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IMAGINE

Improved Methods for the Assessment of the Generic Impact of Noise in the Environment

WP 4 – Aircraft sound sources

Task 4.1 – Modelling principles and lay-out

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EXECUTIVE SUMMARY

The purpose of Work Package 4 of the IMAGINE project is to implement and adapt the noise impact prediction models resulting from the the Harmonoise project to aircraft noise modelling around airports.

In this report the basic principles of both models, the Reference model and the Engineering model, are discussed and evaluated with respect to their application in aircraft noise modelling. After these considerations proposals are made for the adaptation of both models and a work plan is elaborated that specifies the various tasks that are to be executed in the framework of Work Package 4.

The most important recommendations implied in these proposals are:

- To develop a new aircraft sound source description that may replace the current Noise – Power – Distance tables; this description will be based on characterisation of the sources by their sound power and directivity;
- To develop a conversion method to convert the current NPD-values into the new characterising data;
- To implement two different reference models for low and high elevation angles;
- To elaborate a handy and sufficiently accurate solution for the implementation of directivity effects in the PE model;
- To adapt the meteorological classification from the Harmonoise Reference model to a classification that is suitable to the conditions in higher atmospheric layers;
- To adapt the Harmonoise Engineering model to fit the specific aircraft sound source description;
- To adapt the meteorological classification from the Harmonoise Engineering model to a classification that is suitable to the conditions in higher atmospheric layers.

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INTRODUCTION

Work Package 4 of the Imagine project is aimed at the development of harmonised, accepted and reliable methods for the assessment of environmental noise levels, caused by noise from airports. These methods should be directly linked to the methods for sound propagation modelling as developed in the Harmonoise project and at the same time have a large acceptance in the field of future users and other stakeholders.

The work plan of WP 4 comprises the development of two fully implemented computation methods, a Reference method with a high accuracy, serving as a scientific reference, and an Engineering method, intended for everyday use on a large scale basis. Both methods should be capable of predicting the noise indicators L_{den} and L_{night} as prescribed in the European Directive on the Assessment and Management of Environmental Noise (2004/49/EC). Furthermore the development should provide methods for the determination of relevant input data concerning the sound emission of aircraft, and a method for the conversion of currently available sound emission data into new data formats as required by the above mentioned noise impact computation methods.

Although these development tasks have been identified in the work plan a further elaboration of the character and contents of the tasks is necessary, before an integral acceptance of the work plan can be achieved and a division of tasks and subtasks among the partners can be agreed upon.

This technical report intends to elaborate on the principles of the modelling developments and, through an analysis of possible solutions, provide a proposal for the general design of the aircraft noise assessment methodology and for the actual lay-out and implementation of the various components that will be part of this general design.

The elaboration of the modelling principles in this report will in principle be limited to the sound emission and propagation of aircraft in flight. Sound emission and propagation of aircraft on the ground will not be treated within the framework of Work Package 4 of the Imagine project, except for the take-off and landing ground roll sound. The ground rolls will be included because they form an integral part of the flight operations and are treated as such also in other aircraft noise models like INM and ECAC Doc 29.

All other types of ground related noise are similar to industrial noise with respect to source location, characterisation of emission and propagation phenomena. They may therefore be treated according to the methods for industrial noise that are developed within Work Package 7.

1 Requirements for the Imagine calculation schemes

Though not explicitly formulated in the project description, the calculation schemes are expected to conform to a number of requirements, with respect to accuracy, flexibility and feasibility.

Since the reference method is aimed at special conditions and for increased accuracy, the effort for specifying the input parameters and calculation times can be considerable. The engineering method on the other hand is aimed at routine calculations and the effort for specifying the input parameters and calculation times must be limited. Hence the requirements for the reference method can be considerably more severe than for the engineering method.

However, even though there are no principal objections against a full source characterisation and propagation models that take the complete atmospheric conditions and topography of the surroundings into account, the effort required for such an approach is clearly out of proportions.

For example, by using a linearized Euler technique all meteorological effects and the topography can be taken into account. However, to simulate the sound propagation in the direct vicinity of an airport would require a computation time in the order of 11 Million years [1]! Even when computing power keeps developing with the same pace as the last decades, it will take a number of decades for this type of calculations to become feasible.

Hence, even the reference model requires a limitation of the amount of physics captured in the calculation schemes. Thus, both for the reference model and the engineering model a careful balance must be made between the requirements for accuracy, flexibility, sensitivity and feasibility. The meaning of these notions will be explained in the following sections.

1.1 Accuracy requirements.

The accuracy of the methods signifies the ability to produce results that correspond to the true value of the simulated quantity, although it may be difficult or impossible to establish this true value. The accuracy is determined by the accuracy of the input required by the models and by the accuracy of the propagation model. Thus an accuracy requirement for the complete calculation scheme can be translated into accuracy requirements for the different input parameters and the accuracy of the propagation model. According to the modelling principles laid down in the Harmonoise project the characterisation of the source and the description of the propagation phenomena should be fundamentally separated. Therefore the source emission data will be considered as input data, although they may be used as a fixed data-set after their initial assessment and be treated as part of the noise impact model in a more general sense. In this respect the sound emission data constitute another source of inaccuracy than the modelling of the propagation phenomena.

