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Towards analysing risks to public safety from wind turbines

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ABSTRACT

Wind energy has become an increasingly desirable and viable renewable energy source in recent years. However, wind energy faces a number of challenges, one of them being risks to public safety from wind turbine failures. This paper provides an analysis as a first step towards integrating wind turbine failures with public safety risks. In this paper, an existing Fault Tree Analysis (FTA) of wind turbines is expanded to include wind turbine failures that could be linked to public safety risks. The paper combines knowledge from literature related to wind turbine failures with expert judgements. Quantification of component failures and failure modes in the expanded FTA is carried out, and wind turbine failure modes related to the assessment of risks to public safety from wind turbines are analysed. The failures modes used in the Dutch system for assessing public safety risks from wind turbines are compared with the outcomes of this study and improvements to this assessment procedure are proposed. The paper concludes that the information available about wind turbine failures is still limited and there is a lack of detailed descriptions of incidents in the recorded data.

1. Introduction

In recent decades, alternative energy sources such as wind energy have attracted growing interest. Wind energy is a renewable source of energy with a potential for large-scale application. The use of wind energy is increasing and is seen as the most viable alternative to fossil fuels due to its competitive costs of producing electricity compared to other sustainable energy sources [1].

In its pursuit of sustainable development, the Dutch government is planning to increase the share of renewable energy to 14% of total energy consumption by 2020. This represents a more than doubling of the current share of 6% [2]. Wind energy is seen as the most important source in meeting this goal, and onshore wind energy capacity needs to increase from 2,600 MW in 2014 [3] to 6,000 MW in 2020 [4].

Given the Netherlands' high population density, many wind turbines are situated relatively close to existing infrastructure and buildings. In addition, the policy of the Dutch government has encouraged the installation of wind turbines close to industrial sites [5]. The proximity of wind turbines to existing structures brings issues of concern to the public such as noise, aesthetics, social acceptance and safety risks. Safety risks from wind turbines can be particularly relevant when they are located in the vicinity of certain industrial facilities such as chemical plants. Chemical plants have their own safety risks, and these can be exacerbated by external factors such as nearby wind turbines.

Current studies on safety risks associated with wind turbines are primarily focused on the wind turbine itself as an occupational safety hazard [6–8]. The research into risks to the area surrounding wind turbines is limited to a few studies related to safety risks associated with the throw distances of detached blades [9,10]. The risks to the surrounding area can be caused by wind turbine failures such as detached blade pieces or collapsing towers that could impact a building or a person. In this paper, the external safety risks from wind turbines is referred to as public safety.

In many countries regulations require 'distance buffers', or so-called setback distances, between wind turbines and existing structures to reduce the risks to safety from wind turbines [11]. Denmark for example has a strict setback distance norm of four times the height of the wind turbine. Other European countries such as Germany and Great Britain do not appear to have established fixed setback distances [12]. In the Netherlands, public safety is assessed for each wind turbine individually during the planning stage of a wind farm. This assessment involves a quantitative risk analysis from wind turbine failure and is based on guidelines in the '*Risk Zoning Wind Turbines Manual*' (*Handboek Risicozonering Windturbines*, HRW) [13].

There is a lack of research on which wind turbine failures could endanger public safety combined with the possible effects of these

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failures. This paper describes research that can be considered as a first step in combining wind turbine failures with public safety risks. The purpose is to contribute to developing knowledge about public safety risks from wind turbines by primarily focusing on causes of failure and failure modes of wind turbines. The results of this research can be used to improve the assessment of public safety risks from wind turbines. Following an extended literature review, the starting point for the research was an existing qualitative Fault Tree Analysis (FTA) of wind turbine failures by Márquez et al. [14]. This FTA was expanded, analysed and quantified using available databases of wind turbine failure incidents. The results of the analysis and the quantification were then verified by experts. The outcomes of the research were then compared with the current Dutch approach to assessing public safety risks from wind turbines.

1.1. Literature review wind turbine failure & safety

Only few papers have been identified in the literature that deal with the causes of wind turbine failure, of which only one includes a root cause analysis in which the authors assess a collapsed wind turbine in 2011 in Taiwan [15]. Although assessments of wind turbine failures can be found in several studies, the main topic is the reliability of wind turbines. Publications related to the reliability of wind turbines focus mainly on the topics of downtime and the frequency of wind turbine failures. In [16,17], the authors review operation and maintenance (O&M) costs for wind turbines and focus on reducing O&M costs by improving the reliability of wind turbines. In [18,19], the focus is on frequencies and downtimes of wind turbine failures. In [20,23], the researchers use Failure Mode Effect Analyses (FMEA) to identify the most critical wind turbine failures. The focus of most of these papers is failure of wind turbine components with [20–22,24,25] addressing their failure rates. The studies indicate that failure rates are of the order of 0.9–1.4 failures per wind turbine per year.

In [19], the authors analysed the reliability of wind turbines based on data collected from 1,500 wind turbines over a 15-year period from 1990 to 2005. Based on their analysis, the failure frequency of wind turbines was around 1.5 failures per wind turbine per year. However, this study mostly covered relatively small wind turbines with outputs below 1 MW. In [26], wind turbines failures are quantified in terms of a percentage breakdown of failure causes based on the number of incidents.

Condition monitoring systems have also been researched. Based on a review of wind turbine condition monitoring systems, Márquez et al. [14] constructed a qualitative FTA for wind turbines. A fault tree is essentially a graphical representation of certain relations which traces a system or a process hazard backwards to search for all its possible causes. Such a hazard is named as the top event of the fault tree. Traditionally, quantitative analysis evaluates the probability of the occurrence of the top event in which case the probability of each basic event is already known.

All publications described in the beginning of this section focus on the reliability of wind turbines and are largely related to the components in the nacelle of a wind turbine such as the generator and gearbox. Structural failures in the tower or the blades are only addressed superficially.

Another topic addressed in some publications is the consequences of wind turbine failures. These studies focus on throw distances following blade failure, and are aimed at establishing safe setback distances for wind turbines: the minimum distance between a wind turbine and other buildings. Blade failure in these papers is seen as the most important failure in determining setback distances since blade throw distances can exceed the danger area from other failure types. In some recent papers [9–11], throw distances of detached blades are modelled, with the most comprehensive research related to throw distances described by Sarlak and Sorensen [10]. The research includes four characteristics which influence throw distances of detached blades: pitch setting of the blade, wind speed, tip speed, and the length and weight of the detached blade component. An experimental study into the throw distance of a blade is reported in [28] in which a blade throwing machine was used to simulate the trajectory and throw distance of a detached blade.

Although all of the above described studies about wind turbine failures are valuable, they do not investigate the risks of wind turbines on the surrounding area or on public safety. Research into the probabilities of blade detachment or tower collapse combined with the consequent risks for the surrounding area is lacking. This lack of such research into the topic of public safety risks has been acknowledged elsewhere [6,13].

