might seem obvious to simply maximise the speed of the drone in order to increase the range. Of course it is not so easy as there are factors that limit the maximum speed of the drone, such as the weight and the battery capacity.

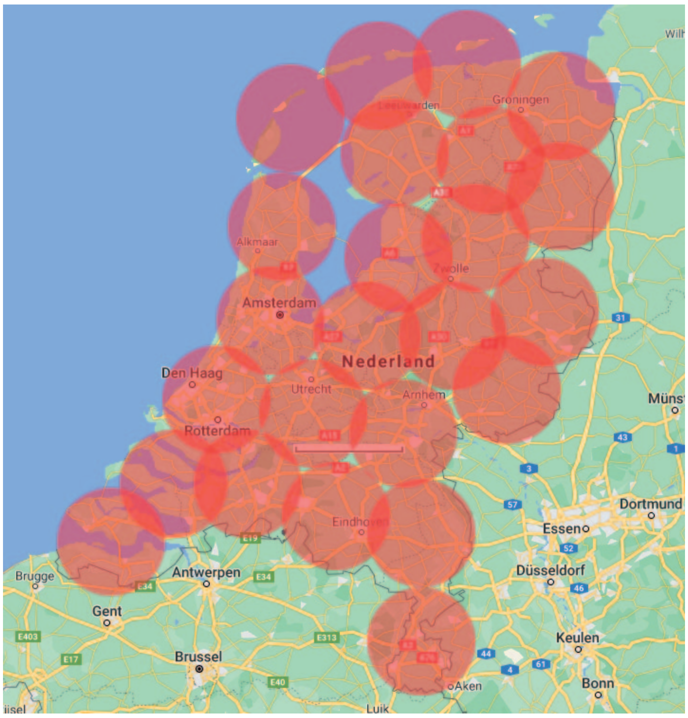


Figure 3: 24 vertiports with 25 kilometer range.

Nonetheless, even at a cruise speed of 100 km/h - which is well within the capability of an eVTOL - a range of 25 kilometres is quite large. Plotting out this range on a map of the Netherlands gives a rough estimate of the number of vertiports that would be needed. Figure 3 shows that approximately 24 vertiports would be needed to cover the whole country, which is dramatically less than the 225 ambulance stations that exist currently.

What is important to realise in the case that ambulance drones will form a full replacement of the ambulance vehicles of today, that the drones will need to provide the same capacity. In fact it can be expected that the capacity of ambulances will need to increase in the future, as this is already the case each year. This means that as the number of vertiports becomes less, more ambulance drones are needed per vertiport. With around 800 ambulances distributed across 225 stations in 2018, a quick calculation shows an average of 3,5 ambulances per station. 24 stations would mean an average of 33,3 ambulances per station.

Ambulance stations as vertiports

Given the density and even distribution of the already in place ambulance stations it makes sense to investigate the possibility of exploiting these for future ambulance drones as well. For this it is necessary to understand the possibilities of adding take-off and landing infrastructure to these buildings. This is not easy as these stations are all different in size, layout and available open space around the building. Investigating every single station is too time consuming, so instead samples are taken from Google Streetview.

Figure 4: Examples of suitable ambulance stations (Google Maps).

What is clear from this investigation is that there is a lot of variation in ambulance stations, but there are a few things that most of themhave in common. A lot of them have parking lots directly surrounding them and/or big roof areas (figure 4). Both are potential spots for the implementation of vertiports. Naturally, there are also exceptions that do not have either of these facilities and it is unlikely that these can be adapted to house vertiports (figure 5)

Figure 5: Example of an unsuitable ambulance station (Google Maps).

Another thing to consider is that spaces such as parking lots need to be adapted to become a vertiport, which means cars will not be able to park there. Especially in urban areas parking spots are quite scarce and removing them is less desirable. Rooftops are therefore more space efficient, but also require a lot more adaptation to carry a vertiport. Depending on the type of structure present in the existing building it might not be possible at all to carry that weight on its roof.

In short, ambulance stations provide some opportunities for vertiports but in a limited amount. Therefore, other infrastructure is needed.

Hospital vertiports
Such infrastructure might be found in existing hospitals. Another look on Google Maps shows that many existing hospitals have roof spaces and/or open spaces around the building. For reference, the rooftop helipads for the ambulance helicopters are 20 x 20 meters. This is only for landing one helicopter at a time and, although an ambulance drone might require less space to land, it is unrealistic to expect high numbers of drones to land on the size of a helipad. So rooftops provide a clear restriction on the size of a vertiport that needs to be taken into account when designing for this existing infrastructure.

Spaces around the hospital might provide more opportunity for higher capacity landing pads. What needs to be taken into consideration, however, is the scale of each 24 vertiports needed in order to have a capacity of approximately 30 ambulances drones. The information gathered from ambulance helicopters in chapter 1 showed that they need a minimum of 25 x 25 meters to land. Assuming an ambulance drone to be more compact and manoeuvrable, let’s say that it needs an area of at least 10 x 10 meters to land. In that case the vertiport would need to be at least 50 x 60 meters; more than half a football field. While this is not completely impossible, a smaller area would bring a lot of benefits and this forms an important design input.

Rooftops of industrial buildings
Industrial buildings, such as warehouses, could be an interesting opportunity for using existing infrastructure. Adapting existing warehouses to house a large vertiport is not feasible, however, since the structure is not fit to carry extra weight. Many modern buildings are constructed with structures that are optimised for the building’s specifications. Adding a large weight on the roof is often not within the capabilities of the original structure. So an alternative to adapting existing infrastructure could be to construct new buildings that allow for the addition of a rooftop vertiport.
Of course, this is a longer term plan and not a solution in case a vertiport network needs to be established quickly.

SCENARIO 2: AMBULANCE DRONES AS LIFELINERS 2.0

Scaled up Lifeliner services
Given that ambulance helicopters (i.e. Lifeliners) are very scarce in the Netherlands (only four) it makes sense to investigate the possibility of expanding this service with ambulance drones.

As explained in chapter 1, the Lifeliners always operate together with a regular ambulance. This means they are a supplementary service and not a primary service. Nonetheless their benefits are very obvious given their ability to carry specialised doctors and medication that standard ambulances do not have.

With the hypothetical ambulance drone from the previous scenario with a range of 25 kilometres it would not be possible to operate from only four vertiports. It therefore makes sense to expand the Lifeliner service into a primary service that replaces part of the regular A1 ambulances. This would mean that unlike the Lifeliners, the ambulance drone can operate independently and is sent to incidents that are estimated to be very critical. Estimating the amount of such incidents is a bit of a grey area, as the narrowest category at our disposal for critical incidents is the A1 response, which, as explained in chapter 1 lies at around 600.000 in 2019. Of these A1 responses, in only around 8000 cases a Lifeliner is called in for assistance. Roughly half of these 8000 cases are called off even before the Lifeliner arrives at the destination, because the ambulance staff can handle the situation on their own. This is the consequence of the Lifeliner being a supplementary service.

Clearly the capacity needed for an ambulance drone system that replaces the current Lifeliners is drastically smaller than in scenario 1. However, this poses the concern that it might underutilise an innovation with so much potential, at least in the case of short range drones as used in scenario 1. Perhaps the Lifeliner 2.0 system would benefit more from larger and faster drones with a larger range similar to current helicopters.

This may beg the question why it is necessary to replace the current Lifeliner helicopters to begin with. For starters, it would be more sustainable (electrically powered) and designed for its function from the ground up, unlike the restricting form factor of helicopters. Next to that, the mechanisms of an ambulance drone are simpler than a helicopter and therefore potentially cheaper to manufacture and maintain. Major cost savings would also come from the possibility to make the ambulance drone autonomous and not require a highly specialised pilot. All the aforementioned benefits point towards the potential of a Lifeliner 2.0 system to be more scalable and available to more patients.

It must be assumed that the roughly 4000 cases in which the Lifeliner is actually utilised are for exceptionally critical incidents. Thich makes sense, as the Lifeliner brings hospital grade care to the patient. In principle making this level of care available to more patients could only be a positive development, and an ambulance drone might make this possible. Situations where half of the responses are called off would not exist when the ambulance drones are a primary service. They would be called in based on the assessed severity of the incident and they would be fully responsible for transporting the patient to the hospital. This inevitably means that there will be a level of redundancy, where a regular ambulance would have been able to handle the call and the Lifeliner would not have been necessary. What counters this are the cases in which the Lifeliner might save a patient's quality of life because of the extra care they receive so quickly. Whereas currently they would be served by a regular ambulance and their injury might be treated too late to prevent permanent damage.

An important factor that also needs to be taken into account when scaling up the current Lifeliner service is that the amount of staff will also need to be scaled up. This means that more specialised doctors will need to be educated.

Lifeliner 2.0 infrastructure

Given the smaller capacity and lower network density of this scenario, infrastructure solutions will be easier than in scenario 1. It is more likely that infrastructure similar to that of the current Lifeliners would suffice for this scenario. This means helipads on hospitals and separate hangars at airports. If a drone with twice the range of that in scenario 1 would be used, the number of vertiports needed may drop to as low as 10-15. This increases the likelihood of implementing this system on existing hospital rooftops. Especially because each of these stations likely needs to house only one or two ambulance drones. Increasing the range of the drone does add to technical complexity and costs.

SCENARIO 3: RAPID RESPONDER DRONES

In the previous scenarios the ambulance drone is also responsible for transporting patients. This has major implications for the design, as it will need to be able to carry two people (nurse and patient) as well as the necessary equipment for treatment during transport. A simple way to decrease the complexity of the ambulance drone is to utilise it as a rapid responder type vehicle. As mentioned in chapter 1, these are vehicles that are constantly mobile and more manoeuvrable than regular ambulances, such as cars, motorcycles and even bicycles. As such they can respond to calls faster than regular ambulances and arrive at the incident first. They carry equipment necessary for starting treatment, until the regular ambulance arrives.

According to Rutger Jongejan, ambulance nurse, response times below 6 minutes can really make a difference in acute life threatening situations such as heart failure, strokes and heavy bleeding. A regular ambulance that arrives after 14 minutes (so still within the 15 minute norm) will likely be too late. This is the gap that rapid responders are meant to fill, and drones could be an addition to this category of acute care. (Jongejan, 2018)

Network
Since the Rapid Responder's added benefit completely rests on the ability to arrive faster than a regular ambulance, a rapid responder drone would also need to prioritize speed. Since the drone only needs to carry a nurse and a limited amount of equipment, it can be a rather lightweight and compact design compared to ambulance drones with a transport function. This has a positive impact on battery capacity, which in turn can be leveraged for more speed. Even though the speed can be increased, the density of the network still needs to remain high to bring the response times to a minimum. This means a network of at least the density of scenario 1, possibly denser.

What works in the advantage of a denser network is the compact nature of a rapid responder drone.

Small vertiports can quite easily be placed on existing car parks and small rooftops. Another benefit of this scenario is that it, like scenario 2, requires only a small amount of capacity per vertiports. In fact, bundling rapid responders defeats the purpose of having a dense network. It is better to have one or two at each ambulance station, hospital and other outposts than ten at a central spot.

APPENDIX C

Vertiport Concepts

1. INTRODUCTION

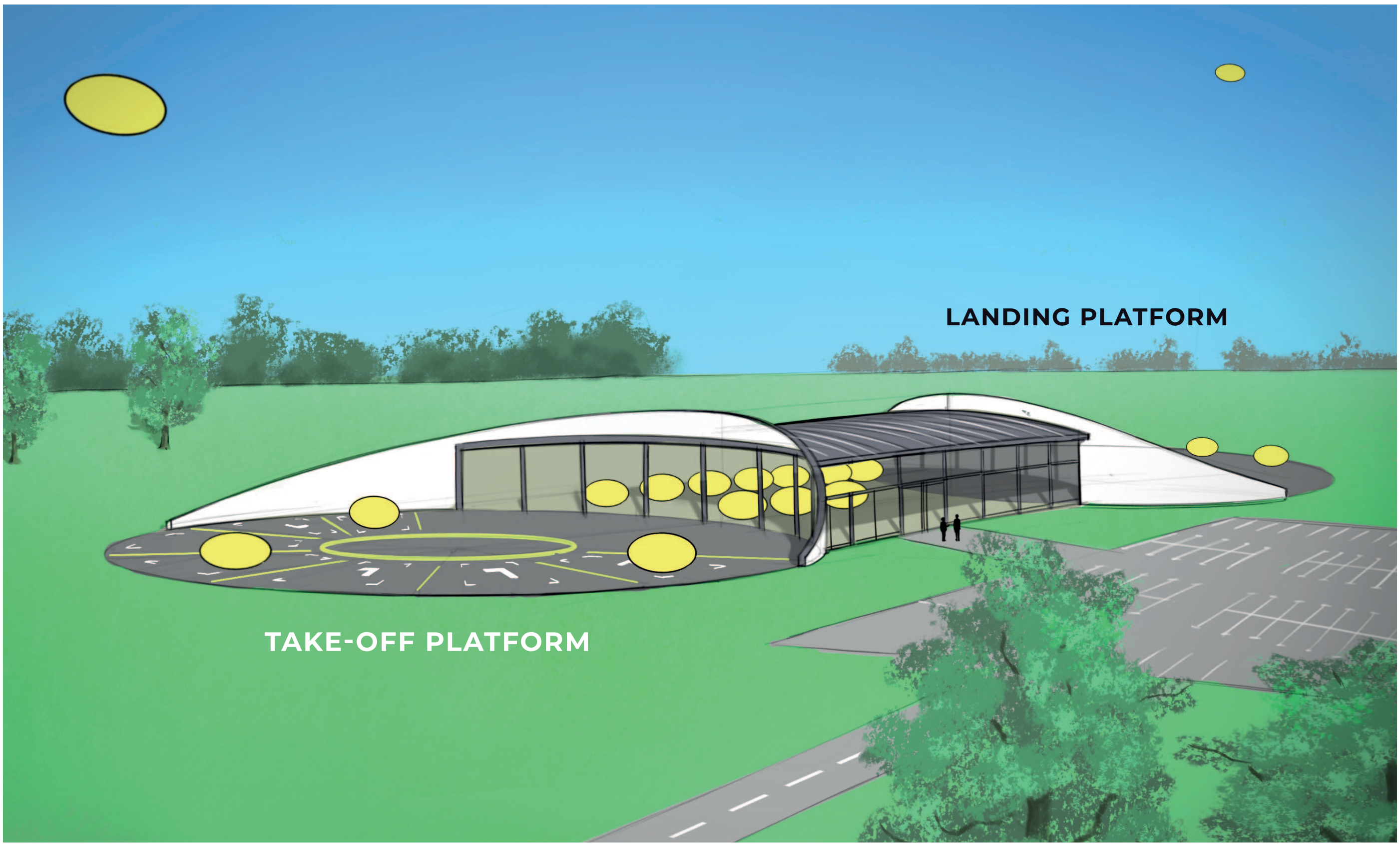
Being able to safely fly an ambulance drone is just as important as for it to take-off and land in the safest and most optimal way. This requires infrastructure that is tailored to the ambulance drone and its staff.
In this appendix, possibilities for take-off and landing infrastructure are investigated, more conveniently called "vertiports" from here onwards. In order to design a vertiport network it is critical to establish the type of vertiport network that is needed. This is based on the way ambulance drones are going to be implemented in the future.

Three concepts are proposed. A comparison is made between these concepts which informs the best final vertiport design. These vertiport solutions take existing infrastructure into consideration, as the design philosophy that the vertiports need to follow is that of simplicity and cost efficiency. Thus solutions that are modular and/or compatible with existing infrastructure are of the highest priority.