In general, higher accuracy requirement for the input will increase the required detail of the input and a higher accuracy requirement for the propagation model will increase the amount of physics taken into account in the propagation modelling. The consequence is an increasing effort needed for both the specification of the input and the propagation modelling, and a reduction of the feasibility. Thus, to optimise the accuracy, within the feasibility constraints, a careful balance of

the error budget for the input and propagation model is required. The error budget should also depend on the type of noise assessments that will be carried out with the models. The production of noise maps (contours) with the engineering model on a yearly basis, for instance, may be carried out using “only” simplified/averaged representations of atmosphere (temperature, pressure, humidity and wind), while the intended accuracy of the reference model will require a higher degree of detail and accuracy of the input data.

1.2 Flexibility requirements

The flexibility of the method relates to the possibility to take into account all relevant parameters and conditions that may influence the noise impact in the vicinity of an airport. The requirements with respect to flexibility will affect the required detail of the input and the amount of physics in the propagation model as well. Again, in general, increasing demands with respect to flexibility will lead to increasing demands on input detail and physics in the propagation model and consequently to increasing efforts/decreasing feasibility. Furthermore flexibility demands may interfere with accuracy demands.

Another aspect of flexibility is the possibility to use input data a different degrees of detail and accuracy. Although the accuracy of the output will be directly related to the accuracy of the input, it would be a great advantage if the Imagine aircraft noise prediction models would be robust in this sense. If the models require a greater level of input detail than is available for a certain application, this gap in the input data has to be filled by default data. It is important that the use of default data does not deteriorate the intrinsic quality of the model.

1.3 Sensitivity requirements

The sensitivity gives an indication of a model's ability to correctly reflect changes in noise impact due to a change in a given input parameter. The reference model is supposed to reach a relatively high accuracy in any type of application, which implicitly means (as a minimum requirement) it is sensitive to all the physical parameters that have a significant effect on the noise perceived on the ground. However, the engineering model may provide also a good sensitivity (which will be measured in terms of differences in dB between different parameter scenarios) but a rather low accuracy (i.e. in terms of the predicted absolute sound level values). Like accuracy, a high sensitivity requires the ability to incorporate a large number of input parameters and therefore a high degree of detail.

If the sensitivity of the models to parameter changes properly reflect the actual physical influence of these parameter changes on the noise impact the models can be used for sensitivity studies of two kinds. The first kind of sensitivity study investigates the relative importance of the different input parameters for the actual noise impact and can be employed to assess which simplifications to the model can be tolerated. The second type of sensitivity study investigates the response of the models to input data errors and may be used to establish the accuracy requirements for to the various input parameters.

1.4 Feasibility requirements

The feasibility describes the effort needed to accomplish a noise impact computation and , in some cases, the restrictions that reduce the possibility to carry out such computations.

The feasibility of the methods is determined by the following parameters, the availability of input parameters, the effort needed to specify the input for the calculations, the type of computer

infrastructure that is required, the computation time and memory and the effort needed for post processing of results. The feasibility requirement will limit the efforts, time and costs involving the computations. Again the feasibility requirements (or effort, time and cost limits) can be translated into an effort, time and cost budget for each of the individual components of the calculation procedures.

2 Aspects of aircraft noise modelling

To obtain balanced calculation procedures, it is important to evaluate the different aspects that determine the production of sound by aircraft and the propagation of sound. The specific features of these aspects affect both the attainable accuracy as well as the effort needed to obtain sufficiently accurate prediction procedures. These aspects both cover the input needed as well as the propagation modelling.

In Imagine the focus will be on the acoustical aspects of the noise impact modelling; i.e. on the modelling of sound as it is generated by aircrafts and propagated towards a receiver close to the ground. In particular, Imagine WP4 will not deal with the acquisition or generation of flight paths, height and speed profiles or with the estimation of thrust settings. All these data will be considered available input to the Imagine model. Preparation of such input data using different levels of available data (flight data recorder, radar tracking, operators' procedures,...) is described e.g. in ECAC.CAEC Doc.29, version 3 (2005), volume 1. Within the general methodology described in that document, Imagine WP4 only deals with the "noise calculation engine" part, not with the other aspects of aircraft noise modelling.

WP4 will also not deal with physical prediction models for the sound generated by aircraft (such as those used by manufacturers to simulate certification levels). Instead of physical simulation, the source model in Imagine shall use a database approach, relating emitted sound powers to observable operating conditions (mainly thrust setting and aircraft configuration). Actual data in the database will be derived from measurements, from certification levels or from in situ monitoring.

2.1 Input parameters

2.1.1 Source description and characterisation

For aircraft several source mechanisms are active. In the following section the focus is on commercial jet aircraft, being the most important source of aircraft noise in the community. For commercial jet aircraft the main sources are, the fan, the jet and the non-propulsive noise (or airframe noise). The relative importance of these sources depends on the phase of the flight and the airframe-engine combination (see Figure 1, based on data from [9]).