2. Research methodology

In this research, the qualitative FTA model developed by Márquez et al. [14] was adopted and expanded to include public safety risks. The research was broken down into seven steps. The first three steps were focused on expanding the FTA to include wind turbine failures that could affect public safety. The fourth and fifth steps were focused on quantifying the expanded FTA. This included investigating if the expanded FTA could be used to improve the assessment of public safety risks from wind turbines. A six step corresponds to the expanded FTA model evaluation. The final step included a comparison of the results of this study and the Dutch approach to assessing public safety risks from wind turbines.

2.1. Step 1: identification of FTA

Márquez et al. [14] constructed a fault tree based on a review of wind turbine condition monitoring systems. For the purposes of this research, only failures that could impinge on public safety were selected and extracted from this fault tree by excluding all failures that could not lead to detachment of components or to structural failures. For example, component failures within the nacelle, such as to the generator, were not considered.

2.2. Step 2: literature study

Information related to public safety risks from wind turbine failures was first sought within the literature. A literature study was conducted to provide data on wind turbine failure causes and failure modes. The results of the literature study were subsequently verified and augmented by additional information through interviews with experts. Information was collected from sources such as:

- Theoretical failure analyses of wind turbines such as FMEA analysis;
- Monitoring studies of wind turbine reliability;
- Documents and reports about failure events from, for instance, insurance companies and media.

2.3. Step 3: expert judgements

As stated earlier, most related publications have focused on the reliability of wind turbines. This led to the decision to rely on expert judgements even though it was clear from the start that expertise in this area of research was limited. To uncover as much information about the subject as possible, diverse groups of experts and institutes representing the wind turbine industry were approached. These included wind turbine owners/developers, manufacturers, research institutes as well as wind turbine certification and insurance companies. Further, social media was used to try to find experts on the subject that would be willing to provide useful information. For example, a request for sharing such information was posted on LinkedIn group ‘Wind Turbine Technicians’. Unfortunately, very few institutes and experts were able to help in this step for a range of reasons. For instance, the University of Delft and research institutes such as NREL and SANDIA, which are all

Table 1
Characteristics of the experts.

Characteristic	Parameter	Number of experts
Number of experts - Interviewed	–	12
Years of experience with wind energy	0–5	3
	5–10	3
	>10	6
Background	Research institution	3
	Wind turbine manufacturer	4
	Wind turbine owners (energy companies)	3
	Engineering companies	1
	Insurance company	1

involved in research related to wind energy, indicated that they did not have experts who are qualified to provide information on failures affecting public safety or their probabilities. They reiterated that the focus of their work was on the reliability of wind turbines and on the consequences of failures on maintenance, costs and downtime rather than on public safety. In total, only 12 experts were found to be interviewed. Their backgrounds and the lengths of their experience are shown in Table 1. Only nine of these experts were able to help in verifying the identified failure causes and modes provided by the FTA shown in Fig. 1. The experts were each interviewed once for the purposes of this step and again to quantify the failure modes as explained in Steps 4 and 5. The length of each interview was one and a half to two hours, and each expert was shown the FTA to verify the failure modes and to add other failures and consequences related to public safety as they perceived them from their experiences. The results of the literature study and expert judgements were then used to specify failure modes and expand the FTA for wind turbine failures related to public safety risks.

2.4. Step 4: quantification of FTA

For the quantification of the expanded FTA, the database of the Caithness Windfarm Information Forum (CWF) was used [29]. This database includes a large number of worldwide wind turbine incidents from 1996 onwards, with information mainly extracted from media reports. The CWF database was selected because it was the most comprehensive publicly available database of wind turbine incidents.

The procedure revealed that the expanded FTA was too detailed and could not be entirely quantified due to inadequate incident descriptions. For this reason, the quantification in the FTA was reduced to three levels: (1) system, (2) components and (3) failure modes. Level 1 is related to the wind turbine as whole and Level 2 is related to components such as blades, tower and nacelle. Level 3 is related to the failure modes of the components, such as the breaking off of a blade fragment. It was not possible to include all the identified causes of failure (a potential level 4) individually since this level of detail was not documented in the reported incidents and therefore the failure causes were grouped for quantification purposes.

Incidents to be included in the FTA were evaluated in order to identify the failure modes and failure causes. Next to the information on the incidents available in the CWF database, an internet search was carried out seeking additional descriptions of the incidents and to check the correctness of the incident descriptions in the database.

For the purpose of this study, only incidents in the CWF database that meet the following criteria were considered:

- Occurred between 2000–2014 – since few wind turbines larger than 1 MW were installed before 2000.
- Occurred within Europe—to ensure comparable conditions with the Netherlands.
- Occurred onshore—offshore wind turbines do not have the same public safety concerns.
- Involved horizontal axis wind turbines—because only this type are employed on a large scale.
- Involved structural failure or detachment of wind turbine parts—-thereby potentially endangering public safety.