2. CONCEPT 1: STRATEGIC HIGH CAPACITY VERTIPORTS

2.1 Network

This concept is based on the analyses that can be found in Appendix B. It provides a network that replaces all A1 ambulances. As the ambulance drones are not bound by traffic or road layouts, it can provide a very consistent range of 25 kilometres in any area of the Netherlands. From this scenario it became clear that with such a range, there would only need to be around 24 vertiports throughout the country, as opposed to the 225 ambulance stations currently. These vertiports will need to carry a high capacity of ambulances drones, however, and therefore require lots of space for take-off and landing infrastructure. It is therefore more difficult to realise this in urban areas. On the positive side, the 25 kilometre range allows vertiports to be placed on the edge of urban areas and still be able to cover an entire city. This can be seen in figure 1, where a possible placement of vertiports around Rotterdam and The Hague is shown.



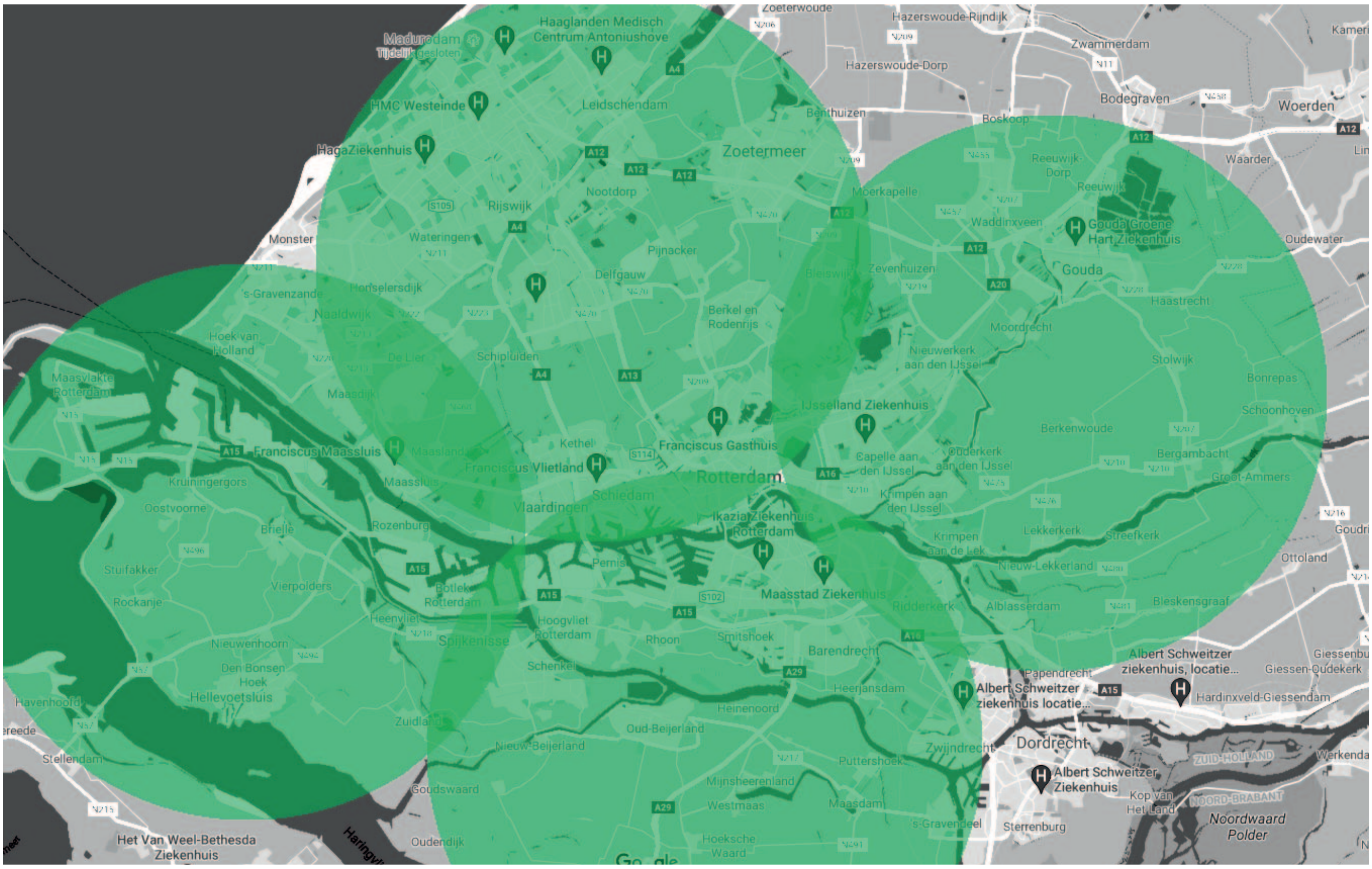


Figure 1: vertiport coverage around Rotterdam and The Hague.

In this example the range is plotted in identical circular areas of 50 km diameter, but in reality the placement will need to be established much more precisely. Given the country's irregular shape and the fact that circles do not fit together naturally, there is always a degree of overlap. This overlap is not necessarily bad as it can be an advantage when used strategically. Placing the overlap on urban areas allows these areas to have two or more vertiports available to them. Determining the optimal location (related to other vertiports and nearby hospitals) and, additionally, the optimal capacity related to the area that a vertiport operates in is an entire investigation in itself. This is beyond the scope of this project. Regardless, this short analysis does give an indication of what might be possible.

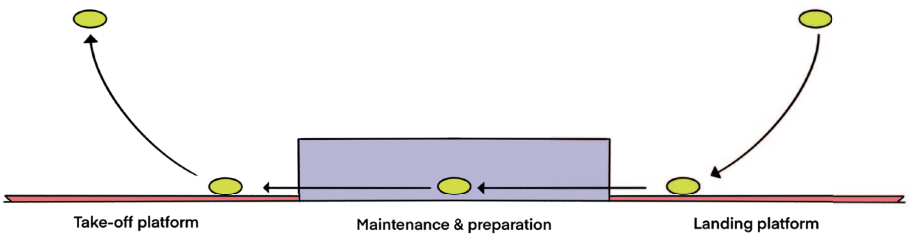


Figure 2: vertiport operating sequence.

2.2 Vertiport operating sequence

In order to sustain such a high capacity of around 30 or more drones per vertiport a sequence has been proposed (figure 2). The landing platform and the take-off platform are separated and placed on opposite ends of the maintenance facilities. As a drone returns from a mission, it moves from the landing platform through the maintenance facilities. Where it can be cleaned, repaired and potentially be fitted with a fully charged battery. After maintenance it can stay docked inside or moved onto the take-off platform ready to answer to a new call. The process is similar to a factory assembly line. Given the complexity that comes with such a large scale vertiport a predictable and efficient process is beneficial.

2.3 Infrastructure

Clearly the infrastructure needed for this scenario is quite advanced. In this scenario, the vertiport is designed from the ground up, instead of using existing infrastructure. The first reason for this is because the system relies on optimal geographical placement. The chance of useable existing infrastructure to be present at the ideal locations are very slim. The second reason is that the vertiport relies on its layout for an efficient operation, so it needs to be built that specific way.

3. CONCEPT 2: LIFELINER 2.0 VERTIPORTS

3.1 Network

This concept is based on the analysis in Appendix B, where ambulance drones provide an upgraded replacement for ambulance helicopters. The network of this scenario requires a small amount of vertiports with a capacity of only a few ambulance drones each.

It was calculated that at 200 km/h cruise speed the drones would be able to cater to a range of 40 kilometres in around 13 minutes.

This is well within the current response time limit of A1 responses (15 minutes) and certainly an improvement compared to ambulance helicopters, which in some areas can take more than 20 minutes to arrive. A cruising speed of 200 km/h is within the possibilities of manned drones, since current eVTOLs such as Joby are already developing to have cruise speeds above 300 km/h for a range of more than 200 kilometres. In the example shown in figure 3, a 40 kilometre range (80 kilometres in diameter) was mapped out on a map of the Netherlands. It is possible to cover almost the entire country with 11 vertiports. Compared to the current situation of four ambulance helicopter stations this improves the network density significantly.

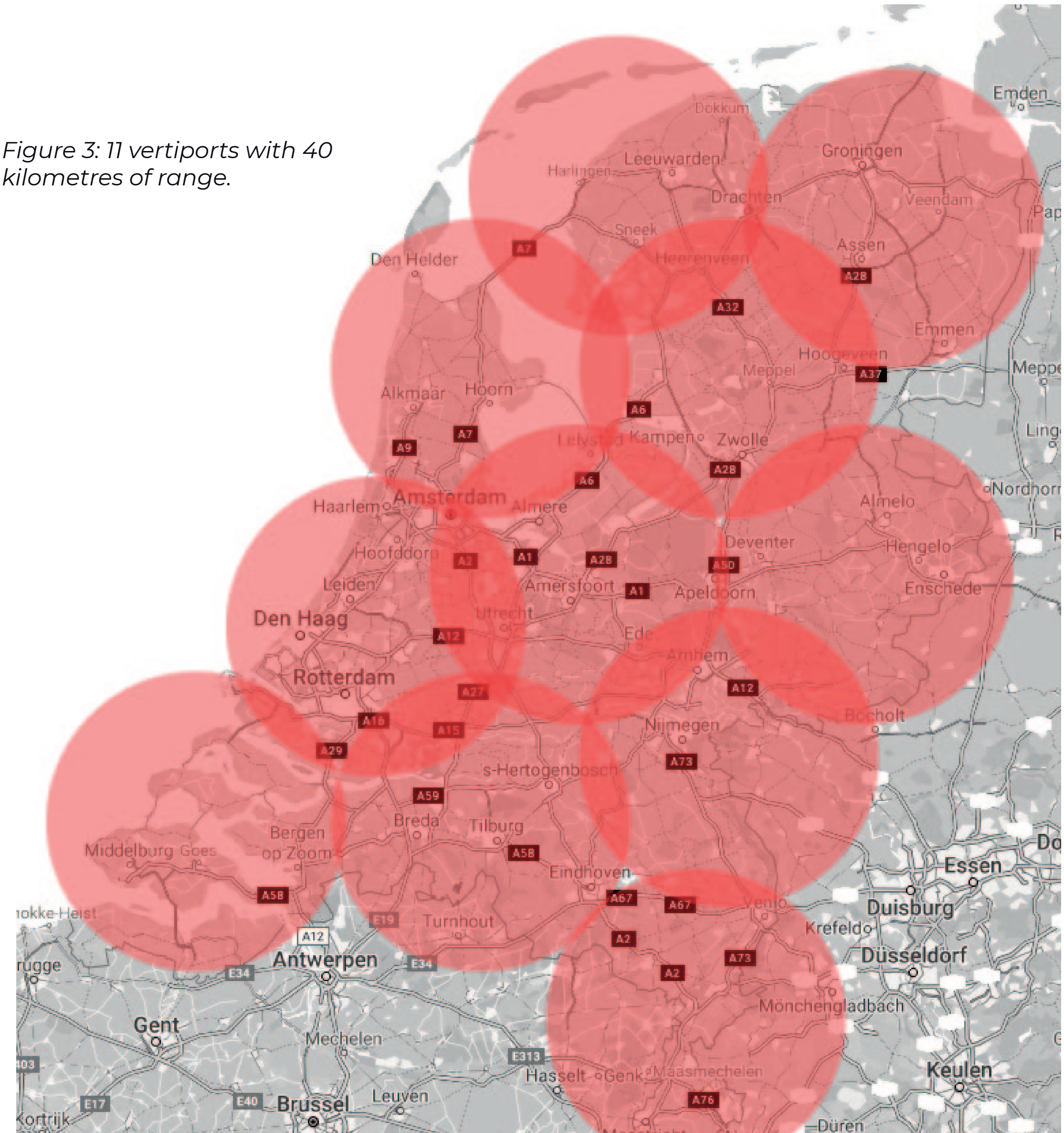
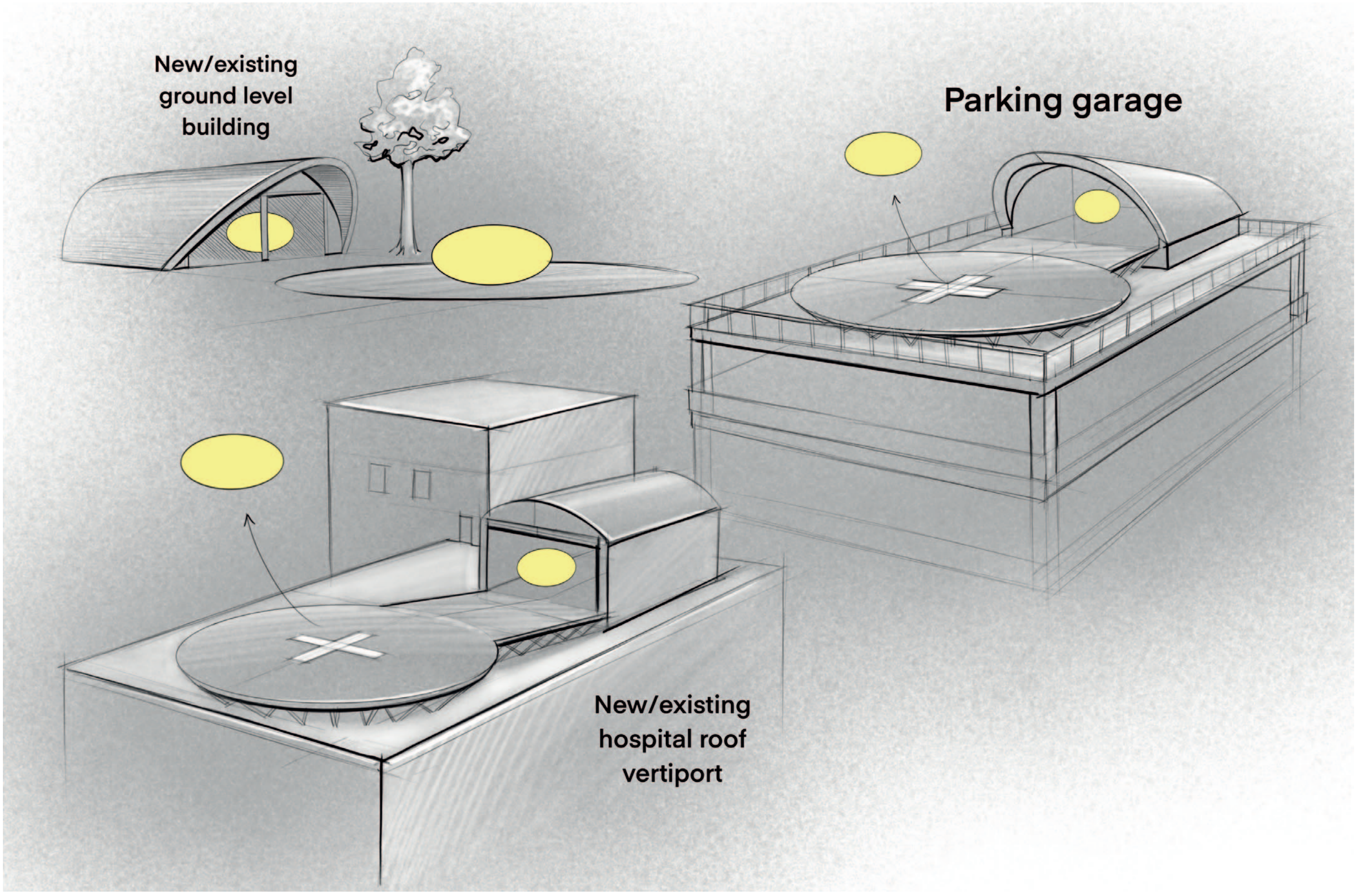


Figure 3: 11 vertiports with 40 kilometres of range.