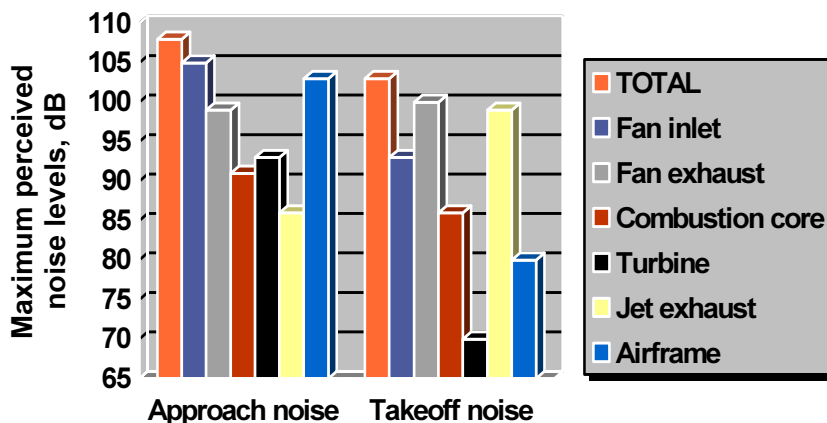


Figure 1 - The relative importance of different sound sources to the total perceived noise

Each of these sources has its own distinct sound power spectrum and directivity. For the isolated sources, (semi)-empirical prediction models are available and are used by aircraft industry for evaluation purposes. However, an approach that is used in Harmonoise [2] in a number of cases, that differentiates between the modelling in the immediate vicinity of the sources to evaluate the effects of shielding, reflection and diffraction by e.g. shielding measures, or parts of the object itself, and the modelling in the region outside this vicinity, is probably not feasible for aircraft sound sources. The reason is that the dominant sources are of an aero-acoustic nature. Hence, apart from geometrical effects such as shielding and reflection by the sound source itself, the installation effects affect the sound generating mechanisms themselves. Examples are the effect of the flap and the wing down wash on jet noise and the reflection of the fan noise by the wing. Most installation effects are not yet understood very well [3]. Although quite some research into these topics is being executed at the moment, it is not envisaged that in the near future aero-acoustic modelling techniques will have evolved to such an extent that these installation effects can be predicted to a sufficiently accurate level and/or within acceptable computation times. Thus, the distinction between the modelling of the source region and the region outside the immediate vicinity of the source appears not feasible.

Instead of differentiating between the region near the source and well away from the source in modelling the sound propagation, all diffraction, shielding and reflection effects of geometric details of the aircraft should be taken into account as an intrinsic source property and determined using the pass-by noise measurements. This approach is comparable to the approach used in Harmonoise for tyre-road noise where the tyre-road interface is considered an intrinsic source property.

2.1.1.1 Source strength

Traditionally aircraft noise is determined using pass-by measurements directly under the flight path and at a fixed lateral distance at reference conditions, constant flight speed and flat terrain. The results of these measurements are translated into noise power-distance data by taking into account effects of distance and atmospheric absorption.

Traditionally (i.e. in CPA or segmentation models like INM), aircraft noise source strength is determined using Noise-Power-Distance relationships (so-called NPDs). These give, for an aircraft flying along an infinite straight flight path at constant speed – and in a specific configuration - noise event level versus slant distance as a function of engine power setting. NPDs are derived from pass-by noise measurements (usually for the position under the flight path), notably carried out for noise certification purpose. NPD's are normalized for a reference atmosphere, and speed, and are valid for soft ground only. Currently NPD's are used to lookup and interpolate noise levels using four entries: type of noise indicator (SEL, $L_{A,max}$ PNLT, EPNL), distance, (net corrected) engine thrust and type of operation (Departure or Arrival). However, characterisation of the sound production, for a number of flight phases, by power settings alone is incomplete. Especially, owing to the increasing importance of the non-propulsive noise, apart from the power settings, airspeed, flap settings and gear position are becoming increasingly important as characterisation parameters. As a result, using current NPD relationships may lead to erroneous estimations of noise perceived on the ground for specific phases of flight where the engine noise component is not dominant (for instance approach segments flown with idle thrust setting). It has to be noted, however, that NPD sets may be provided for different flight configurations to reflect noise-significant changes in the aircraft state not captured by power setting alone, e.g., approach and departure conditions.

The use of NPD's originates from the 1970's when fully detailed simulations of the aircraft noise impact were prohibited by the available computing power. Using an "integrated" quantity like the NPD was a feasible solution. This approach has serious limitations:

- Separate tables are needed for each specific noise indicator (e.g. L_{max} , L_{eq} , L_{pE});
- Separate tables are needed for each specific frequency weighting;
- Only valid for specific atmospheric conditions (air absorption is included);
- Only valid for a receiver position at 1,2 m above a specific (very soft) type of ground.

Therefore, NPD's must be "recalculated" whenever one of these conditions changes. As recalculation can only be performed correctly when all basic spectral information is available, in many cases this recalculation may introduce errors or, at least, increase the uncertainties of the predicted values. Therefore it will be advantageous for the development of more physically based computation methods to drop integrated quantities like NPD and to develop prediction methods based on physically relevant quantities.