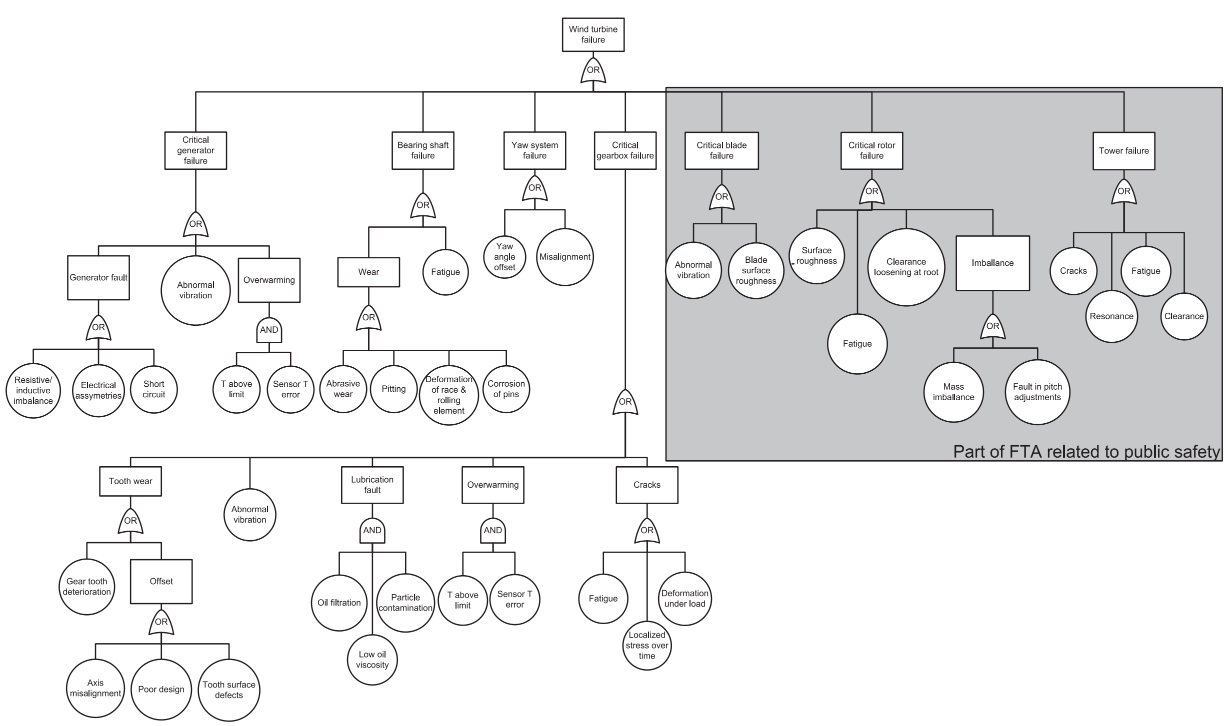

Fig. 1. Qualitative FTA Márquez et al. [14], shaded area is used for this study.

Table 2
Power classes of wind turbines.

Power class		Capacity
Small	1	Less than 100 kW
Medium	2	100 kW to 1 MW
Large	3	1 MW and above

Failure modes were analysed in order to quantify the FTA. Other information related to the incidents such as the weather conditions and the age of the wind turbine was also included in the analysis.

2.4.1. Wind turbines power classes

During the interviews in Step 2, experts indicated that failures in small wind turbines differed from those of large wind turbines and hence the capacity of the wind turbines was included as another variable. For this reason, a classification of the capacity of the wind turbine was developed in this research. The wind turbine power class was identified for all the reported failure incidents. Previous studies, see for example [30], have also classified wind turbines based on their capacity, and the National Renewable Energy Laboratory and the Health and Safety Executive also describe classifications based on rotor swept area and output [6,31]. The classification used in this study is in line with these classifications and includes the three classes shown in Table 2.

2.5. Step 5: expert verification

Expert judgements were used to verify the results from Step 4 since only limited data and sources on wind turbine failures were available. The verification was focused on the failure components and the failure modes.

The experts involved in Step 3 were again approached as well as other experts who had initially declined to participate in Step 3. In total, 15 respondents accepted the invitation to participate. In this step, the verification information was collected through an approach based on the Delphi method [32]. In this approach, information concerning the quantification of the probabilities included in the FTA was prepared using excel sheets which were then sent to each of the experts. Each expert was asked to quantify and insert the probabilities of each of the causes and modes of the failures in the FTA using percentages rather than absolute probability values, i.e. the probable percentage share of each failure mode out of the total number of failures. This approach was taken because the experts had previously indicated that it was difficult to estimate absolute values. Additionally, the experts were asked to provide a confidence level for their verification of the quantification results from Step 4 based on a three-point scale: 5%, 50% and 95%. Important aspects in this verification process were that:

- The Excel form was easy to complete.
- The time required was very short (approximately 15 min).
- Experts had the possibility to add comments and justifications for their verifications.

In line with the Delphi approach, a number of iterations of this process were carried out in order to reach a consensus among the experts as to the final verification results.

2.6. Step 6: model evaluation

To check the performance and reliability of a model, evaluations are usually conducted. Models can be rigorously evaluated by testing how they behave when analyzing well-known scenarios. This option is challenging in this study because information on well-known scenarios is not available. As may be evident, making this rigorous evaluation under the described situation results to be unreliable and impracticable. Therefore, a special evaluation is considered here. The proposed evaluation is based on the use of sensitivity analysis, SA, as described by Borgonovo and Plischke [48] and Khan et al. [49]. The focus of the evaluation resides on determining the impact of uncertainty in the input data on the estimates of the top event probability. More specifically, we verified the impact of the failure modes probability estimates uncertainty.

The proposed SA considers as measure of sensitivity the shift in the top event probability estimates when an input failure mode variable probability estimate change is produced. Thus, comparisons of the shifts obtained by varying input probabilities of different failure mode variables indicate the most sensitive variables. Those variables that produce relatively significant shifts are regarded as the most sensitive ones. This yields an indication on which specific input data pieces deserve further investigation and by doing so providing additional accuracy in the input estimates. The results and their discussion of proposed evaluation process are reported in the respective sections in this paper.

2.7. Step 7: comparison with Dutch approach to risk assessment

The results of this study were compared with the Dutch approach to assessing public safety risks from wind turbines, as prescribed in the HRW. This comparison focused on two parts of the HRW:

- Default failure modes.
- Failure probabilities.

Baseline figures for failure probabilities and failure frequencies were largely based on information available from Germany and Denmark. This was because the number of wind turbines in these countries could be accurately determined based on publicly available data registers [33,34]. Further, the number of incidents reported in the CWF database from Germany and Denmark, seemed to be the most verified. From other European countries, it was not possible within this study to determine the number of wind turbines and classify them into the power classes.

3. FTA model development

In this research, given the enormous limitations related to the data available, which are further described in this section, we have advocated the use of Fault Tree Analysis (FTA). More sophisticated and desired approaches (e.g. fuzzy sets, possibility theory, evidence theory or Bayesian networks) impose an additional data collection burden and consequently are not feasible and therefore not considered in the current stage of the research. FTA techniques have been prominently used in the literature for modelling of failures and for analysing and assessing risks. Khan et al. [49] and Ruijters and Stoelinga [35] have provided exhaustive reviews of FTA techniques used for these purposes. Also recent examples of research works using these techniques are described in [36,37]. However many modelling approaches including FTA have also challenging limitations. The main limitation is the uncertainty that is usually associated with the data used in the assessment of risks [36,50]. In general, uncertainty due to natural variation or randomized behaviour of a physical system is called aleatory uncertainty, whereas the uncertainty due to lack of knowledge or incompleteness is termed epistemic uncertainty [50]. Subjectivity, incompleteness and inconsistency are additional characteristics in input data that also lead to uncertainty in the results of analysis using FTA [37,50]. Dependences among basic events may be uncertain or unknown and this characteristic also contributes to generate uncertainty in a FTA model [49]. Many FTA that have been applied in the past are deterministic and do not address any of the types of uncertainty mentioned [37]. However, Khan et al. [49] have described a number of methods for addressing many of the uncertainties in FTA. These authors demonstrated the potential use of non-parametric inference, Bayesian