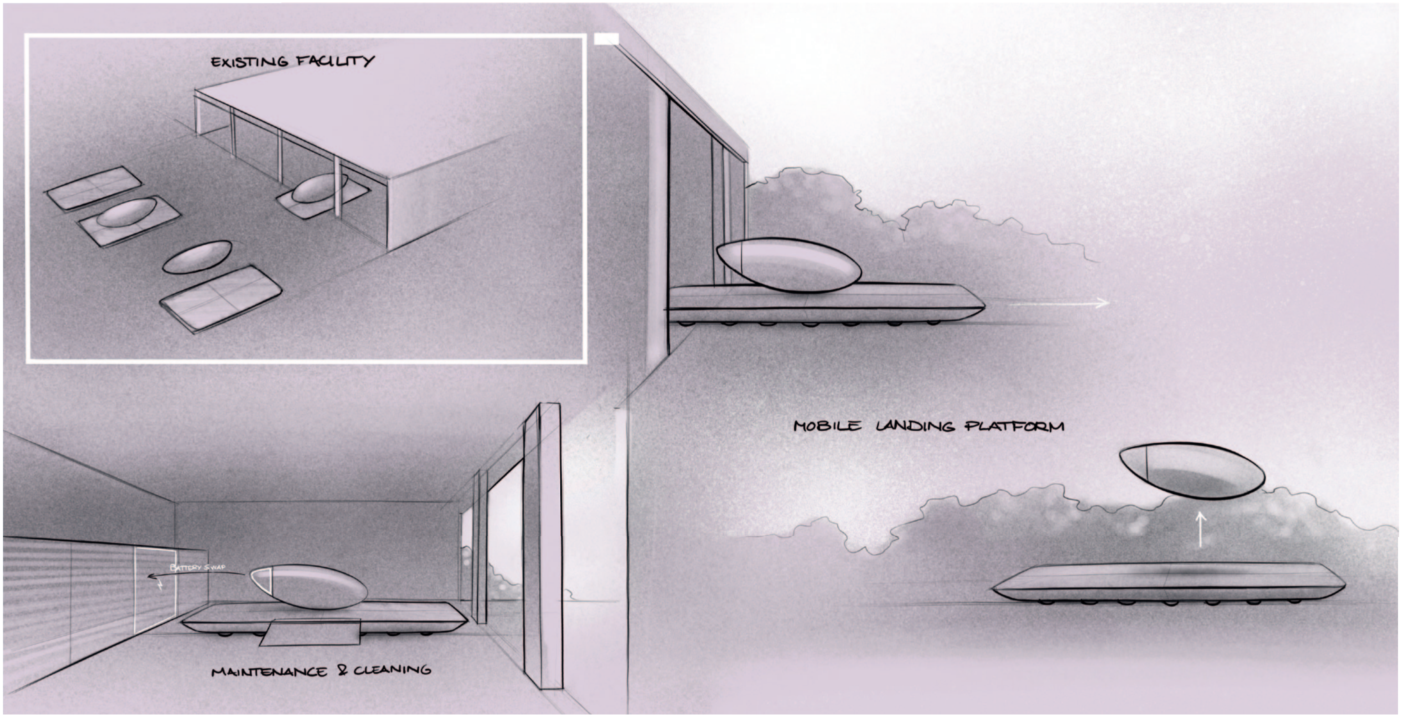
3.2 Infrastructure

Because the scale of the current ambulance helicopter system is also small, a potential replacement system with ambulance drones also remains relatively small. This means the vertiports can be quite small too, allowing more opportunities to be found in or on top of existing buildings. Existing hospital helipads and top floors of parking garages could be adapted to a vertiport for the ambulance drones.

Finding suitable infrastructure for each of the estimated eleven vertiports is likely not possible. However, building new vertiports is also quite cheap for this concept. All that is really needed is a small hangar where maintenance is done and where the crew is stationed with a landing platform nearby. This is very comparable to existing ambulance stations, of which there exist a lot more.



4. CONCEPT 3: RAPID RESPONDER DRONES WITH MODULAR VERTIPORTS



4.1 Mobile platform and battery docks

In this concept, based on scenario 3 in Appendix B, the ambulance drone is an addition to the Rapid Responder type ambulance. It can not transport a patient and is solely used for getting a nurse or doctor to the place of the incident as quickly as possible. The drones themselves can therefore be rather compact and lightweight, as they only need to carry one person. This also puts less demand on the vertiport that is required for such a drone. Therefore a system with modular elements might be an interesting option. A mobile platform which can simply be rolled out of the building where the drones are maintained in, could be a simple solution to provide a place to take-off and land. In fact, current ambulance helicopters use a similar platform, as can be seen in figure 4.

For charging batteries an automated system with battery docks could be a solution. These docks could be seen as separate units that can be placed inside the maintenance hall and connect to the local power grid. That way the batteries can be charged externally and in optimal conditions.

4.2 Infrastructure

Because this is scenario has such a simple vertiport setup, almost no new infrastructure is needed. This is also influenced by the fact that rapid responder drones would need to form a very dense network in order to be useful. As such, there is more chance of suitable infrastructure to be present compared to the previous scenarios. The drone is delivered together with the landing platform and charging dock and can therefore be placed in a wide variety of buildings, which is a major cost benefit.

Figure 4: Landing platform of the ambulance helicopter.

5 SCENARIO SELECTION

Table X: Rating 1 – 5, with 1 representing a negative rating and 5 representing a positive rating.

	Concept 1	Concept 2	Concept 3
Technical feasibility	2	3	5
Expected infrastructure costs	1	4	5
Benefit to acute healthcare (viability)	5	3	2
Innovativeness	5	4	2
Public acceptance	1	4	2
Total rating	**14**	**18**	**16**

Having laid out three scenarios and concepts, it is possible to make a rational assessment of how they compare on factors that are critical to the value that the ambulance drone network could deliver in 2035. These factors are:

- *Technical feasibility* refers to the feasibility of successfully developing the ambulance drone that is required for each scenario. This is assessed based on the roadmap in chapter 2.
- *Expected infrastructure costs* are based on comparing the infrastructure costs of the current ambulance system to that proposed in each scenario (e.g. equal costs to the current system rates 1)
- *Benefit to acute healthcare* means the number of lives that each scenario could potentially save.
- *Innovativeness* relates to the novelty of the scenario, compared to existing services and ideas. This is important as this project also needs to provide a certain inspirational value and not just a pragmatic proposal.
- *Public acceptance* is the likelihood of the general public being in favour of this scenario.

It is certainly not impossible to realise concept 1 in the future, but it is highly ambitious. The low amount of vertiports needed has the advantage that a smaller amount of suitable existing infrastructure needs to be found.

The downside to the low amount of vertiports, however, is that each individual one will need to house a large fleet of ambulance drones.

So each vertiport needs to be rather large compared to an average ambulance station. This also rules out hospital rooftops, since they are unlikely to be able to carry such large vertiports. Looking at the scope of 2035 and a possible roadmap for ambulance drone implementation, it is unlikely that a full scale replacement of the current ambulances would take place at this time. It is not expected that public acceptance and regulations will be of sufficient level for such large scale air mobility.

Concept 2 is certainly a more realistic and achievable than concept 1 in terms of scale, but also less impactful and innovative. This concept could be a stepping stone towards concept 1, since a much smaller fleet of ambulance drones is needed. From a public acceptance and safety perspective, it is unlikely that a full scale replacement of ambulances by drones would happen straight away before it has proven itself in smaller scale applications. With the scope of this project being around 2035, it is unrealistic to expect concept 1 to be ready by that time. Concept 2 is, potentially, more technically challenging since larger and longer ranged drones require more battery capacity.

Concept 3 is without a doubt the least ambitious concept in terms of feasibility. It is the least technically challenging and requires very little infrastructure. Compared to the other two concepts it loses some value in the fields of potential benefit to acute healthcare. This is because it cannot transport patients to the hospital and therefore still relies on the existing ambulances. Similarly, it loses value in the area of innovativeness, because it is only a supplementary service to the already existing ambulance system. Lastly, public acceptance is expected to be lower for this concept as the high quantity of drones would cause more visual and noise pollution. It suffers from the same issue as concept 1, with 2035 being too soon for large scale air mobility.

So in conclusion concept 2 is the most realistic, as it is a sufficient balance between feasibility and innovativeness. Replacing the current helicopters with ambulance drones brings a number of benefits. As shown below, only four helicopters are available in the Netherlands. With an ambulance drone system the capacity could increase drastically, with somewhere between 20 and 30 drones. This also means the density of the network is higher and response times will drop. Ambulance helicopters have to cover such large distances that it can take more than 20 minutes to reach a location. With ambulance drones being potentially cheaper to manufacture and to maintain, a higher capacity can be achieved for similar or lower costs as the current system. In short, more value for the same amount of money.

Next to that, ambulance helicopters are called off in the majority of responses, which makes the system far from efficient. Ambulance drones would be fully responsible for handling a response, which means they will be the primary responder just like ambulance vans. Granted, this means that in some cases the ambulance drone is called in when a regular ambulance would have sufficed, but receiving extra fast and high quality care might improve a patient's quality of life in the long term.
Also, in the current situation it frequently occurs that the regular ambulance discovers that the patient is in a more critical state than initially thought and then a helicopter is called in, losing precious time.

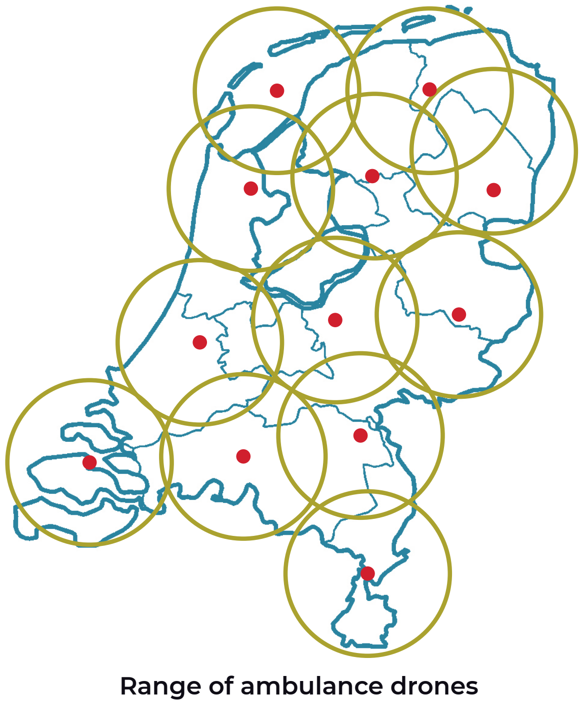
The last major benefit of an ambulance drone compared to a helicopter is not being restricted by a helicopter's architecture and formfactor. Designing a drone with the sole purpose of ambulance care means the vehicle can be made to fit the user, instead of the other way around.

Range of helicopters

-

4 bases, 4 helicopters
Variable range and response times

VS



Range of ambulance drones

-

12 bases, 24 drones
Consistent range and response times

APPENDIX D

Drone technologies

1. INTRODUCTION

In this chapter the technologies related to the development of an ambulance drone are investigated, which forms a basis for the technical architecture in the design phase.

2. A BRIEF HISTORY

First, a look is taken at what drones are and how they were developed to what they are today. The definition of a "drone" is somewhat debatable, but seems to be mostly defined as an autonomously or remotely operated aircraft. As such the first vehicle that could be classified as a drone would be the DH.82B Queen Bee from the 1930's. This was a modified version of a type of aircraft commonly used in WWI. It was adapted into an unmanned, radio controlled airplane used for training purposes. The name "Queen Bee" has also been suggested as the origin of the name "drone" (male bee) for unmanned flying vehicles.

During WWII, bomb drones that were deployed from airplanes were used to place bombs on targets. These are the first example of bombing drones, a task that drones would be cut out for many decades before they would become commercially available as hobbyist drones. The type of drone most closely related to commercial drones are reconnaissance drones used by the U.S military in all wars and missions after WWII and up until today. Today the military use of drones is still on the rise and will continue to form an important part of military missions in the future (Custers, 2016).

3. DRONES: WORKING PRINCIPLES

In order to establish what the technical package of a future ambulance drone might look like, it is important to first understand the basic principles of which drones consist of. How they retain stability, what rotor configurations exist and why, how battery capacities relate to weight, speed and range, etcetera. We will look at the average small commercial drones and in the next chapter the drone's larger counterpart, the VTOL aircraft, will be addressed.

3.1 Drivetrain

It is important to note that drones are not solely propeller driven, but can be any kind of autonomous or remotely operated flying vehicle. In this paragraph, however, the focus will be on the propeller type drones, as these allow vertical take-off and landing; a critical function for a future ambulance drone. In this section the drivetrain of drones will be explained. The drivetrain consists of propellers, motor and battery, which together form the mechanism that lifts the drone.

Propeller configuration

Drones can have different types of propeller configurations. The most common are so-called quadcopters with four separate rotors in diagonally opposite position. Other configurations are all the way from two or three rotors up to eight rotors. Drones with eight rotors are able to carry more weight, but are also more complex. Drones with two or three rotors cannot lift as much and are more unstable, but they are a lot simpler.

The reason quadcopters are the most common type is because they provide a lot of stability whilst being relatively simple in mechanical terms and able to lift a practical amount of weight. For civilian uses this usually means being able to carry a camera to film high quality footage.

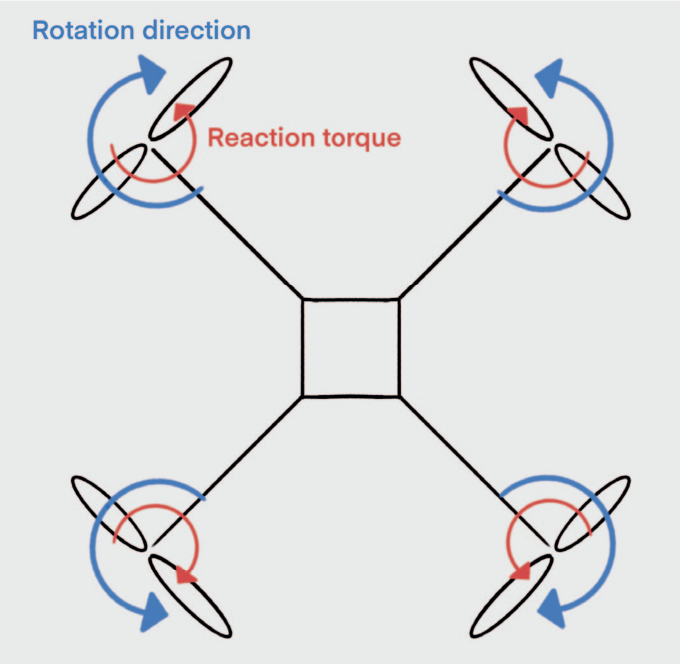


Figure 1: quadcopter stability through counteracting torque.

Rotor speeds and changing direction

So how do quadcopters work? The ingenious thing about this configuration is that the net reaction torque is equal to zero. Or in other words, the drone stays in place and does not spin around its own axis when the rotors are spinning. This is achieved by spinning each set of diagonally opposed rotors in opposite directions. Thereby the local reaction torque from each rotor counteracts that of the rotor directly next to it, as shown in figure 1. Deliberate rotation around the drone's own axis can still be achieved, this direction of movement is known as the "yaw", in aviation terms. By spinning the diagonal pair of rotors that rotate clockwise at a higher speed than the counter clockwise pair, the reaction torques stop cancelling each other out, and as a consequence the drone is able to spin counter clockwise. Obviously, the opposite of this will make the drone yaw in clockwise direction.

Changing the speeds of the rotors that are directly next to each other (not diagonally opposed) will enable other important movements. If two neighbouring rotors are spinning slower than the two other rotors the drone will pitch forward and start travelling horizontally at a constant speed, in the direction of the slower spinning rotors. When the neighbouring rotors on two sides of the drone are slowed down, the drone will pitch both forward and sideways, causing it to make a turn.

And lastly, the simplest manoeuvre related to rotor speed is increasing or slowing all rotors simultaneously, causing the drone to lift or go down. So, all movements of a drone can be controlled through adjusting the individual or collective rotor speeds (Corrigan, 2020).