In addition to the previous considerations one should be aware that in principle the sound source characteristics change with ambient pressure and thus with altitude. Therefore it should be evaluated whether the flight altitude should be taken into account as a source characterisation parameter, and if so, for which accuracy requirements. Some guidance to this end is given in the latest version of the Environmental Technical Manual of ICAO Annex 16 [10].

2.1.1.2 Source directivity

In reality the sound radiation characteristics of aircraft vary both in frequency and level during a fly by owing to a number of reasons:

- The individual sound generating mechanisms each have a distinct frequency dependent directivity, e.g. for high frequencies, jet noise exhibits a 'zone of silence' in downstream direction while for low frequencies the radiation is maximal in this direction.
- Owing to the directivity of the individual sound generating mechanisms, the different sound component contributions dominate the sound radiation in different directions, see Figure 2. Furthermore, as indicated by Figure 1, the relative importance of the different sources depends on the flight phase and the engine-airframe combination.
- The Doppler effect changing the frequency content of the signal and the energy concentration, as received on the ground.

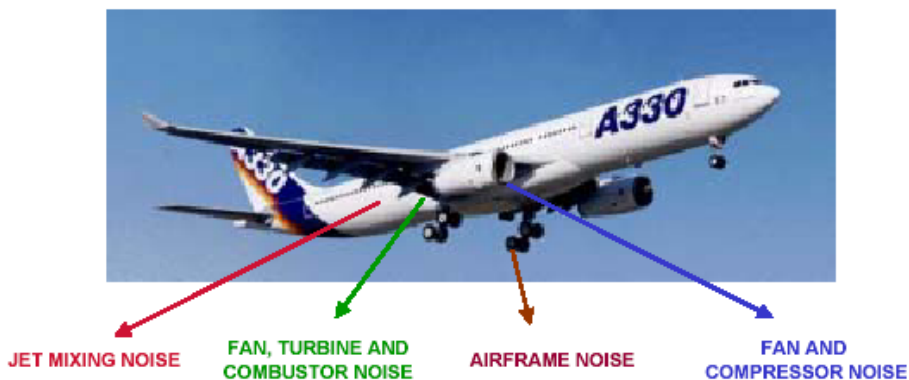


Figure 2 – An indication of the main direction of sound radiation for the different sound component contributions

Thus, in contrast to the commonly used procedures, the directivity of aircraft will be asymmetric.

It may be expected that the asymmetry in the directivity will change in the future. The effect of modifications like chevrons, scarfed inlets, etc is partially based on adapting the directivity of the sound radiation. It is expected that a number of these modifications will become available in the coming years.

The assessment and the evaluation of the directivity of a moving source is generally a complex problem because directivity functions may be described in various co-ordinate systems: fixed to the aircraft, fixed to the flight track or fixed to the ground.

Directivity and spectral content measured from static tests on the ground will be altered when the aircraft is in the air, mainly due to the influence of the forward speed and by the air flowing around the moving obstacle. The Doppler effect changing the frequency content of the signal and the distribution of energy in time will further transform the true radiated directivity (as measured in a co-ordinate system moving with the source) into an apparent directivity as observed at a fixed receiver on the ground.

Removing Doppler effects from recorded sound levels is a possible technique but requires very complex procedures (and lots of signal processing). Moreover, the accuracy of the outcome is mainly determined by the precise and synchronized assessment of the position and the speed of the moving source. Because of this complexity, it seems more realistic to describe the source by its apparent directivity as measured at a fixed receiver position on the ground, as is done for noise certification.

2.1.1.3 Source Position

In contrast to the type of sound source handled in Harmonoise, the 3-D position of the aircraft as sound source is highly variable. In first place, the aircraft follows a predefined flight path or procedure, intended to comply with operational constraints, like safety, airspace capacity, noise impact limitations etc. However, for a number of reasons, the flight path actually flown by the aircraft deviates from the theoretical flight path (when such a theoretical flight path is completely defined, which is not always the case, notably in the case of radar vectoring for approach). Often these deviations are related to operational conditions, including: meteorological conditions, aircraft operational take-off weight, power setting management by the crew (rated or flex (de-rated) thrust; airline-specific parameter). For example, the climbing performance of aircraft will be affected by wind conditions. Thus, in general the actual flight path of individual aircraft cannot be predicted with an infinite accuracy.

For noise mapping purposes the actually flown flight paths (and aircraft positions as a function of time) may be obtained from radar track information. In case of predictive computations a deterministic assessment may be used in which the theoretical flight paths are adapted on the basis of information concerning the actual take-off mass and actual or seasonal weather information. As an alternative one may use statistical flight path distribution data from the past and use these to predict the future noise impact in a statistically reliable way. A higher degree of accuracy can be reached by using seasonal statistics instead of yearly statistics.

2.2 Propagation

An inhomogeneous distribution of wind and temperature may affect the propagation of sound through the atmosphere considerably. To account for this, the Harmonoise models explicitly take the effect of wind and temperature into account.