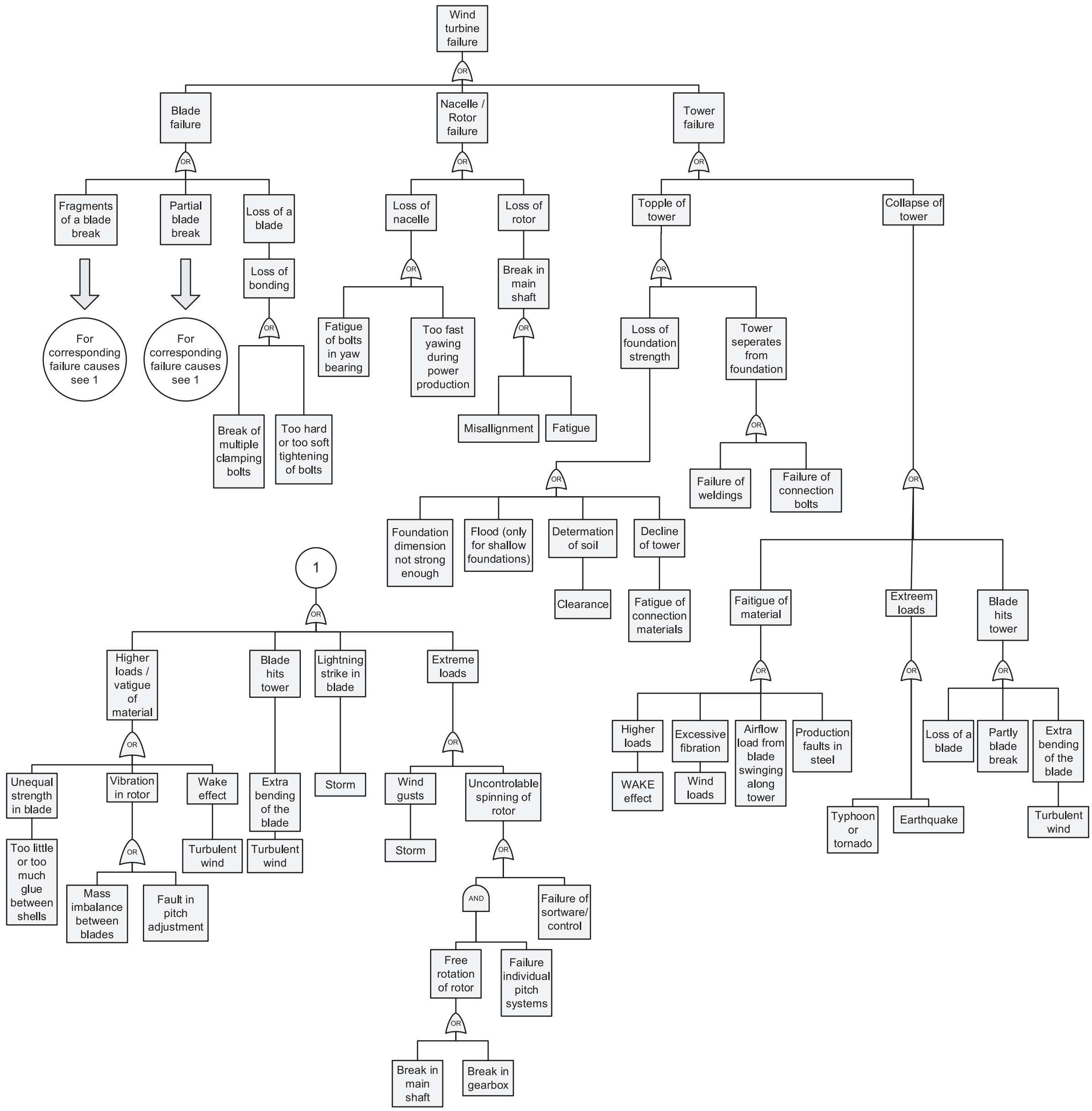

Fig. 2. Expanded FTA derived from this study.

updating, Monte Carlo methods, fuzzy sets, possibility theory, evidence theory, simulation based methods and combination of these methods. Mapping FTA into Bayesian networks or Fuzzy Bayesian networks and sensitivity analysis are also considered to tackle data and model uncertainty [49].

Since, in this research we had to deal with considerable uncertainty in the data and the proposed model, specific provisos were made. The proposed research methodology considered this situation and accordingly stablished a number of steps addressing the uncertainty issues. These include the verification by experts and model evaluation steps described in the antecedent section whose specific results are reported later in the next section.

As outlined earlier, we based our research on Marquez et al.'s [14] work. These authors reviewed wind turbine condition monitoring systems. Their research included eleven types of monitoring techniques such as vibration analysis, oil analysis and performance monitoring. The authors identified potential failures and described these in a qualitative FTA (see Fig. 1). Their study focused on the major wind turbine components: the blades, rotor, gearbox, generator, bearings, yaw system and tower.

The failures included in this FTA that could lead to public safety risks were identified and used as a starting point for this research. The extracted failures are related to component failures of the blade, rotor and tower as shown in the shaded frame in Fig. 1. Failure modes and causes are primarily adopted from [14–26,38]. Monitoring studies for wind turbine reliability [19,39] and other sources such as reports from insurance companies [7] were also used to identify wind turbine failures. Failure modes from effect analysis models of failing wind turbines were also used [9–11,27].

Failure causes and failure modes are in general not very clearly described in the literature. The most detailed descriptions were provided in the FMEA analyses described in [20–23,38] and the failure cause analysis described in [15]. Consequently, the expert judgements were mainly used to identify the links between failure causes and failure modes based on these sources. Some experts presented very detailed failure descriptions of previous incidents. The results of the literature review and the expert judgements were used to derive the expanded FTA.

Experts from different backgrounds and experience were approached as shown in Table 1. On some failure events, the experts had different opinions. For example, when it came to blade damage caused by lightning, some experts stated that this was now irrelevant since modern wind turbine blades are equipped with lightning protection. However, other experts argued that this was still relevant because these protection systems could also be subject to design and quality issues. When there were these widely differing opinions, the failure mode was retained because we did not feel one could for example, rule out of blade failure caused by a lightning strike.

In general, all the experts agreed that the knowledge about wind turbine failures has improved over the last few decades. There is, for example, considerable growth in the knowledge related to the loads on wind turbines due to wind turbulence. This increased knowledge has been used to improve the IEC certification standards for wind turbine designs [40]. Today, the IEC 61,400 standards for wind turbines prescribe minimum design requirements. Modern wind turbines are more developed than models from two decades ago and overall they are safer. However, most of the experts interviewed were not able to quantify how this increase in knowledge would translate to a reduction in failure probabilities.

The majority of experts interviewed were also not able to quantify failures of wind turbines and only few quantitative statements were made. Blade failures were seen as the most common incident, followed by tower failures. Nacelle failure was considered the least likely failure mode. Some experts considered the nacelle failure mode to be a rotor failure and that the throw of a full nacelle was extremely unlikely. Experts also argued that wind turbine failures are conditional, and often have a combination of causes, for instance fatigue failure of materials during storm conditions. Another example given was that part of a broken blade could also hit the tower and lead to tower failure. A comprehensive identification of these combined causes of failure could not be achieved from the interviews held as part of this research, and clearly there is limited knowledge on this subject amongst experts. As such, only limited combinations of failure causes could be identified within this study.