Coaxial rotors

Another way in which the reaction torque can be cancelled out other than in the previously described quadcopter configuration is by using coaxial rotors. Two rotors are mounted on top of each other (on the same vertical axis) spinning in opposite directions. Together their net reaction torque is equal to zero. Coaxial rotors are used in drones, as seen in figure 2. The added benefit of coaxial rotors in that the drone will also have double the amount of disk area and can thus carry more weight, whilst the increase in weight and size is relatively small. The downside of coaxial rotors is the increase in complexity of housing two motors in each arm.

Another important benefit is that coaxial rotors cope better with sudden gusts of wind and thus aid in stabilising the drone (English, 2020).

Figure 2: coaxial quadcopter drone (Watts Innovations, 2021)

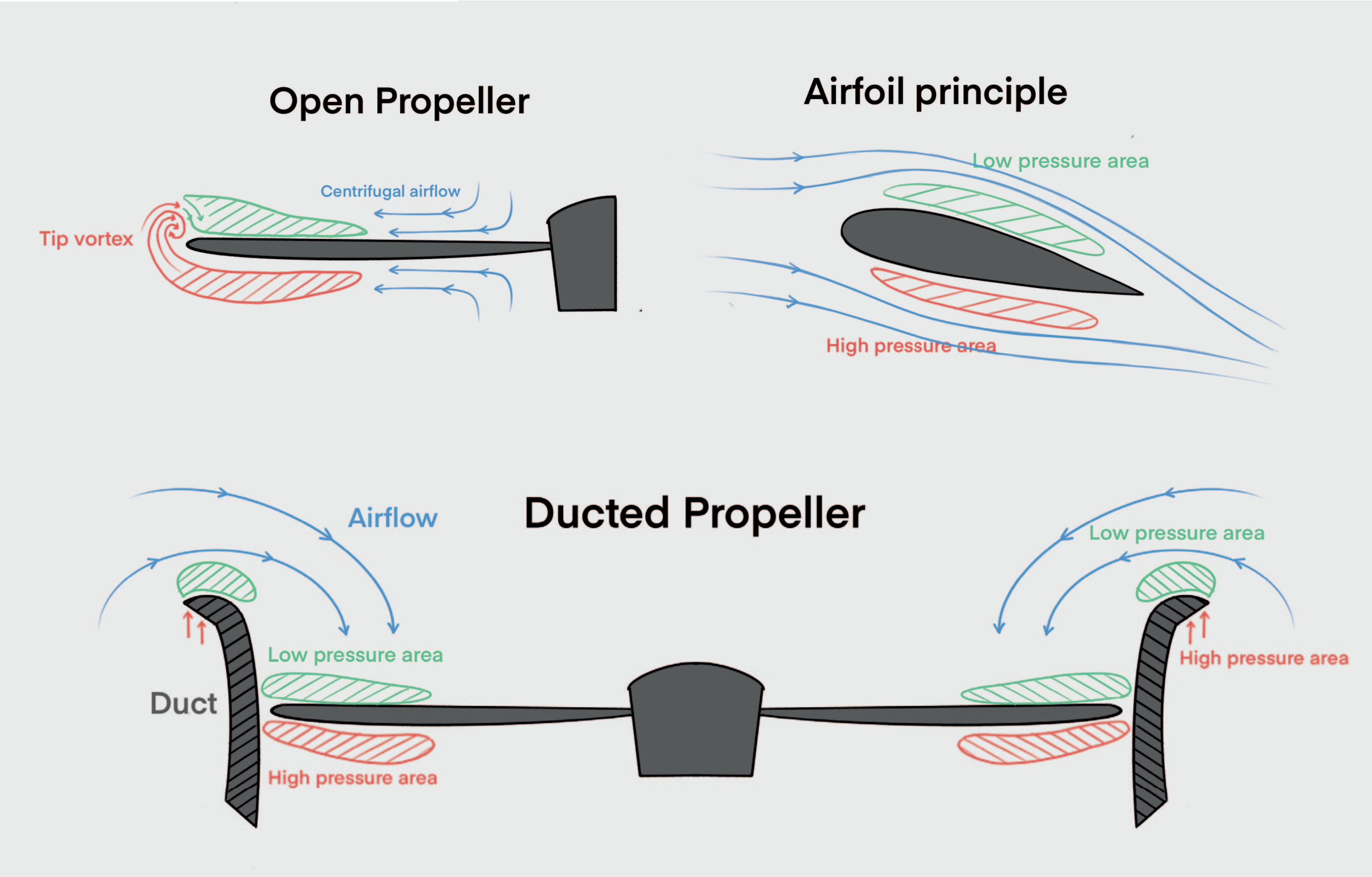


Figure 3: Ducted propeller, open propeller and airfoil.

Propeller ducts
Ducting a propeller is the principle of encasing the propeller in a cylinder. Ducting a propeller can give many benefits, such as an increase in thrust, a decrease in noise and providing safety. To understand exactly how propeller ducts provide these advantages, let us look at how a propeller actually works.

A propeller is basically a small wing, but instead of moving in a linear direction, it spins. As figure 3 illustrates, by spinning, airflow is directed past the shape of the propeller blade and this shape is also known as an airfoil. The shape of the airfoil causes two types of lift. The first way in which it creates lift is from being slightly tilted upwards, this means that more air hits the bottom of the propeller and thus pushes it upwards. The second way in which it creates lift is by differences in pressure underneath and on top of the propeller blade. The airfoil shape causes the air that travels over the top to move faster than the air that travels underneath. This is because the air that travels over the top has to cover a longer trajectory. The air that moves fast creates a low pressure area right on top of the airfoil. Because of this, a high pressure area emerges underneath the propeller blade (regular atmospheric pressure pushing the blade upwards).

Now, as mentioned, a propeller spins and is therefore subjected to centrifugal force. This centrifugal force is a force perpendicular to the axis of rotation. It causes part of the air that flows over and under the blades to flow along the length of the blades. The high and low pressure areas then move outwards towards the tips of the blades. When the low and high pressure area start to flow into each other around the tip it creates a small vortex, which causes a loss of energy and the biggest source of propeller noise.

So how can ducting the propeller stop this from happening? By encasing the propeller with the smallest margin possible between the blade tips and the casing, the low and high pressure areas are blocked from flowing into each other. Keeping the low and high pressure areas separated means less energy is wasted because of the tip vortex and thus more energy is converted into lift. Having a smaller vortex also means noise levels are reduced.

Next to this there is another ingenious trick that can be applied to the duct. By flaring out the top of the duct, another airfoil surface is created. As air is drawn into the duct by the propellers, air moves past this flared edge and, like the propeller blade itself, creates a low pressure area on the top of this flared edge and a high pressure area underneath it. So, the duct itself can also create lift through this principle.
Lastly, the propeller duct also shields the propeller and thereby protecting it from hitting things making an enclosed propeller safer to be around. Of course, the top and the bottom of the propeller are still exposed, so caution is still required (RCModelReviews, 2015).

Motors
Most drones use a so called brushless DC electric motor (BLDC). In figure 4 you see the schematics of such a motor. It works similar to any electric motor in which static magnets are pushed around by coils that create a positive and negative magnetic field. In the schematic view the static magnets are indicated in blue and yellow and are located on the inside of the coil ring (inrunner motor). In the right picture the magnets are mounted on the outside (outrunner motor) of the coils and can be seen on the inside of the cap. This cap connects to the rotor blades and makes them spin. The speed of the motor can be adjusted by increasing or decreasing the frequency of changing the poles of the coils

BLDC's are often categorised by their KV number. This number indicates the rotations per minute the BLDC can achieve when combined with a certain battery voltage.
RPM = KV x Volt

So for example a 1000KV BLDC with a 5V battery will be able to produce a maximum of 5000 RPM. (Mechatronics, 2019)

Batteries
Most common drones use Lithium Polymer (LiPo) batteries. These are built up in cells of 3,7V each. The number of cells used in a battery is shown as a number followed by 'S'. So a 4S battery has four cells and is an 14,8V battery. The battery voltage needed depends on the number of rotors the drone has and the specifications of the motors. A 4S LiPo is currently the most used battery for quadcopters.

The capacity of the battery is what determines the duration the drone can fly. The capacity is usually measured in mAh. A higher capacity means longer flight times, but also a heavier

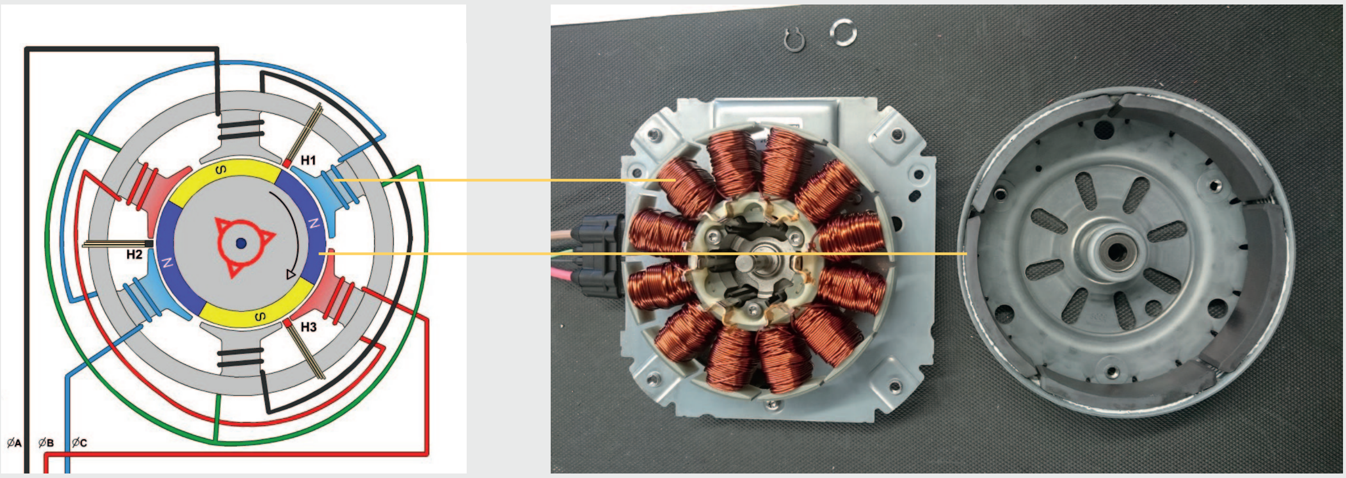


Figure 4: brushless DC motor schematic and disassembled (Doustmohammadi, 2015).

battery. At some point increasing the capacity of the battery returns diminishing results as the weight increase becomes too much of a negative factor.

The last factor that influences the battery's performance is the discharge rating, or C-rating. The higher the discharge rating, the quicker the battery can discharge, making the drone more responsive and faster (DroneNodes, 2015).

3.2 Hardware, sensors and actuators

Of course the drivetrain of the drone cannot function on its own and needs to be controlled through sensors and actuators. Let's take a look at the hardware components of a civilian drone, in this case the common quadcopter layout. Figure 5 shows the schematics of the hardware. Every item is explained in the rest of this section.

Electronic Speed Controller (ESC)
In a drone each propeller has its own motor and each motor is controlled by an ESC, which enables the RPM to be adjusted. The ESC measures the position of the static magnets, which allows it to calibrate to the frequency at which the coils change poles. The ESC is then able to adjust this frequency according to the desired RPM of the rotor by decreasing or increasing the voltage, as explained in the KV formula mentioned before. The ESC also regulates current coming back to the battery from the motors during regenerative braking. (UST, unknown)

Power Distribution Board (Power Hub)
This board forms the connection between the battery and all the other hardware that requires power. It controls how power is distributed to each component according to how much power they require.

Flight controller (FC)
As the name implies, the flight controller is the brain of the drone. It has a micro processor which contains firmware that processes all the incoming and outgoing data. The FC also contains several sensors that allow the drone

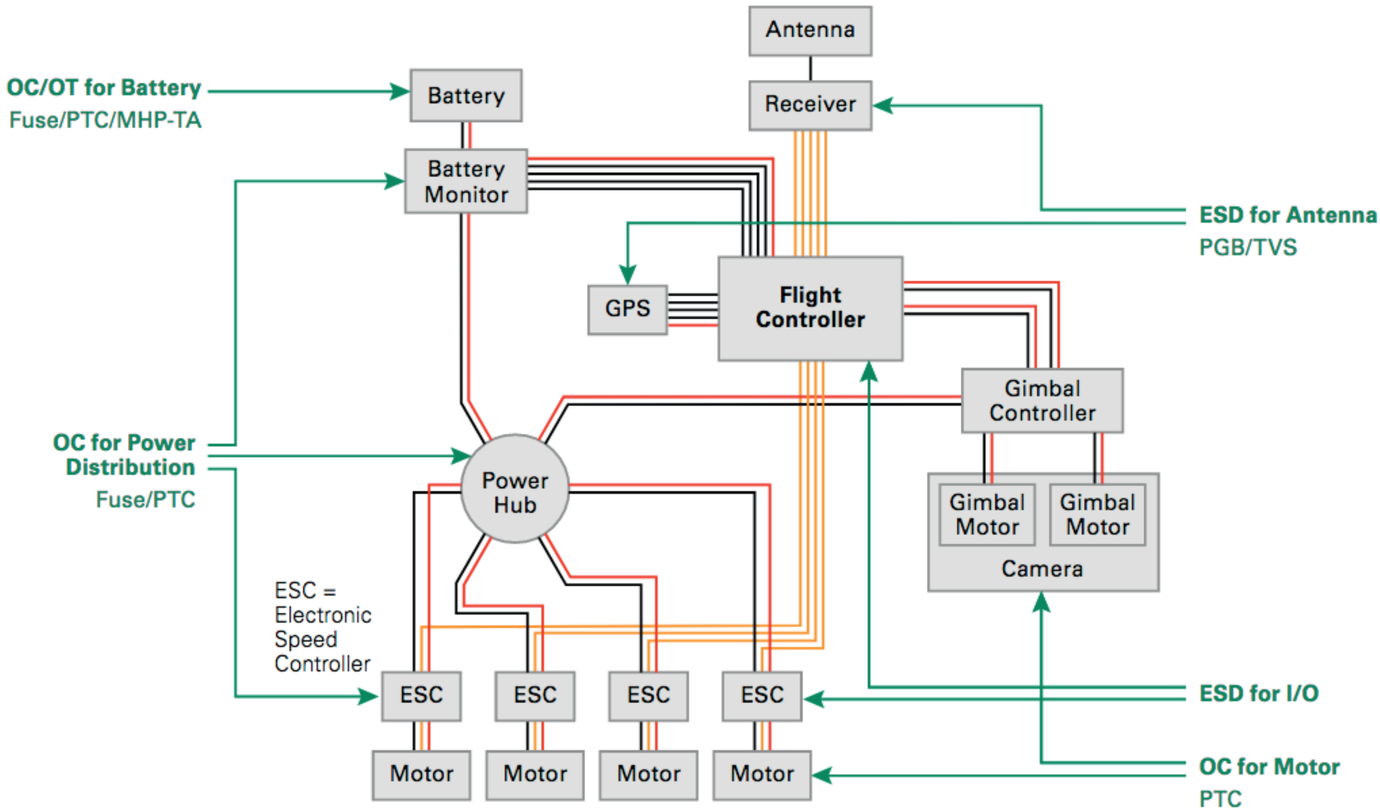


Figure 5: Hardware schematics of a quadcopter drone (Phillips & Littelfuse, 2019).

to determine its position in space, such as an accelerometer, gyroscope, barometer and a compass. It uses the information from these sensors combined with user commands from the antenna to control the drone. (Liang, 2020)

Global Positioning System (GPS)
GPS allows the drone to map its position relative to the operator. That way if the connection with the remote controller is lost the drone has a built in safety feature of flying back to the last logged location of the remote controller.

Antenna & receiver
The antenna and receiver are for receiving signals from the remote controller and to send signals back, such as GPS data, video data and, depending on the drone type, Bluetooth or WIFI.