One of the essential differences between sound produced by aircraft and sound produced by the land-based sources considered in Harmonoise is the source position. Apart from the initial phase during take off and the final phase during landing, for aircraft noise, the source is located well above the receiver position.

One consequence is that the description of the atmosphere at high altitudes is less well defined than at low altitudes. For example, the use of the logarithmic / linear wind distribution (used in Harmonoise) is questionable.

An important consequence of the difference in the position is a less complicated influence of wind and temperature gradients on the sound propagation. Using calculation schemes such as PE it can be shown that for a large part of the flight, the physics of the propagation is relatively simple. Therefore for the larger part of the landing and take-off phase a two-ray propagation model applies [4,5]. Hence, for a large part of the flight path, the propagation model can be considerably simpler than the Harmonoise reference propagation model, such as geometric ray theory based models.

Ray theory-based prediction schemes, such as the Nord2000 scheme [6], are capable of predicting the propagation for large part of the flight with a high level of accuracy and are even capable of taking effects of inhomogeneous sound speed gradients into account. However, for low aircraft altitudes and for large propagation distances, owing to the erratic behaviour near caustics, ray models are less reliable.

In the Harmonoise Reference model for this reason, the PE method is used for the whole propagation area except in the immediate vicinity of the source. However, while the PE method is superior in predicting the effect of meteorology, the standard PE approximation is not valid for high elevation angles. Although there are possibilities to increase the range of validity of the PE method, limitations of the application range will remain. It is therefore proposed for the aircraft noise Reference model to develop a combined approach in which the propagation for lower elevation angles will be treated with the PE model, while the higher elevation angles will be treated with a generalised ray model approach or with the Fast Fourier Program (FFP). The transition between the two models is a point of special attention.

Presumably the aircraft noise Engineering model will be based on a ray model methodology for all elevation angles, in line with the analytical approach followed in the Harmonoise Engineering model. The problems with caustics and multiple reflections on the ground, mentioned above, will have to be solved.

2.2.1 Topography

Generally the topography between the source position and the receiver position affects the propagation attenuation between source and receiver. Firstly, depending on the source height and meteorological condition, large-scale elements such as hills but also the level of ground

absorption may affect excess attenuation very strongly. Apart from that, small-scale topography, e.g. shielding and reflection by buildings in build-up areas, may affect the ‘receiver’ directivity.

2.3 Levels of detail and accuracy in input data and calculation procedures

The above sections indicate that the physics of sound generation, radiation and propagation can be approximated to several levels of detail, depending on the total effort invested in both the preparation of the input data and the computation. The next sections give an overview of the different levels theoretically possible and the consequences for the amount of work involved in attaining these levels of detail and the accuracy of the calculation procedures.

2.3.1 Input data

Parameter	Effort and consequences for accuracy
<i>Source directivity</i>	
<ul style="list-style-type: none"> ▪ Spherical symmetry 	<ul style="list-style-type: none"> ▪ Common practice in many noise predictions models.
<ul style="list-style-type: none"> ▪ Prototypal non-spherical directivity functions 	<ul style="list-style-type: none"> ▪ Used in e.g. the INM model (90 deg dipole directivity)
<ul style="list-style-type: none"> ▪ Axisymmetric symmetry <ul style="list-style-type: none"> ○ Mean (parameterised) directivity for all aircraft ○ Directivity pattern for each individual aircraft (class) 	<ul style="list-style-type: none"> ▪ Used in the e.g. FLULA model, when combined with a point source propagation model no additional penalty in computational costs ▪ Especially spectral information on directivity is scarce ▪ Essential step to increase the accuracy
<ul style="list-style-type: none"> ▪ Lateral directivity 	<ul style="list-style-type: none"> ▪ Directivity is function of lateral radiation angle; relevance endorsed by Airmod group ▪ Exhibits left-right symmetry for jet and prop aircraft
<ul style="list-style-type: none"> ▪ No symmetry <ul style="list-style-type: none"> ○ Mean (parameterised) directivity for all aircraft ○ Directivity pattern for each individual aircraft (class) 	<ul style="list-style-type: none"> ▪ No additional computation costs compared to the above approach ▪ More intensive with regards to input preparation ▪ At this moment important for helicopters ▪ Importance will increase, since aircraft manufacturers start to ‘exploit’ directivity as noise reducing measure ▪ Data is almost absent
<i>Source strength characterization</i>	
<ul style="list-style-type: none"> ▪ Characterisation of the total source strength on engine power settings for each individual aircraft class and flight condition (flap settings, landing gear, etc..) 	<ul style="list-style-type: none"> ▪ Recording of power settings is common practice, but the availability of data may be limited ▪ Recording of airframe parameters is essential when an accuracy of the source strength in the landing phase better than 3 dB has to be achieved
<ul style="list-style-type: none"> ▪ Separate characterisation of the source 	<ul style="list-style-type: none"> ▪ When a point source propagation model is