Fig. 2 shows the expanded FTA developed in this study. The component failures are broken down by failure mode, adding a new layer to the original FTA developed by Márquez et al. [14].

Wind turbines could fail in various modes. For instance, blades could lose a tip, split open, small or large parts could break off or an entire blade become fully detached. In this paper, based on the expert judgements, the failure modes of wind turbines that are relevant to this study include the following types of incident:

- Blade failure:
  - components of a blade break off
  - Partial blade break: a part of a blade or (a part of) of the blade shell become separated.
  - Loss of a blade: a complete blade becomes detached from the hub.
- Tower failure
  - Toppling of the tower: the tower breaks at ground level or the mounting fails, leading to the entire turbine toppling.
  - Tower collapse: The tower fails somewhere along its length and collapses.
- Nacelle/rotor failure
  - Loss of nacelle: The entire nacelle including the rotor becomes detached from the tower.
  - Loss of rotor: The rotor becomes detached from the nacelle.

Wind turbine incidents have been reported in Wales, Spain, Germany, France, Denmark, Japan, New Zealand and Scotland in which parts and whole blades have become detached because of high winds, malfunction, or fire, flying as far as 8 km and through the window of a home in one case. Whole towers collapsed in Germany in 2002 and in the US in 2005.

In areas prone to earthquake or hurricane and floods, the likelihood of failure modes, such as collapse of the wind turbine tower or flying debris, which are some of the risk safety scenarios that impinge on other facilities and on the general public, increases. Furthermore such risks will be exacerbated in cases where the wind turbines are near sensitive facilities such as a petrochemical plant, research as well as medical facilities

Modelling the above issues was the main focus of the work reported in this paper. However, there are many other risks associated with other failure modes that are not included or modelled here. For example, we have not included the safety risk due to blade icing in ice-prone climates. Under icing conditions, all exposed parts of the wind turbine are liable to ice build-up and, in particular, ice on a rotor blade ice has the potential to be cast some distance from the turbine and cause injury to the general public.

Another risk related to wind turbines is fire and associated smoke. For example, a 100-m tall turbine caught fire during hurricane-force winds in Scotland in December 2011, reportedly due to a lightning strike [42]. The wind turbine was completely burnt out and debris scattered over large distances due to the strong wind. The main causes of wind turbine fires are lightning strikes and technical reasons such as overheating and sparking electrical connections and even human error. In 2005, a turbine at the Nissan factory in Sunderland in the UK was engulfed in fire before falling onto a nearby major road causing traffic disruption. The blaze was believed to be caused by a loose bolt jamming a mechanism and causing it to overheat [43].

It is well known that any large structure, whether stationary or moving, in the vicinity of a receiver or transmitter of electromagnetic signals may interfere with those signals and degrade performance. Electromagnetic disturbance interrupts, obstructs, or otherwise degrades or limits the effective performance of electronics or electrical equipment. It can be induced intentionally, as in some forms of electronic warfare, or unintentionally as a result of spurious emissions and responses or intermodulation products. Wind turbines can both transmit and receive electromagnetic interference and two issues are relevant. First, the possible passive interference with existing radio or TV signals and mobile communication; second, the possible electromagnetic emissions produced by the turbines which can influence and degrade the performance of local electricity grids. Wind turbines may also indirectly influence safety by disturbing radar systems and aircraft navigation.

Furthermore, when looking at the failures of wind turbines as part of an open and interconnected system environment, the impact of other important external factors and scenarios such as sabotage, terrorism, cyber-attacks and explosions should be considered and evaluated. Systems of critical infrastructure are becoming increasingly interconnected and dependent on each other and, as beneficial as this may be, it can also be very disruptive. The increased interconnectivity of neighbouring control areas and the integration of volatile renewable energy sources enhance the risk of cascading failures in power systems [44]. Failure in one subsystem can lead to spiraling failures in the other parts of the greater system and eventually have indirect, if not direct, impacts on public safety. For instance, in certain circumstances, blackouts can be caused by cascading failures triggered initially by single or multiple disturbances, such as extended overload or stability issues in bulk power systems [45]. With the rapid development of wind power around the world, its penetration in the power grid increases. The intermittent and variable nature of the output power of wind farms, as well their easy tripping out under abnormal conditions, will increase the probability of cascading failures in power systems and, since a vast number of services are dependent on electricity, significant blackouts can have disastrous consequences, particularly in urban settings. The consequences of the US 2003 blackout illustrate this well: when a cascading failure hit New York City, traffic lights and subway trains failed immediately. Both were vital to the flow of people in and out the city and, as a result, thousands of people were forced to abandon their cars, walk through subway tubes, and walk off the islands. Mobs of commuters were reported to have stormed empty buses and refused to let them pass. In large buildings across the city, hundreds of people were stuck in elevators. Even air traffic suffered since LaGuardia International Airport could not restore power for passenger screening, delaying air traffic throughout the country. Numerous commercial losses resulted from the blackout. Metal fabrication plants sustained multimillion-dollar losses when molten metal hardened inside machinery. Grocery stores in the affected area had to discard massive amounts of refrigerated food. Before long, the blackout began to affect vital city services. Water and sewage pumps across eastern parts of United States failed, putting stress on those systems. One New York City pump station spilled millions of gallons of sewage. With heavy rains on 15 August, untreated sewage flowed into waterways in Detroit and Cleveland. Four million Detroit water customers were asked to boil their water due to the risk of cross-contamination between the sewer and water systems. Telecommunication infrastructures also suffer immediate damage after a blackout. While most telecommunication systems, such as cell phone towers, have backup batteries allowing the service to continue for hours after the initial power loss, longer blackouts can lead to service failures. If the blackout lasts longer than the design time of the energy storage system, or backup power supply equipment is not sufficiently maintained, communication failures can propagate to other services that rely on telecommunications, such as stock markets or emergency responders. In an another scenario, a cyber-attack by a hacker intending to collect information on the large interconnected national electric grid in order to disrupt the whole system could use a small wind farm as an entry point to the large system. If the control system for a single generating facility communicates with control systems covering a larger area, a hacker could simultaneously hit several plants to take them offline creating a series of cascading effects with no electricity, clean water or transport to follow.

4. Results: quantification of the FTA

As indicated earlier in this paper, the interviewed experts were unable to quantify failures of wind turbines. Consequently, the quantification of failure modes was based on a database analysis. Further note that, such quantification was performed with a reduced FTA including only three levels: (1) system, (2) components, (3) failure modes. The results of this reduced FTA are shown in Fig. 3. The quantification was based on 209 incidents in the CWF database [29] of which 86 failures concerned wind turbines of 1 MW or larger. The quantification is expressed in percentages. Failure modes were identified for 82% of the failure incidents, whereas failure causes could only be identified for 38% of the failure incidents (potential level 4 in Fig. 3). This lack of information is due to most incidents being identified from media reports, which only include limited descriptions of the incidents. Consequently, failure causes quantification is not further addressed in this paper and we only focused on failure modes aggregated information which could be obtained from the CWF database.