Camera & gimbal
Many drones are used for the purpose of filming footage. As such their payload usually only consists of a camera suspended on a gimbal device. The gimbal stabilizes the camera during flight in order to keep the footage smooth. The gimbal uses an integrated inertial measurement unit in order to counteract the rotation and movement of the drone and keep the camera level. (UST, unknown)

APPENDIX E

Types of eVTOLs

1. EVTOL AIRCRAFTS

Electric Vertical Take-off and Landing Vehicle (eVTOL) are aircrafts that are electrically powered and are able to move completely vertically, allowing them to land in most places that are large enough to accommodate them. This ability creates a lot of interest in use cases such as air taxis and other forms of short-ranged air mobility. In the past several years there has been increased attention and resource directed towards eVTOL development all around the world and as a result many companies and institutions are putting forward concepts and prototypes of eVTOLs.

One only needs to perform a quick search for eVTOL concepts and a wide array of vastly different designs show up. So it seems like every eVTOL company has a completely different system, but most eVTOLs can be assigned to categories.

Vectored Thrust
These are eVTOLs with wings for efficient cruising and a propulsion system that is used both for vertical take-off and for cruising. Joby and Lilium Jet (mentioned in the next section) fall within this category. This principle often requires the use of tilt rotors which move into a horizontal position during cruise. The advantage of wings is that they provide the aircraft with a lot more range, because the rotors only need to account for forward movement during cruising and not for lift. The downside is that wings are large, so this principle is less applicable to eVTOLs that require a small footprint.

Lift + Cruise
This category is almost entirely the same as Vectored Thrust, however here two different propulsion systems are used for vertical take-off and cruising. Think of a set of propellers directed vertically for take-off and another set of propellers directed horizontally for cruising. The benefit of this is that there is no need for tilt rotors, which reduces failure sensitive mechanisms. The downside is that one part of the propulsion system is always dormant.

Wingless
Like the name implies, these are eVTOLs without any wing surfaces. This means that horizontal cruising is done solely by the propulsion system, which requires a lot more energy. As such, these eVTOLs have a lot less range and cruise speed and are more suited for short urban trips. The main benefits of this system are their high stability while hovering and their compact size compared to winged variants. Examples of aircrafts in this category are the Skydrive, EHang 216 and VoloCity (mentioned in the next section) (Bacchini & Cestino, 2019)

Although it is expected that the majority of concepts will never see the light of day, they can provide insight into the trends and different approaches in design philosophy that are around in this domain. A good starting point for this analysis is the website evtol.news. They have been scanning the field of eVTOL developments extensively since 2016 and have a vast catalogue of news articles and descriptions of existing eVTOLs and concepts that are in development. From this website it also becomes apparent how much the interest in eVTOL's has grown over the past five years, as their website featured only a dozen eVTOL concepts back in 2016 and have now a list of over 200 initiatives.

The full analysis of existing concepts & prototypes is explained in the next sections. The gathered insights form a basis to extrapolate current technological capabilities to future capabilities.

2. EXISTING EVTOL CONCEPTS

Figure 1: The SkyDrive in flight (evtol.news, 2020)

I. Skydrive SD-03

This one person "flying car", as they call it, has been the first first public demonstration of an eVTOL in Japan. Skydrive SD-03 is very compact eVTOL, with a length and width of 4 meters and a length of 2 meters. It takes up the space of two parked cars. It has four coaxial rotors, so eight propellers and eight motors. According to Skydrive eight motors are a safety measure as they can compensate for a damaged or malfunctioning motor.

The SD-03 is meant as a car replacement in the traditional sense that it would be commercially available as your private everyday vehicle. No mention is made of the range and speed (evtol.news, 2020).

Figure 2: the EHang 216. (Forbes, 2019)

Insights:

It is interesting to see coaxial rotors being successfully applied to an EVTOL. The craft seems stable in the video of a test flight, although it is only hovering and not cruising at speed.

II. EHang 216

The EHang 216 is perhaps the furthest developed eVTOL at the moment and E-Hang itself appears to be one of the most promising eVTOL companies. They have been performing test flights for a number of years now and have attracted a lot of international attention. In 2018 their E-Hang 216 had already made 1000 successful manned test flights. In January 2021 they announced that they will join the European Air Mobility Urban – Large Experimental Demonstrations (AMU-LED) project, which will conduct flight tests in The Netherlands, Spain and the UK in order to prove that eVTOL applications are possible.

The E-Hang claims to work fully autonomous, being able to take off by itself and avoid obstacles. A pilot can still take over controls in case that is necessary.

It has a maximum speed of 130 km/h and a cruise speed of 100 km/h. The flight time is 21 minutes and the range is 35 km. It has eight coaxial rotors and 16 motors, which carry two passengers.

Insights:

EHang shows a hopeful picture of what is possible for eVTOL's. Carrying two passengers, flying autonomously, having a long track record of successful flights and having quite decent performance statistics. It is clear that the largest drawback is the battery capacity, which is reflected in the flight time of 21 minutes. This is expected as battery technology simply cannot provide higher performance currently. Like the Skydrive, here too coaxial rotors are used. EHang also mentions similar benefits to safety because of decentralising the failure risks.

Figure 3 : the Volocity, a digital concept for the next iteration. (evtol.news, 2021)

Figure 4: the Joby S4. (evtol.news, 2021)

III. Volocopter VoloCity

Like EHang, Volocopter is at the forefront in the development of eVTOLs. This German company focusses mainly on providing air taxi services, which is reflected in their main model; the Volocity. This is a two people EVTOL, currently carrying a pilot and a passenger. The goal is to develop towards full autonomy and thus carrying two passengers. Volocopter made many successful test flights so far. The Volocity currently has a range of around 40 km at a speed of 90 km/h. It has a maximum take-off weight of 900 kg and can carry 200 kg of payload.

Insights:

Volocopter's design is quite distinct in the sense that it uses a lot of small rotors. It does this in order to create a smaller and less intrusive noise signature, as smaller rotors produce lower tip speed and the high amount of rotors causes the noise to be spread out over a larger spectrum. They claim this is less intrusive than one large rotor with a very specific noise. Another interesting solution that Volocopter implements are interchangeable batteries. Allowing their crafts to remain operational continually whilst the batteries can be charged in optimal conditions (i.e. slowly and properly cooled), increasing their longevity. Volocopter follows the philosophy of simplicity in order to meet safety regulations. The simpler the parts, the less likely they are to fail. This is reflected in their fixed pitch rotors and landing skids. Using static parts like these prevents the use of more failure sensitive moveable parts.

IV. Joby S4

Joby has stayed relatively under the radar compared to other companies who are at the forefront of eVTOL development, but their aircraft is no less promising. Joby is a player that needs to be taken seriously, as they have acquired a large manufacturing deal with Toyota and have partnered with Uber's Elevate program, in which Joby supplies aircrafts and Uber supplies the air taxi services. Next to this they are officially registered with the FAA, the U.S. institution responsible for certifying aircrafts. As such they know exactly what to improve in order to pass certification and become a commercially available aircraft.

Joby's eVTOL combines features from aircrafts with those of drones, such as the multirotor system and the wings. Their S4 model is the newest iteration and has performed successful test flights, showing to be very agile and stable. It can fly up to 240 km and has a maximum speed of 322 km/h, which makes it very viable for city to city taxi services. It has six tilting rotors, which allow the aircraft to fly like a regular propeller plane while cruising, thanks to its wings.

Insights:

Joby is extremely quiet for its size and capabilities. One video shows the founder of Joby talking right in front of the S4 whilst it is taking off and barely having to raise his voice. In fact Joby claims its craft is 100 times quieter than a helicopter during take-off and near silent during forward flight.

Joby's stats are also rather impressive. It is able to carry 5 people (a pilot and 4 passengers) while having a range of 240 km and weighing around 1800 kg. The Joby is of course quite large within the scope of an ambulance. It is even larger than a helicopter. This is mostly caused by the size of its wings and its 5 people capacity. (evtol.news, 2021)

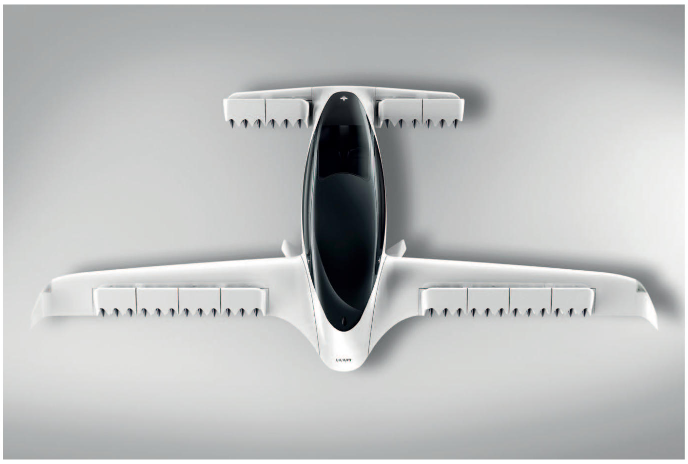


Figure 4: the Lilium jet (evtol.news, 2021)

V. Lilium Jet (5 seater)
Lilium is another German based company. They developed a working prototype of a 5 seater electric jet, which uses 36 small fans integrated into the wings for propulsion. Lilium claims the final version will be capable of 300 km range at a cruising speed of 300 km/h. Their prototype has only flown at low speeds and short distances and has not yet carried passengers.

Insights:
What is interesting about the Lilium Jet, however, is its unusual design and choice to use so many small fans. They claim this aids manoeuvrability, because small motors react faster to inputs. Many motors also creates a high amount of redundancy, aiding safety. The way the fans are integrated into the wings allows for more lift to be created by the wings, as they accelerate the airflow over the top of the wings. Like Volocopter Lilium's aim is to keep every element as simple as possible for reliability's sake. As such they claim there is no single point of failure within their design.

APPENDIX E

eVTOL technologies

1. EVTOL TECHNOLOGIES

Appendix D describes the working principles of an average civilian drone, which are roughly the basis for how eVTOLs are built up. However as scale increases, complexity increases. This is because variables that have just a small influence on a regular drone become much more impactful on a large scale. Optimization, efficiency and safety are all very high priority in eVTOLs and that is reflected in the way technologies are selected and designed.

In this paragraph the aim is to gain a deeper understanding of different technologies existing in the field of eVTOL aircrafts today and what their implications are on the eVTOL's performance and use cases.

Rotors
As became apparent from looking at different eVTOL concepts and prototypes that are being developed at the moment, there are a lot of types of rotors being used of all kinds of configurations, sizes, shapes, etcetera. In order to gain understanding of the benefits and drawbacks of some of these variations it is important to understand the technological implications, which are explained in this section.

Many small rotors vs. fewer large rotors
One of the most common configuration variations lies in the number of rotors and their size. Either many smaller rotors or fewer larger rotors. Let's look at the benefits of either option.

Small rotors create less absolute thrust, but more relative thrust compared to their weight. For example a rotor of 90 cm diameter produces a thrust to weight ratio of 12, whereas a rotor of 250 cm diameter produces only a thrust to weight ratio of 6.

Given this, using smaller rotors saves weight. Next to that, small rotors react faster to input changes as their momentum is lower, so they are more responsive. The last benefit of many small rotors is redundancy. This means that having so many separate rotors does increase the chance of some failing, but the aircraft can easily handle a few malfunctioning rotors as it can use the remaining rotors to land the aircraft and so this increases safety (Electric Aviation, 2020).

Of course a lot of small rotors also have downsides. The first being that they require more power, as they spin at a higher RPM. Compared to large rotors they are a lot less effective in the hovering stages. This also means that they are best used on eVTOLs that fall in the Lift + Cruise category (i.e. eVTOLs with wings), as they do not rely on the hovering capabilities of the rotors during cruising.

The "holy grail" of battery technology: high energy density, low production cost, recyclability, low weight and longevity.

Battery performance
With the rise of electric cars, batteries have become increasingly in demand. Current technology is mostly based on the Lithium Ion Battery (LIB), as this technology is mature, well understood and provides the highest performance. The "holy grail" of battery technology could be described by four factors: high energy density, low production cost, recyclability, low weight and longevity. The LIB is currently the best battery technology for use in vehicles. It has the highest energy density of all battery technologies commonly available. It is relatively easy to dispose of and is less prone to losing capacity over time.

But it is not there yet, as there are a number of downsides.
Firstly, compared to traditional fuel, the ener-

gy density is much smaller. For reference, the energy density of a kg of jet fuel is around 45 MJ compared to 0,7 MJ for a kg of Li-Ion battery cells. However, this is a bit of an unfair comparison without factoring in efficiency. For example, electric power trains generally operate at much higher efficiency than combustion engines, around 70-90% versus 30-40% respectively. This means that in combustion engines, on average, 5% of 45 MJ is converted into kinetic energy, or roughly 16 MJ. The rest is lost to heat.

In electric power trains, on average, 80% of 0,7 MJ is converted into kinetic energy, or 0,56 MJ. So in reality, jet fuel is 22 times more energy dense than Li-Ion batteries. This is still a significant difference which cannot be compensated by optimal aerodynamics and lightweight materials alone. Advancements in battery density are therefore needed to fully support power hungry vehicles and aircrafts, such as passenger drones.

Li-Ion batteries are also rather fragile and need to be charged at optimal speeds and temperature to ensure the longest possible lifespan. Because they use a liquid electrolyte, these batteries are flammable and require a special architecture that lowers the risk of short circuiting. This adds extra mass and volume to the battery.

Hydrogen

An alternative to battery electric propulsion are hydrogen fuel cells. Hydrogen fuel cells have several advantages over batteries that make them suitable for longer range and heavier vehicles. Firstly, hydrogen is much more energy dense than a Li-Ion battery unit. This makes it easier to increase the range of a hydrogen powered vehicle, as the storage capacity versus the added range has a ratio of nearly 1:1. This means that doubling the capacity of fuel also doubles the range, whereas a battery's low energy density causes diminishing returns when increasing capacity, as the added weight becomes increasingly problematic (Garrett, 2020).

Secondly, hydrogen is much lighter than batteries. For reference, the hydrogen powered Toyota Mirai only carries 5,6 kg of hydrogen in its tanks for a range of up to 650 kilometres. The tanks weight around 90 kilograms, the fuel cell circa 40 kilograms and a Li-Ion battery weighs 45 kilograms.

A Tesla model 3 carries around 500 kilograms of batteries and has range of around 500 kilometres.

Thirdly, hydrogen can be refilled similar to regular petrol vehicles. There is no long wait for the batteries to charge.

Lastly, hydrogen brings advantages with regards to lifespan and end of life compared to batteries. Batteries generally last around 7 years in Electric Vehicles (EV's), after which their capacity and power have shrunk beyond an acceptable point and have to be replaced. As batteries contain a lot of chemicals which are detrimental to the environment, discarding old batteries is a serious challenge. Hydrogen cells last longer and do not have such a large negative impact at the end of their lifespan (FuellCellsWorks, 2020).

According to experts, the downside of hydrogen cells is that they are poor at delivering bursts of high power output, which means they always need to be coupled with a small battery to provide this function. For application that require longer bursts of power, for example hovering an aircraft, this becomes a real challenge.

Autonomous flight

Fully autonomous flight is an ambition many eVTOL developers have in their plans for the future. The reasons for this make sense. Autonomous flying could potentially remove human pilots completely, thereby removing human errors, decreasing operating costs and increasing energy efficiency (Airbus, 2021). A lot of challenges need to be overcome, however, in order to make such a system a reality.

For manned drones, fully autonomous systems exist in a prototype form. An example is the

EHang eVTOL, which can already operate fully autonomously with passengers onboard. The development of an autonomous flight system is already possible from a technical standpoint. All necessary sensors exist and today's processing power and wireless connection capabilities are sufficient for sending and receiving large amounts of data. The main reasons why implementing fully autonomous systems is a slow process have mostly to do with the validation of these systems. Concerns about safety need to be overcome through extensive reliability testing. For context, a level of reliability compared to a human operator is not acceptable, as we expect a much higher reliability from an autonomous system. Secondly, a watertight security system needs to be developed which prevents hackers to hijack the flight system and to prevent privacy sensitive data to be leaked. Also, in case the autonomous system does fail or makes a mistake, the question of liability becomes more complex than with a human pilot. Lastly, a regulatory framework needs to be established which clearly sets the boundaries for technical requirements and liability.