strength of the individual components on engine power and airspeed	<p>used no principal objections against separate characterisation</p> <ul style="list-style-type: none"> ▪ Though semi-empirical models exist for the description of the various noise sources, no specific data is available ▪ Not feasible the coming years, due to the large amount of detailed data required.
<i>Source position</i>	
<ul style="list-style-type: none"> ▪ Single flight path 	<ul style="list-style-type: none"> ▪ Basic approach in some noise prediction schemes
<ul style="list-style-type: none"> ▪ Statistical flight path distribution with a finite width 	<ul style="list-style-type: none"> ▪ Common practice in many noise prediction models, e.g. ECAC Doc 29, Vol. 2 ▪ Requires a non-recurring analysis of the flight movements ▪ Apart from that no additional effort needed ▪ Not suited for large departures from the 'official' flight path
<ul style="list-style-type: none"> ▪ Approximation of track dispersion by effective receiver directivity (see section 3.2) 	<ul style="list-style-type: none"> ▪ No example of this type of model available ▪ Reduces computational effort ▪ Elaboration of method necessary
<ul style="list-style-type: none"> ▪ Simulated or measured flight paths of each individual aircraft 	<ul style="list-style-type: none"> ▪ Data is often available from noise monitoring systems, through airport authorities ▪ Requires additional effort, both in data preparation and calculations ▪ Able to capture large departures from the nominal flight paths
<i>Meteorological conditions</i>	
<ul style="list-style-type: none"> ▪ No (direct) input regarding meteorological conditions 	<ul style="list-style-type: none"> ▪ Common practice for noise predictions ▪ Reference meteorological conditions are assumed in commonly used NPD tables ▪ Meteorological influence on runway use is always taken into account
<ul style="list-style-type: none"> ▪ Meteorological conditions averaged over airport surroundings and time periods 	<ul style="list-style-type: none"> ▪ Data is available ▪ Needs a non-recurring effort to analyse the effect of meteorology on sound propagation
<ul style="list-style-type: none"> ▪ Detailed time accurate description of the meteorological conditions (for example based on a micrometeorological model) 	<ul style="list-style-type: none"> ▪ Large recurring effort needed for preparation of input data ▪ Considerable recurring computations costs ▪ Gain in accuracy compared to 'statistical' models not clear
<i>Topography</i>	
<ul style="list-style-type: none"> ▪ No specific topography taken into account 	<ul style="list-style-type: none"> ▪ Common practice for noise predictions ▪ Models assume flat landscape around airport
<ul style="list-style-type: none"> ▪ Description of only the large-scale topography (hills, large water surfaces, global description of impedance) 	<ul style="list-style-type: none"> ▪ Essential step to increase accuracy ▪ Requires at least ray-based propagation models

<ul style="list-style-type: none"> ▪ Description including a statistical average shielding/reflection of small-scale details such as buildings 	<ul style="list-style-type: none"> ▪ Requires a non-recurring analysis of the airport surroundings ▪ Analysis is needed to evaluate when this effect is significant
<ul style="list-style-type: none"> ▪ Description including deterministic shielding/reflection of small-scale details such as buildings 	<ul style="list-style-type: none"> ▪ Requires a large recurring computational effort ▪ Large non-recurring effort in data preparation ▪ Not feasible for engineering method, maybe feasible for reference method

2.3.2 Propagation modelling

Parameter	Effort and consequences for accuracy
<ul style="list-style-type: none"> ▪ Based on Noise Power Distance Tables, line segmentation, Noise Fractions and Lateral Attenuation 	<ul style="list-style-type: none"> ▪ Common practice for noise predictions ▪ Lateral Attenuation accounts for (lateral) directivity effects caused by shielding (air-to-air component) and ground reflections (air-to-ground component)
<ul style="list-style-type: none"> ▪ Improved method based on NPD tables and line segmentation 	<ul style="list-style-type: none"> ▪ Separation of directivity and ground effects ▪ Introduction of more realistic directivity function
<ul style="list-style-type: none"> ▪ Based on point source simulation using: 	<ul style="list-style-type: none"> ▪ Allows for: <ul style="list-style-type: none"> ○ Arbitrarily flight paths ○ Calculations of all A-weighted metrics ○ Flexible use of propagation models ▪ Requires: <ul style="list-style-type: none"> ○ No lateral attenuation ○ No level correction for speed ○ Directivity characteristic for each flight operation
<p>→ Transfer function based on geometrical ray tracing</p>	<ul style="list-style-type: none"> ▪ Computationally feasible ▪ Refraction effects can be taken into account to a limited level <ul style="list-style-type: none"> ○ Requires meteorological data: increased effort in input preparation
<p>→ PE based transfer functions (for several atmospheric classes)</p>	<ul style="list-style-type: none"> ▪ Essential for accurate predictions for low aircraft altitudes <ul style="list-style-type: none"> ○ Requires meteorological data: increased effort in input preparation

3 Base line of the Imagine prediction models

The methodology followed in Imagine is similar to the Harmonoise methodology: i.e. using an Engineering method and Reference method. The Reference method is aimed at 'special conditions' and when extra accuracy is required, the Engineering method is aimed at 'standard conditions' and 'routine' conditions.

In the following a description will be given of the modelling approach that has been followed in the Harmonoise project.