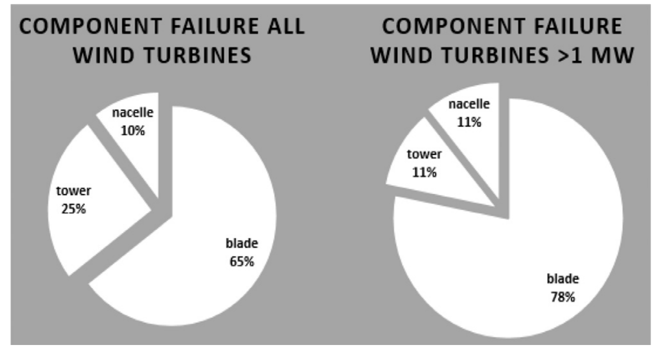

Fig. 4. Results of quantification, component level.

Fig. 4 shows the percentages of failures on the component level, first for all wind turbines and then for wind turbines of 1 MW or above. The figure shows that the most component failures take place in the blades, and that blade failures constitute over three-quarters of all component failures in wind turbines larger than 1 MW, failures in towers and nacelles are relatively rare.

For most of the failure incidents, limited descriptions are available such as '*a blade flew off*'. There were only two incidents where it could be stated for certain that an entire blade was detached. Since most of the blade weight is located close to the hub, a partial blade loss will involve a much lower mass. Unfortunately, it was not possible to assess how much of a blade had been detached for most of the blade incidents, and the '*partial blade break*' failure mode will include a wide range of a blade parts from maybe under 1 m to over 25 m.

Incidents described as '*a blade flew off*' were interpreted as a '*full blade break*' failure mode. Incidents described as '*parts of a blade flew off*' were considered a '*partial blade break*' failure mode. For some incidents, photographs were available to help interpretation.

In total 135 blade failures, 22 nacelle/rotor failures and 52 tower failures were identified. The percentages of the failure modes are shown in Table 3. The results of the quantification show some interesting findings. The nacelle/rotor failures include only one definite nacelle failure but 18 incidents of rotor failure, with three unspecified. The tower component failure category also includes an interesting finding. Considering only wind turbines of 1 MW and above, five towers collapsed and for two of these incidents the failure mode was not reported.

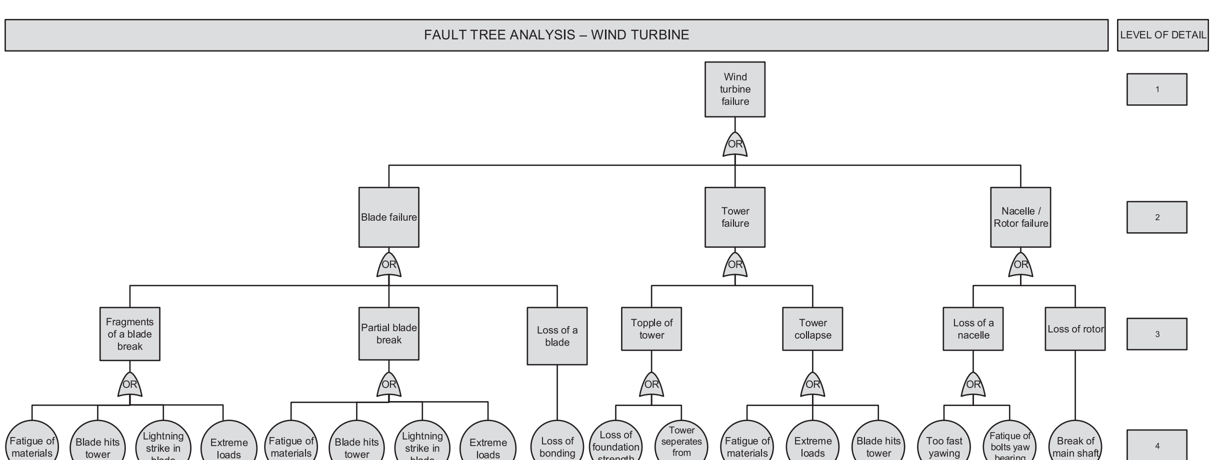

Fig. 3. FTA wind turbine, level of detail for quantification.

Table 3
Quantification of component failures based on CWF database [26].

Blade			Tower			Nacelle		
Failure modes	Total	WT > 1MW	Failure modes	Total	WT > 1MW	Failure modes	Total	WT > 1MW
Fragments	7%	8%	Toppling	33%	0%	Nacelle	5%	0%
Partial blade	53%	57%	Collapse	67%	100%	Rotor	95%	100%
Full	39%	35%						

No wind turbines of 1 MW and above have been reported where the entire tower has toppled over.

Another notable result of the database analysis, which is not presented in the quantification, concerns the described weather conditions. For more than half of the incidents, storm or lightning conditions were reported. We have not investigated whether weather conditions influence the failure modes but, for the risk calculations, the weather condition are important because wind speed influences the distance that detached blades are thrown.

The results of the quantification were presented to experts in order to verify the results. The verification was focused on the component failures and failure modes, (i.e. Levels 2 and 3 of the FTA shown in Fig. 3). The experts still had difficulties in attempting to verify the presented results, and only 7 of the 15 consulted experts felt comfortable with reflecting on the results of the quantification. All the consulted experts stated that they were unable to reflect on exact percentages and that these percentages should be seen as indicative rather than applied as a rule. Two experts indicated that they could not reflect on the results, but thought that the presented quantification was in line with current experience.

Five of the seven experts willing to reflect put the percentages for component failures close to those presented. The other two experts thought that blade failures were more common than the analysed percentages, maybe accounting for 85–90% of total wind turbine failures.

However, in general, the quantifications of the failure modes for blade failure were supported by the experts. The experts agreed that it is more likely that a blade breaks into parts rather than becomes fully detached. The two experts who believed that blade incidents were more common than the presented quantification, also argued that the 'fragments' failure mode was underestimated using the information in the database and they believed that it should be around 40–50% rather than 8%.

The experts were even less confident when it came to verifying the nacelle and tower failure modes. The following qualitative statements can be made based on the expert verification related to these failures:

- The '*collapse*' of the tower failure mode occurs more frequently than the '*toppling*' of the tower mode.
- The '*rotor*' failure mode occurs more frequently than nacelle failure, but none of the experts excluded the possibility of an entire nacelle becoming detached.