The fact that these barriers have not yet been overcome are reflected in autonomous systems that are in use today, such as Tesla's autopilot. In theory it could operate fully autonomously, but is not permitted to do so due to safety and reliability concerns and the law not having caught up to this innovation.

A temporary option, to bridge the gap towards fully autonomous flight, is remote operation. This is a hybrid between human control and autonomous operation, where a human operator performs certain tasks remotely with the drone performing only selected tasks autonomously. This is similar to how an airliner pilot can use the auto-pilot function, but can still take over control when needed, only in this case remotely. It still brings some of the benefits of full autonomy, such as reduced operating complexity and costs, efficiency gains and not needing an extra human onboard to pilot the aircraft.

APPENDIX F

Evaluation of Concepts based on the Program of Requirements

Met
Partly met/expected to be met
Not met

Type	Number	Description	Concept 1	Concept 2	Concept 3
	Dimensions and weight				
R	1.01	max. payload of 1000 kg	Met	Met	Met
R	1.02	max. landing area of 25 x 25 m	Met	Met	Met
W	1.03	max. landing area of 15 x 15 m	Met	Met	Met
R	1.04	weight distribution that favours stability	Met	Met	Met
R	1.05	max. width 250 cm	Met	Not met	Met
	Performance				
R	2.01	max. response time of 15 minutes	Met	Met	Met
R	2.02	energy reserve for emergency landing/take-off during transport to hospital	Met	Met	Met
R	2.03	automated flight system in combination with remote operator	Met	Met	Met
W	2.04	fully autonomous flight system	Met	Met	Met
	Safety				
R	3.01	redundancy in critical components	Met	Met	Met
R	3.02	battery reserve for unforeseen delays	Met	Met	Met
R	3.03	safe workspace	Met	Met	Met
R	3.04	rotor units placed on top of aircraft	Met	Met	Met
R	3.05	cybersecurity system	Met	Met	Met
R	3.06	ambulance drone is able to operate at night	Met	Met	Met
	Operation and connectivity				
R	4.01	remote operator communicates effectively with onboard staff	Met	Met	Met
R	4.02	remote operator communicates effectively with control room	Met	Met	Met
R	4.03	remote operator communicates with hospital	Met	Met	Met
W	4.04	nurse can be virtually assisted by doctor	Met	Met	Met
R	4.05	access to patient records	Met	Met	Met
	Interior				
R	5.01	space for two nurses + patient	Met	Met	Met
W	5.02	space for extra passenger	Partly met/expected to be met	Not met	Partly met/expected to be met
W	5.03	modular storage unit	Not met	Not met	Partly met/expected to be met

R	5.04	sufficient lighting at night			
W	5.05	adjustable lighting			
R	5.06	easy to clean surfaces			
R	5.07	seated access to monitor, patient records and a selection of gear			
W	5.08	visual comfort: reduction of visual complexity			
W	5.09	psychologically comforting environment			
R	5.10	min. 1,50 m^3 of storage space			
	Exterior				
W	6.01	friendly/approachable appearance			
W	6.02	access to equipment from outside			
R	6.03	loading stretcher conveniently and safely			
W	6.04	privacy; no visual access to the interior			
R	6.05	yellow paint with ambulance striping			
	Stretcher				
R	7.01	sufficient access to head and lower body			
W	7.02	sufficient access to head and lower body			
W	7.03	access to both sides of the patient			
R	7.04	can be raised or lowered in order to position the patient			
R	7.05	needs to be compatible with other healthcare facilities			
W	7.06	integrated storage units			

Concept 1
All requirements met
Wishes met: 7
Wishes partly met: 4
Wishes not met: 3

Concept 2
One requirements has not been met
Wishes met: 6
Wishes partly met: 6
Wishes not met: 2

Concept 3
One requirement has not been met
Wishes met: 7
Wishes partly met: 7
Wishes not met: 2

APPENDIX G

Insights from experts

JAAP HATENBOER
UMCG Innovation Manager

1. Innovation in the ambulance sector happens in small steps, but they happen very quickly.

2. There is no discussion about whether ambulance drones will be the future, the question is when.

3. The people working in the ambulance sector are cautiously progressive. Which means that seeing is believing. When an innovation proves itself to be valuable to them, they will be the first to pick it up and drive it forward. If the innovation is not up to their standards, they will dismiss it quickly too.

4. Hydrogen is a range extender and the battery is (mostly) determined by the power that is needed for lifting off and landing.

5. It is important to consider the use case of the drone in relationship to how it is equipped. Smaller, wingless multicopters would be suitable for shorter response times, as they will not need to provide much treatment during flight and so less equipment is needed onboard. This is a lot like Medical Evacuation, where the main goal is to get the patient to a safe location with better facilities for treatment. Generally these patients do not have acute life-threatening injuries. For longer range flights, where healthcare facilities are not closeby, larger winged eVTOL's would be the best suited as it basically becomes a flying emergency room where treatment can be performed during transit. The Netherlands is a country with lower need for a system such as this, especially in the beginning. This is because it is flat and has excellent infrastructure. Try to identify areas that would benefit even more from an ambulance drone system.

6. Modular interiors are increasingly implemented, even in ambulances and helicopters of today.

SABINO VALENTINO
ZERO-G design

1. Rotor tree should preferably be integrated into the roof for aerodynamic performance.

2. Landing gear oriented along the length of the aircraft for aerodynamic benefit.

3. The vehicle would the most aerodynamic with a airfoil profile. For purpose of maximizing useable space and still retaining aerodynamic efficiency, this airfoil contour can be cut off at the rear.

4. Batteries in the floor, hydrogen system on the roof.

5. Tilting the stretcher to keep patient level during flight might be a good alternative to tilting rotors as it reduces complexity greatly.

6. Being able to lock the chairs in place might be a requirement for certification of the aircraft. This means the desired configuration of the chairs and stretcher should be set up before taking off.

7. A flat rear that opens as a ramp could be the solution for loading the stretcher.

8. The power density of hydrogen fuel cells is at present quite low. There is also a delay in power output, making it a less responsive system than batteries.

9. Fuel cells, currently we are looking at 100-150 Wh/kg – for the whole system, the requirement could be around 800 Wh/kg.

10. With the premise the batteries for EV's are different from those for VTOL, we can foresee the following variation from today towards the future:
    - Today: 250-350 Wh/kg
    - In 5 years: 500-600 Wh/kg
    - In 10 years: 700-750 Wh/kg.

11. While in road vehicles the split between EV/hydrogen would be around 40/60, for

VTOL it is advisable to use a 50/50 proportion.

12. To calculate the space allocation, maybe consider a digit on the high side of 600 Wh/liter. The main factor is weight & mass distribution. It is not easy to just say: we design a VTOL with E power and then upgrade it to hybrid, as the amount of components required will change and so will the center of gravity.

13. The consideration for the weight distribution will have to be done with an educated guess on the technology available in 2035, not the current one. The main factor being: guarantee the aircraft's stability.

14. Above all – keep it simple and make sure to adopt solutions that make the vehicle certifiable.

CHRISTOPHER COURTIN
MIT

1. Because the design is wingless, high amounts of power are needed at all times during flight. It might be an option to create a fuel cell large enough to perform at the required peak power, with a small battery for extra boost for controls/manoeuvring.

2. The best bet in determining the size and weight of batteries, payload and total weight is to use an existing eVTOL as a basis (like the CityAirbus) and use weight fractions (e.g. W_payload/W_total). Scale these factors to the desired amount for the ambulance drone and use these weight fractions to see what the weight of each of the elements will become. Of course this only holds true for the same range and speed.

3. To estimate the total weight of the new configuration, keep the same weight fractions and scale based on the payload. That will give you a reasonable first estimate, assuming the cruise speeds, ranges and battery specific energies are the same.

4. To then estimate the effects of changing speed: power consumption in cruise scales with velocity^3. Cruise power consumption from city airbus may be published - if not, for that configuration max power / 1.3 is probably a good estimate.

5. Based on the new cruise speed, you can estimate the relative increase in power from the batteries and either the reduction in range, or the increase in battery energy required. To estimate the increase in maximum take-off weight for a constant range, keep the battery weight fraction constant.

6. A good estimate for battery weights is 200 Wh/kg. 350 or 400 might be reasonable for 2035.

ALEXANDRA SLABUTU
United Rotorcraft

1. Modularity is definitely a big part of the interior design. The modular system is very much floor based, so you can place or remove equipment quickly.

2. In terms of materials, aluminium, composites and carbon fibre are the most used for interior surfaces.

3. The lighting system is very important, as the nurses also have to work during the night. Right now this is a big challenge, because the lighting causes problems for the pilot's visibility. In an autonomous drone this issue is removed.

4. Obstacle detection is a big part of the pilot's responsibility. Lots of small obstacles cannot be detected by the helicopter and need to be visually discovered. Think of objects like fences, cables and poles.
5. Certification of interiors can take up to a year. There is some difficulty for United Rotorcraft as they need to get US approved interior approved in Europe.

6. The simpler the interior, the more chance of approval by EASA.

INTERVIEW FRANK LATOUR
Trauma helicopter nurse
02-06-2021

Responses
1. What are the average response times for calls in which you actually arrive at the scene> Do these vary a lot or are they consistent?
In the countryside this is a lot more difficult than in the west of the Netherlands, because there most responses are in urban areas and close to the airbase. However, according to Frank, in these areas cars are used predominantly, as it they are usually quicker than helicopters. It takes the helicopter a lot of time to find a suitable landing spot in cities.

2. Is it true that a helicopter first makes a scouting round before landing.
a. How much time does this take?
That is correct. The time is dependent on the area and whether it is daytime or nighttime. At night, the helicopter is less suitable, because finding landing spots is harder and riskier.

3. Does it ever occur that the helicopter can not land anywhere near the place of the incident.
a. If so, what do you do in this case?
Yes this does occasionally happen. If there is still a long distance to cover, the MMT is picked up by an ambulance or a police car.

4. When you have arrived at the place of the incident, which equipment and gear do you usually bring?
The gear is packed in a couple of large backpacks. Often these contain the most gear as possible. This can be a nuisance to take out of the helicopter.

5. I have come to understand that a trauma helicopter is also used to carry certain specific medication. Why does the regular ambulance not have these?
Because this medication can only be admitted by the MMT doctor.

Transport
6. Are there times when specialists in the hospital are called during the stabilisation of the patient?
This does occasionally happen, usually to ask about the dosage of a medicine.

7. Does it ever occur that the helicopter needs to make because the patient needs acute treatment.
This does not really happen, because only patients that are in stable condition are transported with the helicopter. If it does happen, the treatment will be performed during flight, which is quite difficult.

8. If a patient has to be transported by the helicopter, do friends or family ever fly along.
Sometimes, but only if absolutely necessary and the amount of fuel in the helicopter is sufficient.

9. How is it determined which hospital the patient is transported to?
Depends on the medical facilities that are present in this hospital. In many cases the hospital with specialist facilities are preferred, as the patient needs this. Also, the MMT prefers to return to the hospital which is their base.

10. Does the nurse ever need to stand in order to perform treatment or is everything done seated?
In the helicopter everything is done seated. This is possible, because it is such a small space. The seat of the nurse can be rotated around towards the head of the patient, if necessary.

11.Are there cases of fear of flying among patient and how is this dealt with?
Not really, because patients usually are not conscious. Patients who are conscious often regret having to lie down, as they would have liked to see the view.

12. I have come to understand the MMT also

travels by car in certain circumstances, how does this work exactly?
That has to do with the accessibility of the location of the incident. At night the car is used more often anyway. In a sense, the mode of transport is secondary. The priority is to get the MMT to their destination.

General
13. Do you have an estimate of the costs of the ambulance helicopter (maintenance, responses, cost price helicopter), or a reference to where I can find this information?
Perhaps contact Medical Air Assistance.

14. Are there things that could be improved, but are impossible due to lack of space?
There is little space and freedom of movement. For the doctor it is difficult to reach the lower body of the patient. Next to that, it is difficult to take equipment in and out of the helicopter.

15. Is there a lot of noise inside the helicopter during the flight?
a. Does this bother the patients?
b. Does this bother the MMT?
c. Does this impact the communication with the patient?
Yes this is certainly a factor. It does complicate the monitoring of the lungs, because the noise overpowers the breathing. The patient is usually not in a communicative state, so that is of less importance.

16. Is it possible to scale the MMT's to higher amount?
Yes that should be possible, as there are enough new specialists in training in The Netherlands.

APPENDIX H

List of all Design Challenges + solutions

Challenge 1: Last Mile Mobility		
FUNDAMENTALS	Design for Simplicity	• Self-driving stretcher • Storage compartments attach/de-tach quickly
	Design for Trust	• Professional and modern design • Rounded shapes • Sturdy components • Minimal design/no visual clutter • Stretcher anchors to floor
	Design for Maintenance	• Rounded surfaces for easy cleaning • Unrestricted access to all major components
	Design for Adaptability	• Modular storage units for different configurations • Independent adjustable ride height per wheel • Adjustable mattress • Can be lowered to as little as 35 cm from the ground • Access to storage from all sides
	Other	• Designed to dimensional specificati-ons of existing stretchers

Challenge 2: Layout		
FUNDAMENTALS	Design for Simplicity	• Symmetrical cabin • Modular components • Stretcher storage is compatible with wall rail system
	Design for Trust	• Simple design language • Soft blue coloured walls
	Design for Maintenance	• Modularity allows cabin to be com-pletely stripped down for cleaning • Modular components can be re-placed easily
	Design for Adaptability	• Modular storage compartments • Moveable chairs allowing access to all parts of the body • Overhead monitor unit for informa-tion
	Other	

Challenge 3: Visual Identity		
FUNDAMENTALS	Design for Simplicity	• Graphic elements consist of simple shapes that are easy to read • Graphic elements are derived from their underlying functional purpose (form follows function)
	Design for Trust	• The front design has a clear “face”, making the vehicle relatable • Soft shapes • Smooth transitions between shapes • No exposed mechanical compo-nents • Ducted rotors • Perforated windshield wrap for pri-vacy
	Design for Maintenance	• Closed off exterior surfaces means dirt cannot settle in difficult to reach areas
	Design for Adaptability	• Matrix panels to display messages to bystanders
	Other	

Challenge 4: Comfort & Safety		
FUNDAMENTALS	Design for Simplicity	• Tilted rotors • Storage-rail system and chairs are simple to use • Rear door ramp • Exterior storage
	Design for Trust	• Windscreen wrap for privacy • Rotor redundancy • Patient’s field of view is clutter and equipment free • Exterior matrix panels display infor-mation to bystanders
	Design for Maintenance	• Rounded edges and surfaces • No sharp protruding edges
	Design for Adaptability	• Storage-rail system • Electronically adjustable chairs
	Other	• Sufficient interior lighting

Challenge 5: Technical package		
FUNDAMENTALS	Design for Simplicity	• Mechanical simplicity takes away visual complexity • Fixed landing gear
	Design for Trust	• Rotor ducts for safety and noise reduction • Coaxial rotors for providing more stability in windy conditions
	Design for Maintenance	• Swappable battery pack • Mechanical simplicity reduces complex maintenance
	Design for Adaptability	• Swappable battery makes upgrading to new or better battery easy
	Other	

APPENDIX I

PERFORMANCE FACTORS

TECHNICAL ARCHITECTURE

In order to integrate the technical architecture into the design of the ambulance drone it is important to have a well-founded estimate for the dimensions of the batteries, which are the most crucial part of the technical package. Calculating this from scratch is beyond the scope of this project, as it would require complex propeller calculations, drag dependent variables and redundancy safety margins. A lot of these values are obtained experimentally by the manufacturers.