3.1 Description of the Harmonoise Reference model

For the modelling methodology in the Harmonoise Reference model and the incorporation of the meteorological influences the following three assumptions have been employed:

1. The variability of atmospheric changes will always be slow in comparison to the duration of the propagation of sound;
2. Although the detailed characteristics of the propagation path are continuously changing due to atmospheric changes, it is permissible to describe the changes in discrete time steps of short duration (15 – 30 minutes) and to assume that the real short term average sound pressure level does not deviate significantly from a computed average sound pressure level that is based on short term average source emission characteristics and short term average propagation conditions;
3. For long term (day, week, month, year) averaging of sound pressure levels it is permissible to replace the actual infinite variation of atmospheric profiles by a limited set of representative atmospheric profiles (e.g. 25 logarithmic – linear profiles), each with a statistical weight factor that depends on time and propagation direction.

The central element of the Harmonoise Reference model is the modelling block [2]. The modelling block generates both long-term average levels L_{den} & L_{night} and short-term levels L_m based on four categories of input parameters: geometry, emission, atmosphere, and acoustical properties of surfaces.

Both the long-term average levels L_{den} & L_{night} and short-term levels L_m are derived from partial levels L_{ijm} . The partial level L_{ijm} is the level contribution from point source i through propagation plane j , for atmospheric state m . Summation over all point sources i and propagation planes j yields short-term levels L_m , and summation over all atmospheric states m yields the output levels L_{den} and L_{night} .

The partial level L_{ijm} is calculated from:

- the sound power spectrum of point source i , taking into account directivity
- geometrical attenuation corresponding to spherical spreading of sound,
- atmospheric attenuation,
- the relative level $L_{rel,ijm}$. (= level relative to free field propagation; equal to minus excess attenuation)

For the calculation of the relative level $L_{rel,ijm}$ two regions in the propagation plane are distinguished: the close proximity of the source or source region and the region outside this source region.

The source region comprises the source itself and noise reducing measures such as barriers. For prediction of the propagation in the source region, the details of the source region and noise reducing measures are taken into account. Thus, depending on the properties and geometry of the source, SRAY (Straight Ray tracing), BEM (Boundary Elements), or PE (Parabolic Equation) calculation schemes are required. At the outer edge of the source region the output of these calculation schemes is coupled to the large-distance propagation models.

The propagation outside the source region is modelled using PE-type calculation schemes. Crank-Nicholson PE [CNPE] or Green's Function PE [GFPE] for high angles is used for flat ground, while Generalized Terrain PE [GTPE] is used for non-flat terrain. Screening and reflections may be calculated with PE using a Kirchhoff approximation.

An essential element of the model is the representation of the atmosphere. A set of sound speed distributions is defined, with statistical weights (probabilities of occurrence) that depend on local climatological data, time of the day, and on the sound propagation direction. The definition of the set of sound speed profiles (classification) is based on an acoustical sensitivity analysis.

The model requires a CFD tool for the calculation of range-dependent profiles in situations where noise barriers or terrain unevenness constitute obstacles for the wind flow.

Another essential element of the model is the representation of absorbing surfaces. The material type selected from the catalogue in the input block determines the impedance model and parameters that are used for this representation. An effective impedance may account for small-scale surface roughness.

Atmospheric turbulence can be taken into account either by explicit simulation with randomised sound speed profiles within PE or by adding some amount of incoherently scattered sound energy, which in practice results in using a lower limit for the relative level $L_{rel,ijm}$ (both in sound shadows and in interference minima). The latter option is preferred because of computational efficiency, and drawbacks of the use of a random number generator in a noise prediction model.

The model is able to handle various types of complex noise barriers, such as barriers with a T-top. This may require the use of 'external data' for the performance of these barriers, either obtained from measurements or from dedicated simulations. Application of the external data requires an algorithm that extrapolates the data to other receiver positions, atmospheric conditions, etc.

The computational effort of BEM and PE increases considerably with frequency. An approximate approach for the highest frequency is inevitable. A possible approach is to keep the relative level $L_{rel,ijm}$ constant above a frequency that depends on the situation.

3.2 Application to Imagine (Reference method)

Base line of the method is chosen similar to the method used by Harmonoise, i.e. deriving long-term average levels such as L_{den} & L_{night} from partial levels L_{ijm} .

To allow maximum flexibility with respect to the use of directivity models, propagation models, and averaging procedures, analogous to the FLULA prediction model, see for example [7], these partial levels will be based on the concept of a point source moving along a flight path.