In addition to the verification by experts procedure, which was useful to validate the structure of the model and to reduce model's uncertainty, an additional step in the modelling process was added. The additional evaluation consisted of conducting a sensitivity analysis, SA. As mentioned in the research methodology, such SA mostly assesses the effects of the failure modes input data uncertainty.

By using the proposed procedure described in Section 2.6, a ranking of the failure modes according to their sensitivity can be obtained. Table 4 summarises the results.

To calculate a probability shift, a baseline or reference top event probability is first estimated using the model in Fig. 3. Such initial top event probability is calculated based on the input failure mode data obtained from the CWF database. Each variable in the model is removed and a new probability is then estimated for the top event. The difference between the original estimation and the new one corresponds to the shift in the top event probability.

Table 4
Ranking of failure modes according to their sensitivity.

Failure mode variable	Shift in the top event probability as a given failure mode is not considered in the model
1.Fragments of a blade break	0.000715206
2.Loss of a blade	0.000469579
3.Partial blade brake	0.000361215
4.Topple of tower	0.000110667
5.Collapse of tower	5.53333E-05
6.Loss of nacelle	5.26909E-05
7.Loss of rotor	2.90526E-06

Table 4 shows that 'fragments of a blade break' failure mode is the most sensitive mode and further research should focus attention on providing accuracy for this sensitive event if one wants to improve the top event probability estimation. The ranking in Table 4 also informs that all the events related to the 'blade failure' (three first items in the ranking, see Fig. 3) are critical and therefore should be prioritised in future research undertakings. However note that, these results depend on the specific model configuration validated by the experts, see Fig. 3.

Results in Table 4 were somewhat expected given the configuration of the model which consists of seven events (level 3 in Fig. 3) linked by the connective OR gate to three components (level 2 in Fig. 3) which in turn are connected to the top event (level 1 in Fig. 3) by the same connective. With this fault tree configuration any single failure mode event occurring is sufficient to the materialization of the failure top event. Consequently, those relatively most probable events result to be the most sensitive ones as well, and their associated uncertainty is critical to the estimation of the top event probability/frequency.

5. Comparison with risk assessment used in the Netherlands

The comparison between the results of this research and the Dutch risk assessment focuses on the failure modes and the failure probabilities as included in the HRW guidelines.

5.1. Failure modes

In the Dutch risk assessment procedure for public safety risks from wind turbines, three default wind turbine failure modes are defined [7]:

- Throw of a full blade.
- Collapse of the tower.
- Separation of the nacelle or rotor.

These failure modes were investigated and established in the 2005 version of the HRW as the three relevant failure modes for the risk assessment of wind turbines. The assessed failure modes represent simplifications of the investigated failure modes. For instance the assessed 'throw of a full blade' failure mode is a simplification of '*The break and throw of detached blades and large parts of blades*'. Other failure modes were evaluated as irrelevant because it was assumed that they would not influence risk assessments because of their limited impact [41].

The FTA developed in this research contains more details than what is in the Dutch assessment, and the results of the analysis show that there are other failure modes than those documented in the HRW guidelines. The blade-related failure mode in the HRW is focused on the detachment of an entire blade. The results of this study show that blade failures can be split into various failure modes. The loss of part of a blade is more common than the detachment of a whole blade. The detachment of a complete blade was only recorded in two incidents.

As noted earlier, the distance a blade part can potentially be thrown, based on the model by Sarlak and Sorensen [10], is further than a full blade. As such, assessing partial blade failure is relevant. This is even more so given the increasing scale of wind turbines. In 2005, a commonly installed wind turbine was the Enercon E-66 with a rated capacity of 1.5 MW and a blade weight of 3.9 tonnes [46]. Today, the Enercon E-126 with a rated capacity of 7.5 MW and a blade weight of 31 tonnes [47] is one of the largest onshore production wind turbines. As such, the investigation of failure modes for the 2005 HRW guidelines was based on incidents with relatively small wind turbines. A blade part of an Enercon E-66 would probably have less impact than part of a 31-tonne blade. For this reason, partial blade failure is becoming increasingly relevant in assessing public safety risks from wind turbines.

The tower failure mode in the HRW only relates to the toppling of a tower, that is one where the attachment to the ground fails. Our study shows that a tower is more likely to collapse than topple, and such a failure will have a different impact. The nacelle/rotor failure mode in the HRW is focused on the detachment and throw of the entire nacelle and rotor combination and therefore the risk assessment only includes this event. Our quantification identified only one incident concerning the throw of a whole nacelle, and that the loss of 'just' the rotor is much more likely. The impact of a detached rotor will again be very different to that of the throw of an entire nacelle/rotor combination.

5.2. Failure frequencies

A failure frequency for wind turbines was estimated based on the quantification in this research. This failure frequency estimation was limited to the system level, i.e. the entire wind turbine. This failure frequency was compared with the figure used in the HRW. The difference between the calculated frequency and the probability of failure, as described in the HRW, is as follows:

- Failure frequency—based on the number of failures that have occurred.
- Failure probability—related to the expected number of failures that might occur.

The HRW figure, used to assess public risk in the Netherlands, is focused on wind turbines of 1MW and above. In our case, five-year average failure frequencies are calculated. This failure frequency is based on wind turbine incidents in Germany and Denmark recorded in the CWF database. The corresponding total number of wind turbines was extracted from data registers [29,30]. These databases also include the capacities of wind turbines and hence it was possible to create failure frequencies for wind turbines of 1 MW and above.

Given there were only a few incidents (see Table 5), it was only possible to create failure frequencies for the wind turbine system as a whole. The low number of incidents is also the reason for adopting a five-year average failure frequency. The five-year average failure frequency is shown in Fig. 5. The graph shows a strong 80% decrease in failure frequency over the last 15 years. This is an indication of improvements in wind turbine safety over time.

6. Discussion

The expanded FTA developed in this study provides additional knowledge about wind turbine failures. It ought to be developed further to address additional public safety risks from wind turbines. However due to limitations in the data and in experts having addressed this field, more work will be required to fully describe all the causes of failures and their probabilities for an extended FTA. Further research can consider this point by using more sophisticated modelling approaches including e.g. fuzzy sets, possibility theory, evidence theory or Bayesian networks in conjunction with specific structured expert judgement elicitation procedures as in [51].

Experts indicate that wind turbine failure often occurs because of a combination of causes. It was not possible to identify these combinations in the FTA within this research and this is therefore an area for further research. The quantification in the FTA was based on the limited available information on previous incidents. However, due to the lack of detailed descriptions of the failure incidents, it was not possible to provide a reliable quantification of failure causes or to make a clear distinction between failure modes for component failures. For instance, a failure described as '*a blade flew off*' was classified as a full blade failure even though we were not certain that this involved the detachment of a full blade or only part of a blade. The quantification of the failure modes should therefore be seen as no more than indicative. This conclusion was also supported by the experts during the verification process.