The best alternative is to compute the properties of the ambulance drone based on what is known about existing eVTOLs. To do this, the CityAirbus eVTOL is used as a reference, because it is the most similar in size and configuration to the ambulance drone.

Table 1 shows what the properties of the ambulance drone would be based on the properties of the CityAirbus. By using ratios, the properties have been scaled to the requirements of the ambulance drone and an estimate for the battery weight was computed. Some values come from various experts that were consulted, more on which can be found in appendix G.

Maximum Take-off Weight
The maximum Take-off weight of the ambulance drone is based on the empty weight of the CityAirbus, which is its total weight minus the payload weight. Adding the ambulance drone's payload of 1000 kg on top of the empty weight of the CityAirbus yields a maximum take-off weight of 2850 kg for the ambulance drone. The payload of the ambulance drone is based on estimates from experts.

Thrust per duct
The CityAirbus has four ducts with double stacked propellers. Together they must generate enough lift to overcome the maximum take-off weight. So each duct produces one fourth of the maximum take-off weight of lift.

Table 1: Extrapolation of performance factors ambulance drone.

Unit	Method	CityAirbus	Method	Ambulance Drone
Max. Take-off weight	Source (Airbus, n.d.)	*2200 kg*	Estimate	*2850 kg*
Empty weight	Computed	*1850*	Computed	*1850*
Payload weight	Estimate	*350 kg*	Estimate	*1000 kg*
Thrust per duct	Computed	*550 kg*	Computed	*712,5 kg*
Battery capacity	Source (Airbus, n.d.)	*110 kWh*	Computed	*377 kWh*
Max. Power	Computed	*440 kW*	Computed	*1508 kW*
Cruising Power	Computed	*338,5 kW*	Computed	*961,5 kW*
Energy density	Source (George Bower, 2019)	*250 Wh/kg*	Prediction	*750 Wh/kg*
Battery weight	Computed	*440 kg*	Computed	***579 kg***
Volumetric battery weight	Computed	*2,8 kg/L*	None	*2,8 kg/L*
Range	Source (Airbus, n.d.)	*30 km*	Requirement	*80 km*
Speed	Source (Airbus, n.d.)	*120 km/h*	Computed	*120 km/h*
Total flight time	Source (Airbus, n.d.)	*15 min*	Requirement	*40 min*

Battery Weight
The battery capacity of the CityAirbus was take from Airbus' website. From this the maximum power was computed, using the flight time. Knowing the energy density of the best lithium-ion batteries is around 250 Wh/kg today, the approximate weight of the batteries can be simply calculated by dividing the battery capacity with the energy density. Based on insights from experts, a threefold battery density increase by 2035 is a plausible estimate. This means the ambulance drone might have a battery energy density of 750 Wh/kg.

But before the battery weight of the ambulance drone can be calculated, the battery capacity must first be found. By using fractions between the take-off weight of the CityAirbus and the ambulance drone, the battery properties are scaled accordingly.

The maximum take-off weight increases by a factor 1,29 (2850 kg/2200 kg)

The range increases by a factor of 2,66 (80 km/30 km)

So the battery capacity increases to: 110 kWh x 1,29 + 110 kWh x 2,66 = 434.5 kWh

Dividing the battery capacity by the energy density again gives a battery weight of approximately 579 kg (434.5 kWh/0.750 kWh/kg).

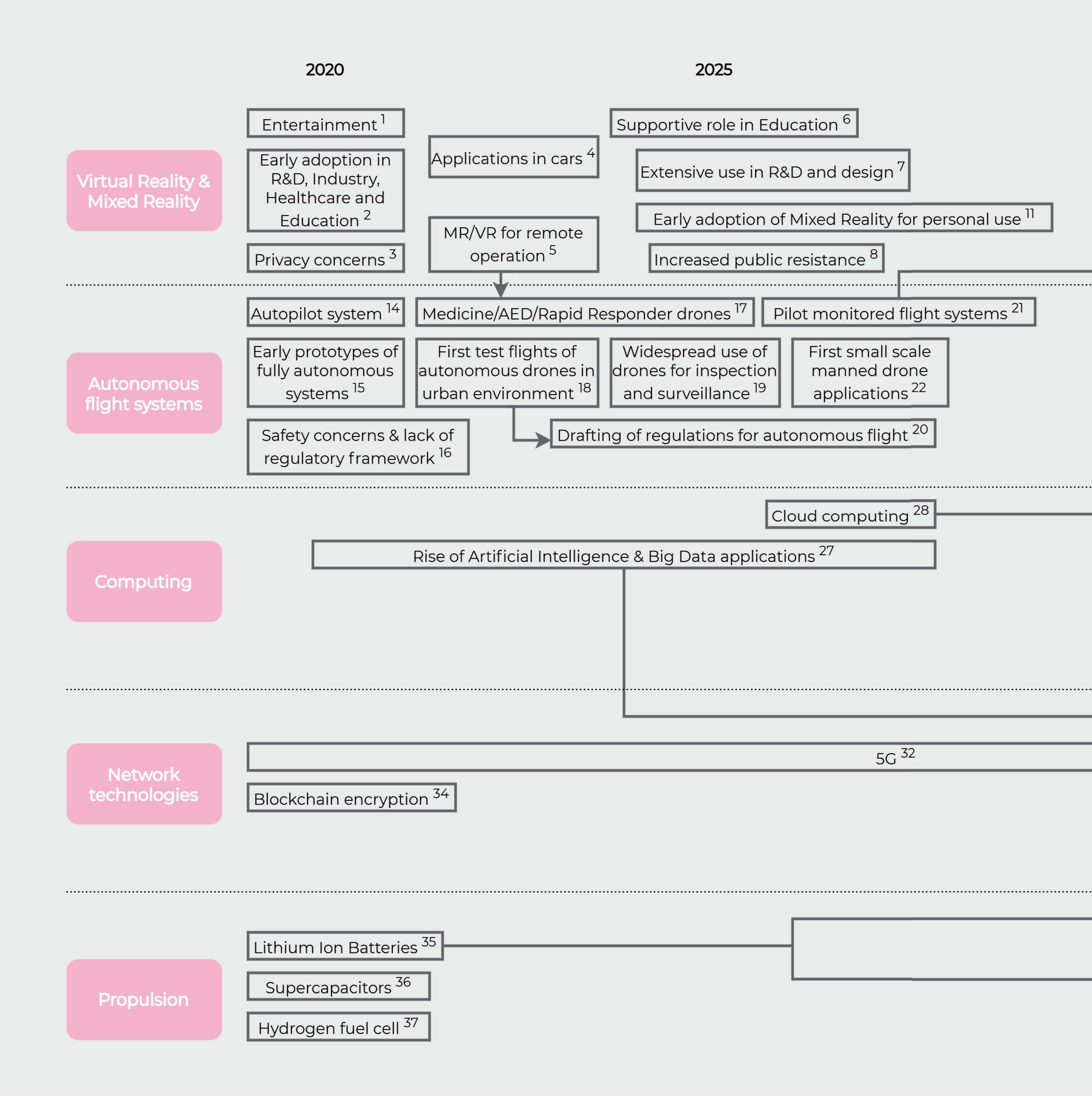
Battery size
According to Insideev.com the volumetric energy density of a tesla Model S P100D is 721 Wh/L. Dividing this by the energy density of the battery (250 Wh/kg), the volumetric battery weight is 2,8 kilograms per liter. Dividing the ambulance drone's battery weight by 2,8 yields a battery volume of ca. 206 L. To give an impression: this would fit in a battery of 100 x 206 x 10 cm, a shape that can easily be integrated into the floor of the aircraft. It must be noted, however, that this excludes the housing of the battery.

Conclusion
The method used to determine all the values in this section is obviously not very exact. The estimates can easily vary, and there is no proof that things will scale in perfect ratio's like this in real life conditions. As mentioned before, some values are estimates from experts in the field of aviation. While these values are not verified and exact, they are the most educated "guesses" available. No one can predict the future, however, so values like the future battery energy density are speculative. Nonetheless this computation is a good basis for a preliminary design and forms an input for the "black boxes" of the technical architecture that needs to be integrated into the ambulance drone.

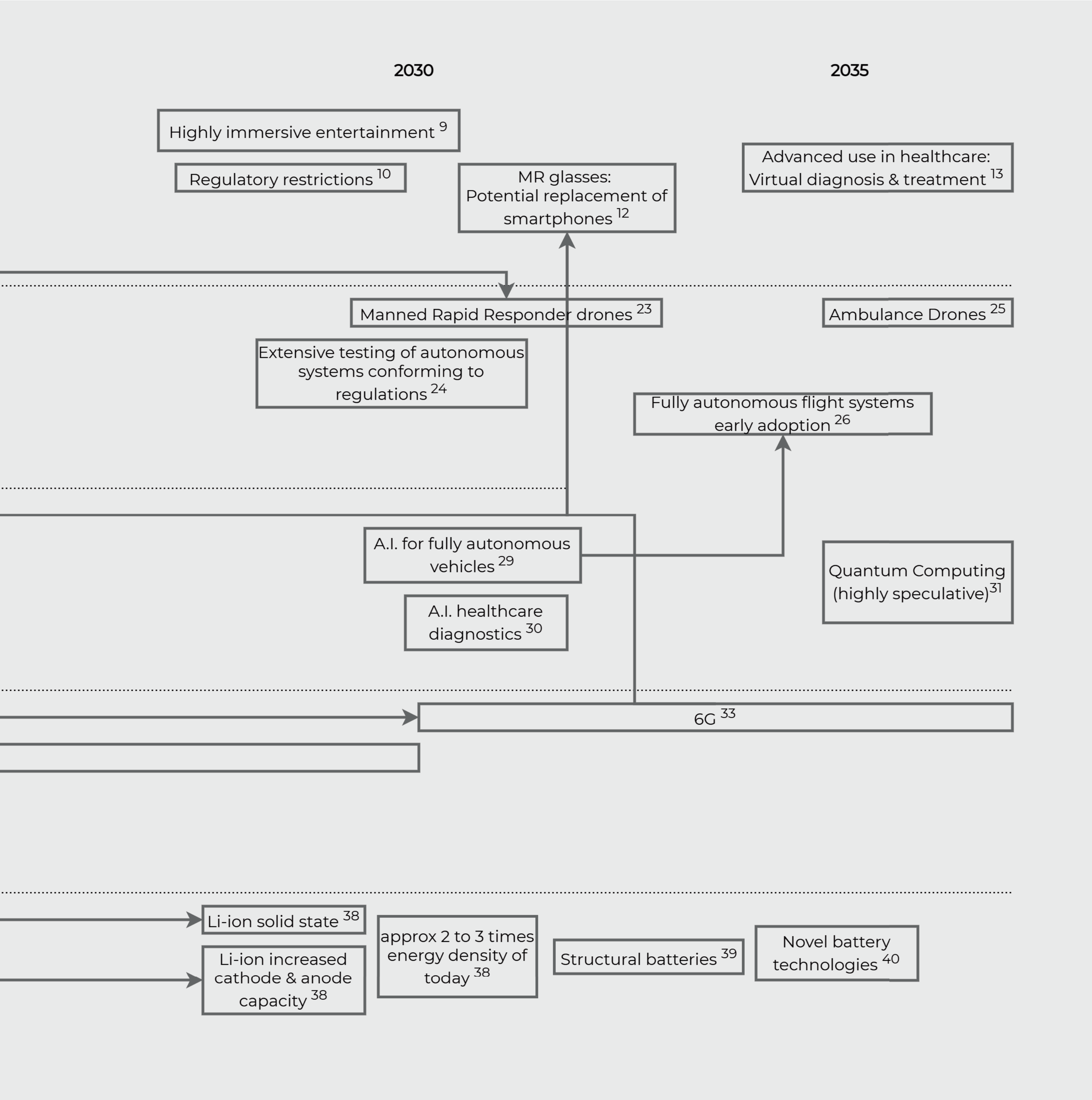
With this information the choice for battery propulsion is clear. Hydrogen as a range extending measure is not necessary with the predicted battery weight and size for the ambulance drone. The size also means a swappable battery system is feasible.

APPENDIX J

Roadmap



2020
2025
Virtual Reality & Mixed Reality
Entertainment [1]
Early adoption in R&D, Industry, Healthcare and Education [2]
Privacy concerns [3]
Applications in cars [4]
MR/VR for remote operation [5]
Supportive role in Education [6]
Extensive use in R&D and design [7]
Early adoption of Mixed Reality for personal use [11]
Increased public resistance [8]
Autonomous flight systems
Autopilot system [14]
Early prototypes of fully autonomous systems [15]
Safety concerns & lack of regulatory framework [16]
Medicine/AED/Rapid Responder drones [17]
First test flights of autonomous drones in urban environment [18]
Widespread use of drones for inspection and surveillance [19]
Drafting of regulations for autonomous flight [20]
Pilot monitored flight systems [21]
First small scale manned drone applications [22]
Computing
Cloud computing [28]
Rise of Artificial Intelligence & Big Data applications [27]
Network technologies
5G [32]
Blockchain encryption [34]
Propulsion
Lithium Ion Batteries [35]
Supercapacitors [36]
Hydrogen fuel cell [37]


2030
2035
Highly immersive entertainment 9
Regulatory restrictions 10
MR glasses: Potential replacement of smartphones 12
Advanced use in healthcare: Virtual diagnosis & treatment 13
Manned Rapid Responder drones 23
Ambulance Drones 25
Extensive testing of autonomous systems conforming to regulations 24
Fully autonomous flight systems early adoption 26
A.I. for fully autonomous vehicles 29
A.I. healthcare diagnostics 30
Quantum Computing (highly speculative)31
6G 33
Li-ion solid state 38
Li-ion increased cathode & anode capacity 38
approx 2 to 3 times energy density of today 38
Structural batteries 39
Novel battery technologies 40

Explanation

[1] Entertainment is VR's main market as of today.
[2] According to Sky News (2020), VR is already being adopted in Research & Development, industry, healthcare and education
[3] Privacy concerns have been present since the first applications of VR/MR, especially with the Google Glass.
[4] Based on current trends in the automotive industry with the use of Heads-Up-Displays and AR elements in parking camera's and lane assist.
[5] Granting virtual access to a flying aircraft is already possible with MR/VR. In the coming years, as the 5G network expands further, reliable use for remote piloting might be feasible.
[6] The first adoption of VR/MR in education is already happening. In the near future, it can be expected to keep establishing its role in education.
[7] VR is already widely used in R&D, within the automotive industry, architecture and industrial design. This trend is expected to continue and eventually be accompanied by MR applications as well.
[8] As VR/MR finds its way into regular society more and more via education, industry and healthcare, more resistance from those with concerns can be expected to occur.
[9] By 2030 we might watch interactive movies in VR. Gaming will also be a lot more realistic and might even involve senses like touch.
[10] In response to the increased resistance to VR/MR and potential cases of exploits/harm that have surfaced stronger regulations are developed.
[11] As VR/MR finds its way into regular society more and more via education, industry and healthcare, domestic adoption of VR/MR will also start to become more common.
[12] Eventually VR/MR will firmly establish itself as a part of the daily routine, in similar fashion to smartphones.
[13] By 2035, a lot of healthcare might be performed virtually. This might even mean that some treatments can be performed remotely, with virtual instructions.
[14] Autopilot systems are the most basic form of automation in aviation and have been in use for decades.
[15]EHang has already tested their eVTOL with fully autonomous flying system with passengers on board (Chua, 2021).
[16] EASA's public acceptance study showed one of the main concerns the public has concerning air mobility is safety and security.
[17] Unmanned drones for medical transports and AED have been in development in the last couple of years. It is expected that they will become the first widespread use of drones for medical purposes.
[18] EHang has performed autonomous test flights over urban areas in China already, but in Europe that has been strictly prohibited up to now. As part of the AMU-LED program test flights will be performed above cities in Europe for the first time, around 2022-2024.
[19] In The Netherlands, drones are already used for inspection purposes, most notably in the port of Rotterdam. (Koopman, 2020)
[20] Assumption based on plans such as AMU-LED, Dutch Drone Delta and EASA's study on public acceptance, which all bring focus on the need for a regulatory framework.
[21] Pilot actively monitors the aircraft, while it does multiple tasks autonomously. Similar to Tesla's autopilot.
[22] By this time we might see the first real implementation of a manned drone system. Most likely air taxis for a select group of people.
[23] Around 2030 we might see the first application of acute healthcare with drones. Volocopter has already tested Rapid Responder type healthcare in collaboration with ADAC (ADAC Luftrettung, 2021).
[24] Around 2030 the pressure of public acceptance may have led to clearer regulations regarding autonomous flight. This will force new autonomous systems to be tested and designed conforming to these regulations.
[25] Around 2035 the first ambulance drone with passenger transport might be possible. The first implementation of such a drone will likely be small scale at first, similar to today's ambulance helicopter.
[26] Around 2035 the first fully autonomous systems (without any pilot supervision) might be adopted into commercial use. In this stage

an ambulance drone will likely still be supervised by an operator, for reliability and liability reasons.
[27] As the field of A.I. is so vast and unpredictable a very broad timeframe has been labelled as the rise of A.I. applications. This means significant developments in this area are expected in the coming decade, but there is no clear answer exactly when and how.
[28] Cloud computing hinges on strong and steady data connection, as such a 5G network with good coverage and eventually the new 6G network are necessary to reliably implement cloud computing.
[29] At some point it can be expected that A.I becomes an even bigger factor in the development of autonomous driving and flying systems.
[30] Within healthcare there is a trend towards digital diagnosis. A.I. promises to eventually be much better at diagnosing cancer and other diseases.
[31] Quantum computing is one a technology with a lot of potential, but at the same time it has proven to be very difficult to develop. As such it is difficult to predict any time frame for it. It is included in the roadmap purely for its significance. It would be a revolutionary technology when it comes to fruition.
[32] 5G has recently been implemented on a large scale in The Netherlands. It is expected to remain the primary mobile network standard for the next decade.
[33] 6G will be the next generation of mobile internet, after 5G.
[34] Currently used in cryptocurrencies and other digital value encryption methods. It could be a useful technology for cybersecurity systems in autonomous flight systems.
[35] The most common battery technology as of today.
[36] Energy storage that can be discharged very quickly, for short bursts of high power.
[37] Another technology for electric vehicles that is used today, in lesser degree compared to batteries.
[38] According to an expert from a major eVTOL manufacturer, the expectation is that battery energy density could become two to three times the amount of today in 10 years.
[39] Batteries that are an integral part of a vehicle's structure. These are in very early stages of development.

APPENDIX K

Costs

COSTS

To get some grip on what the price of the ambulance drone might be, the same method is used as with the technical architecture; comparing with existing examples. In this case the ambulance helicopter is a logical reference. So what types of costs are involved with these helicopters?

1. Cost price
The cost price of an ambulance helicopter is around 5 million euro's, according to ANWB (2021).

2. Maintenance
Exact figures are not available, but maintenance is part of the lease contract that trauma centres have with ANWB Medical Air Assistance. Their website states that their helicopters undergo daily maintenance and at least once a year a large check which can take several weeks.

3. Staff
According to the Dutch government the total salary costs for the MMT's are around 2.000.000 euro's annually (in 2016), excluding the pilot. The costs of the pilots are also part of the lease contract provided by ANWB.

4. Infrastructure
According to the Dutch Government the costs of a roof station was around 105.000 euro in 2016. While not all stations are on rooftops, a similar expense is assumed for the other three helicopter stations.

5. Responses
Next to the aforementioned fixed costs there are also variable costs related to the amount of deployments of the MMT's.
These variable costs per hour of flight time are also part of the undisclosed lease contract between the trauma centres and ANWB. (Nederlandse Zorgautoriteit, 2019)

Looking at an ambulance drone it is clear that the same types of costs apply, but the costs will be distributed differently across these types. Cost price of an ambulance drone would likely be lower than that of current helicopters, given that their technical architecture is less complex. This expectation is strengthened by what other eVTOL manufacturers are aiming at in terms of cost price. For example, the CityAirbus, which is a similar type of eVTOL to the ambulance drone, aims at a cost price of around 1 million euro's. (Lecompte-boinet, 2019)
A lower cost price is beneficial as it enables more ambulance drones to be purchased for the same investment.

In similar fashion to the cost price, maintenance costs are also expected to be lower, because of simpler technical components. This is already evident in electric cars versus cars with combustion engines. Less maintenance means less operational costs as well as less downtime, which also lessens the amount of backup drones needed.

Total staff expenses are expected to increase, because the amount of MMT's will increase in the ambulance drone system. A cost reducing factor, however, is that the costs of pilots will be mitigated by a remote operator or by an autonomous flight system.

Infrastructure expenses are also expected to increase because of upscaling, with 12 locations needed instead of four. The positive side is that the ambulance drones come with a simple setup of a landing platform and separate battery charging units that can be implemented in any suitable existing building.

Another factor to consider is that the ambulance drone system has an impact on the costs of the regular ambulance care, as it takes over some of their tasks. Next to that, the ambulance drone system could have an impact on overall healthcare costs for the patient, as fast aid may lessen the consequences of the injury and the need for intensive and costly treatments. Also, funds are used more effectively, as a the ambulance drone will carry out their mission independently. Current ambulance helicopters are called off in more than half the cases.

Conclusion
Because there is a lot of unclarity regarding the manufacturing and implementation of the ambulance drone system at this stage of the development it is difficult to create a cost estimation with exact figures. Next to that, not a lot of numbers are provided by the ANWB and the Dutch government regarding the costs of ambulance helicopters. Nonetheless, this section aims to give a global indication of how the ambulance drone system would perform in terms of value versus costs.

Overall the ambulance drone system is expected to be slightly more costly (neglecting inflation), due to it being a larger scale system than the current helicopters. But, because each cost factor in itself is lower or equal to that of the current helicopters, the costs do not scale relative to the size of the system. Or in other words: the ambulance drone system is expected to provide more value for the same price.

APPENDIX L

Project Brief

Personal Project Brief - IDE Master Graduation

TU Delft

Ambulance drones in the Netherlands: a vision + concept design for 2035 project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 29 - 03 - 2021 04 - 09 - 2021 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The client, Modyn sees an opportunity for ambulance drones to provide a solution to the current problems in the ambulance system, as they could provide a national network with consistent and short response times, while also taking complexity away from the ambulance staff. Modyn have set up this visionary project in order to gain insight into how an ambulance drone system could provide meaningful solutions in the future. With this project, Modyn aims to profile themselves and attract potentially interested parties for future development.

POTENTIAL BARRIERS
The main challenge of this project is the scope of 2035. A timeframe like this means a lot has to be left open, because there is simply no clear answer yet. Other challenges are:
- Technological limitations: battery energy density, noise pollution, (semi) autonomous flight
- Social limitations: (semi)autonomous flight is prone to safety concerns, liability and societal prejudice.
- Implementation limitations: heavy scrutiny from govermental institutions, extensive testing and regulatory hurdles before approval.

STAKEHOLDERS
Primary
- ambulance service provider
This is the potential target client, as they will be responsible for implementing an ambulance drone system. For example: ANWB is now the provider of trauma helicopters in the Netherlands.
- ambulance staff
- (remote) operator
Currently those would be ambulance drivers and helicopter pilots. In the future they may be ground control operators.
- patient
The core stakeholder, with a passive role, now and in the future.
- maintenance staff
Currently responsible for maintaining ambulance equipment and helicopters.
- landing/take-off infrastructure providers
This is a stakeholder that does not exist yet.
Secondary
- (private) hospitals
- federal & local government
- general public
- emergency hotline
Project-related
- TU Delft
- me, the student
- company Modyn
- chair
- mentor

space available for images / figures on next page

Personal Project Brief - IDE Master Graduation

TUDelft

introduction (continued): space for images

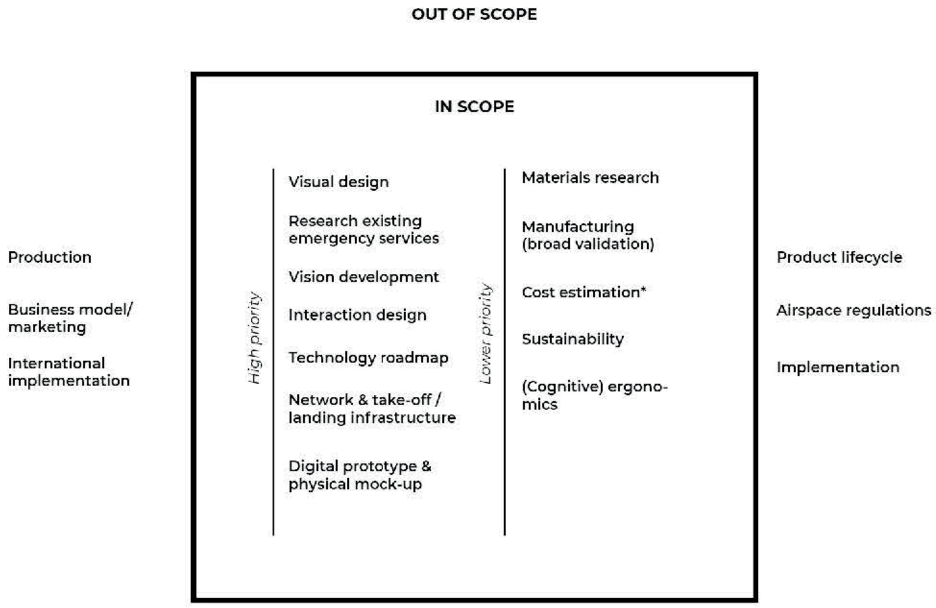


image / figure 1: Project Scope visualized

TO PLACE YOUR IMAGE IN THIS AREA:

- SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER
- CLICK AREA TO PLACE IMAGE / FIGURE

PLEASE NOTE:

- IMAGE WILL SCALE TO FIT AUTOMATICALLY
- NATIVE IMAGE RATIO IS 16:10
- IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN

image / figure 2:

Personal Project Brief - IDE Master Graduation

TU Delft

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

In the Netherlands, around 385.000 people cannot be rescued in life threatening emergencies, due to ambulance services not being able to reach them within the norm of 15 minutes. According to the law, ambulance response times need to be within 15 minutes for at least 97% of citizens. As of now only three out of 24 regions live up to these standards, all of them within the highly urbanised "Randstad" area (Algemeen Dagblad). One issue with scaling up in rural areas is that ambulance staff often do not get enough calls in order to acquire mandatory work experience (RTLNieuws). In short, the ambulance system has been aware of its shortcomings for years, but is limited in solving these due to funds and shortages of staff, especially in rural areas.

Image 1 shows the scope of the project. A clear emphasis is put on the development and design of the concept and less on the strategy and implementation, as this is a much more speculative endeavor when designing for 15 years in the future. Also, within the scope, less priority is put on subjects such as manufacturing, materials and cost estimation, as these are strongly subject to change over time. They are still part of the scope, since they will need to be taken into consideration when designing the concept.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Developing a conceptual design of an ambulance drone for the scope of 2035, proposing solutions in user interaction, scalability, infrastructure and technologies. The concept functions as a motivator, inspirator and guide for future development of ambulance drones, and as such requires a recognisable visual identity.

This assignment aims to deliver a concept for the future implementation of ambulance drones in The Netherlands, through product, service and infrastructure ideas. These ideas are a result of careful consideration and substantiation based on the research of existing ambulance systems, context, stakeholders, technology and roadmaps about the future of technology and societal developments that are expected to be relevant to the product. This concept will be visualised with the use of VR modelling and other digital tools deemed useful. A physical mock-up (scale model) will function as a tangible conversation piece.

The concept aims to deliver a desirable and feasible result within the scope of 2035.
- Desirability through proposing solutions that outclass the current ambulance system.
- Feasibility through substantiation based on trends, roadmaps, and experts and comparing with current ambulance system.

Note: viability is excluded as this mostly depends on the parties who will be interested to bring an ambulance drone PSS to the market. Predicting this for 2035 is not very meaningful.

Personal Project Brief - IDE Master Graduation

TU Delft

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 29 - 3 - 2021   4 - 9 - 2021 end date

	Calender week	13	14	15	16	17	18	19	20	21	22	23	24
	Week	1	2	3	4	5	6	7		8	9	10	11
Activities	Date	29 Mar-4 Apr	5-9 Apr	12-16 Apr	19-23 Ap	26-30 Apr		10-14 May	17-21 May	24-28 May	31 May-4 Jun	7-11 Jun	14-18 Jun
Meetings		*Kick-off*										*Mid Term*	
Milestones												*Freeze*	
												Infr. Design	
Report													
Research													
- Current ambulance system							B						
- Current drone technology							R						
- Stakeholder insights							E						
- Technology roadmap							A						
Infrastructure design							K						
Vision development													
Ideation													
Conceptualisation													
Final design													
Presentation													

	Calender week	25	26	27	28	29	30	31	32	33	34	35	36
	Week	12	13	14	15	16	17	18	19	20	21	22	23
Activities	Date	21-25 Jun	28 Jun-2 Jul	5-9 Jul	12-16 Jul	19-23 Jul		2-6 Aug	9-13 Aug	16-20 Aug	23-27 Aug	30 Aug-4 Sep	7 -10 Sep
Meetings								*Green Light*					*Final Presentation*
Milestones		Freeze techn.											
		& interact. design											
Report													
Research													
- Current ambulance system							B						
- Current drone technology							R						
- Stakeholder insights							E						
- Technology roadmap							A						
Infrastructure design							K						
Design fundamentals & challenges													
Ideation													
Conceptualisation													
Final design													
Presentation													

The project is structured so that the bulk of the research has been done before the Mid Term. The research aims to provide insight into:
- the current ambulance system and the stakeholders involved.
- general drone technology and how it is expected to develop.
- ways to develop ambulance drone infrastructure

The take-off/landing infrastructure design, vision development and the ideation phase start early, in parallel to the research. This way I can ensure the research finds its way into design ideas right away, and provide many iterations of ideas. An important stage in the project is the development of a vision for the future context of the ambulance drone system concept. It forms a bridge between research and the design phase. It helps structure the research into important insights, requirements and boundaries that inform the concept design. Using a method like Vision in Product Design could be useful tool in this stage. Also I would like to use a method I developed in previous projects, called "design fundamentals & design challenges". These are very concise visualisations of the most important conclusions from the research phase and the most important design challenges it has identified. This method helps to constantly remind me of the core values of the project, as it can be quite hard to keep track of your vision over a long and complex project.

After the Mid Term the board is clear to dive straight into conceptualising ideas and creating a final design. This phase stretches for almost the entire second half of the project, so that a lot of time can be spent on digital modelling/animation and a physical mock-up of the final design. In the end there is also quite some time reserved for the presentation. This includes activities such as creating a videoclip, finalising the report and preparing the presentation.

Personal Project Brief - IDE Master Graduation

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

MOTIVATION
This project allows me to deepen my knowledge and improve my ability to design conceptual and visionary project. On top of that, this project has an extremely important goal: saving lives. As a designer I am very drawn to projects that have such a big impact on society. This also brings a lot of responsibility, which is something I would like to experience and learn how to deal with.

I am a strong visualiser; sketching and modelmaking is a big part of my design process. My aim is to use and improve this strength during the graduation project.
Next to that I would like to develop my digital visualisation skills, through modelling in VR and other CAD/Rendering software.

PERSONAL AMBITIONS
- Be project leader: involve relevant parties, experts, stakeholder, knowledge and expertise.
- Structuring and managing my own project, through my own methodology.
- Learning how to use a predictionbased approach for designing future products/systems.
- Using concept design as a tool to inspire future development of ambulance drones.
- Gaining experience digital and physical visualisation methods to communicate the final design
- Aim to employ visual language to generate, develop and iterate in an insightful way.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

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