The internet search for the incidents reported in the CWF database shows that 20% of the incidents were not classified correctly in terms of public safety risks. For instance, fifteen incidents classified by CWF as a fire accident, could also be characterized as blade incidents.

In addition to the limited details of the incidents, there is also a lack of expertise. The research institutes approached that had a strong focus on wind turbines did not have expertise on the topic of public safety risks from wind turbines and were therefore unable to participate in this research. Furthermore, all the consulted experts stated that they could not verify the exact percentages or probabilities of failures due to limited knowledge, and hence it became impossible to fully quantify the FTA because of the general lack of knowledge related to public safety risks from wind turbines. However in this research, by a modelling evaluation step using sensitivity analysis, it has been identified the most critical failure modes which require particular research efforts, if one wants to increase accuracy in the top event probability. This analysis informed that additional investigation of the probabilities of the 'Fragments of a blade break', 'Loss of a blade' and 'Partial blade brake' failure modes is worth making.

As mentioned earlier the major limitation encountered in this research has been the shortage of information available to be included for analysis in the study. The study had to rely primarily on a very limited number of experts in this field to expand the FTA to identify and include failures that are relevant to safety risks to public. Also there were only very limited records of past incidents frequencies available that were

Table 5
Number of incidents on wind turbines of 1 MW and above in Germany and Denmark.

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Number of incidents	2	5	6	5	1	5	6	1	1	1	1	1	4	1
Number of WT's > 1 MW	3,648	5,559	7,209	8,247	9,255	10,252	10,998	11,393	12,741	13,558	14,531	15,682	17,112	18,856

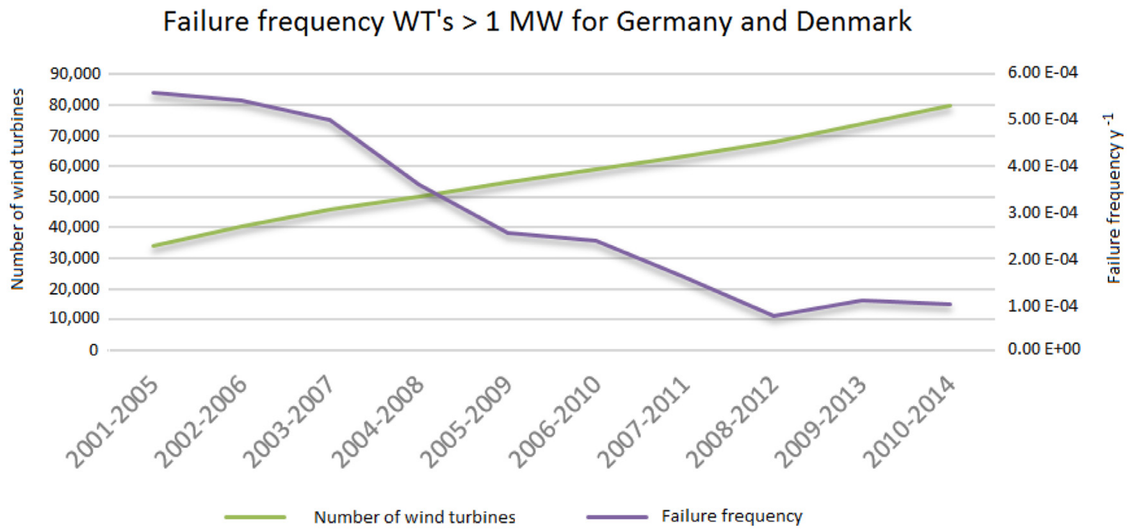

Fig. 5. Estimated failure frequencies of wind turbines of 1MW and above based on Germany and Denmark statistics.

used to estimate the likelihoods of the various events triggering such failures. Both of these two sources of data, the subjective nature of expert judgements as well as the limited records carry uncertainties in them. This is expected to affect the accuracy of the analysis. For instant even though the collected data from Germany and Denmark show a decrease in the failure frequencies as shown in Fig. 5, these result are based on limited and uncertain data and any increase of failures in one year to the available data would result in significant changes to these results. The amount of recorded WT failures used to create failure frequencies in Fig. 5 is shown in Table 5.

Nevertheless, using the limited information acquired during this study, the analysis and the results can be used to improve the assessment of public safety from wind turbines. The quantification in the FTA highlighted differences, in terms of some failure modes, between practical experience and the failure modes used in the Dutch risks assessment of public safety from wind turbines.

The study has shown that it is not sufficient to assess only the throw distances of wind turbine components after a failure, as is the case in the Dutch risks assessment practice. In the Dutch approach to risk assessment, the failure probabilities are important in assessing the likelihood of a failure that could endanger people's safety. This study, based on the recorded information in the CWF database, has indicated a downward trend in the failure frequency. However, it is not certain that the CWF database contains all incidents since the incidents reported in the CWF database primarily originate from media reports. It is likely that small incidents, such as detached tips from blades, are not always reported in the media. Therefore, the estimated failure frequencies noted in this study should be interpreted as indicating a declining trend in wind turbine failures rather than as accurate data. Further research into failures is required to determine more accurate failure probabilities.

There is no compulsory incident registration requirement in most countries. The only obligatory incident registration identified is in Denmark, but this is not publicly accessible. A wider introduction of compulsory incident registration would improve knowledge of wind turbine failures. Such registration should include a detailed description of the incident, a description of the wind turbine type, the failure mode, the failure cause, the impact of the failure, weather conditions and the distance the failed component was thrown.

7. Conclusions

This paper has described an analysis of wind turbine failures that can lead to public safety risks. An existing FTA has been expanded and developed to include risks to public safety from wind turbine failures. The quantification of the identified wind turbine failure modes related to public safety has shown that the most common such failure is the loss of a blade or part thereof. In a further analysis, this failure was split into three distinct failure modes: full blade failure, partial blade failure and loss of blade components.

Improvements to assessing the public safety risks from wind turbines have been recommended. In terms of the existing Dutch risk assessment approach, these improvements are focused on modifying the default failure modes included in the HRW. In order to support the relevance of improving the categorisation of failure modes, the distinct consequences for the different blade failure modes were presented.

Existing throw distance models state that partial blade failures have much larger throw distances than full blade failures. The likelihood quantification showed that partial blade failures are more common than entire blades being shed. Given the increasing size of production wind turbines, partial blade failures are increasingly relevant when assessing public safety risks from wind turbines. Further, the potential throw distances following partial blade failures are larger than the wind turbine setback distances demanded in many countries. These setback distances are generally limited to one and a half to two times the tip height of a wind turbine, less than the throw distances, following partial blade failure, calculated in the available models.

Overall, the research described in this paper shows that there is limited knowledge about public safety risks from wind turbines and that this is not helped by missing details in the recorded incident descriptions of wind turbine failures.

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