To construct long-term levels, several options are open:

- The summation over the aircraft movements can be performed at the receiver position using a fully deterministic approach for the propagation from the source positions to the receiver. Summation of the resulting levels at the receiver position taking retarded time into account yields a level-time history at the receiver position for every flight event. When full detail is used in the description of the aircraft as source, and full detail used in propagation modelling, this requires a large effort in describing the necessary input parameters (such as a detailed description of the atmospheric state, details of the topography near the receiver, etc...) and when advanced propagation models are used, this is computationally relatively expensive. During the validation of the Harmonoise Reference propagation model it was established that even with meteorological measurements on site it was not possible to calculate the full time history of the noise impact of a motorway at larger distances (> 500 m) in close agreement with measured data. Apparently the variation in atmospheric conditions along the propagation path cannot be assessed with sufficient accuracy to enable an accurate prediction of the short term noise impact at larger distances. This would require highly detailed meteorological input data and the use of an advanced meteorological simulation model. Such an approach is not feasible for noise mapping purposes or statutory noise impact computations. The long term average noise impact, however, could be predicted within a narrow band of deviations from the measured results. Therefore it is advised to limit the effort of input data acquisition and to employ the advantages of time and event averaging in achieving a high accuracy of the computed long term noise indicators.
- Instead of a fully deterministic description of the individual events and subsequent summation, part of the summation can be captured in statistical models. These statistical models can take the effect of 'rapid' temporal and spatial variations in the atmospheric state into account, variations on the average flight paths, and local (spatial) variations in the topography near the receiver.
 - Averaging over statistical variations in the temporal and spatial atmospheric state, thus effectively reducing the number of atmospheric states taken into account. However, at present, the knowledge needed to construct such a statistical model is lacking.
 - The effect of variations in the flight path might be taken into account by introducing an effective receiver directivity. Though, in principle this approach seems possible, at present both the implementation details of such a model and the revenues are not yet clear. It is to be expected that a reduction of computational effort could be achieved by representing the average effects of track dispersion in the form of a receiver directivity. This approach seems more relevant for an engineering model than for a reference model where maximum accuracy gets a higher priority than computation efficiency.
 - The effect of small-scale details in topography can be taken into account by introducing effective receiver directivity.

Clearly, the above effects are not independent, e.g. atmospheric variations will affect the generation and propagation of sound and the level of variation of the flight paths, the averaging procedures should take these dependencies into account. Long-term levels are obtained by summing the contributions from the flight events assuming a standard flight path, a limited number of atmospheric states and a limited number of topography classes. Thus the amount of

input data that is required is smaller and the computation effort is less than a full deterministic approach, especially when basic propagation models are used.

3.3 Base-line reference model

- Aircraft is considered as a point source. In addition to this the trajectory flown by the aircraft will be modelled as a series of point sources in which each point source represents the integrated sound power over a flight path segment and is positioned in the middle of the segment. The lengths of the segments correspond to the distances travelled during the time intervals that are used for the SEL-calculation.
- Construction of long-term averages based on
 - Actual flight paths (based on simulation/radar data)
 - Limited number of atmospheric states
 - The number of atmospheric states and the statistical 'width' of these states based on Harmonoise results and optional sensitivity study
 - Option: developing a model for effect of details in topography by an effective receiver directivity and additional absorption
- Input data
 - Source description
 - Based on the following flight parameters:
 - Appropriate estimate of engine thrust setting
 - For landing phase:
 - Flap settings, Landing gear settings
 - Effect of airspeed on source strength
 - Taking directivity into account
 - 2D vs. 3D description of (spectral) directivity in 1/3 octave bands depending on aircraft class
 - Either based on parameterised directivities, (when accuracy is sufficient or when measured directivity is lacking) or measured directivities
 - Measurement technique for directivity and parameterised directivity model based on [8]
 - 3D directivity measurement based on techniques used for Helicopters (e.g as performed by Qinetiq)
 - Meteorology
 - If available: meteorological data of airport (wind speed and direction at standardised height, temperature, temperature gradient, visual observation of cloud cover)
 - Divided into a limited number of states (see Construction of long-term averages)
 - Alternative 1: Observations from nearby meteorological towers [temperature and wind speed and direction measured at different heights, (thermal flux if available)]
 - Alternative 2: On site measurements with an ultra sound 3D wind flow meter that enable direct assessment of important parameters like the Monin-Obukhov-length, the temperature and the wind speed friction parameters (on condition of flat terrain and stable meteorological conditions)
 - Topography

- Large-scale topographic elements fully taken into account
 - Terrain profile, roughness height, etc...
 - Ground impedance/flow resistivity (based on standardised values for a limited number of ground types)
- Small-scale elements taken into account by 'statistical' description
 - Effective receiver directivity and additional absorption
 - Required data: position and height of scattering objects, the average object density and average scattering cross section, mean absorption coefficient of the scattering objects
 - The model for such a receiver directivity is not yet available
- Propagation model
 - Depending on source position a different propagation model will be used:
 - For low aircraft altitudes, the propagation will be modelled using a PE propagation model
 - GTPE can be used for non-flat terrain
 - For higher altitudes, where a two-ray approach is valid either:
 - A geometrical ray approach will be used.
 - For the transition between the two approaches a dedicated model needs to be developed.
 - An extended PE model will be used, that allows high elevation angles
 - No model for the coupling between the low altitude model and high altitude model is needed.
 - An FFP model will be used
 - In a layered atmosphere without range dependent effects the FFP model may be suitable.
 - A finite number of meteorological states will be taken into account, taking small statistical variations in the temporal and spatial atmospheric state into account (see Construction of long-term averages)

3.4 Description of the Harmonoise Engineering model

The base-line engineering model differs from the reference model in the sense that the most complex components of the prediction scheme have been replaced by less time consuming ones and that it allows for different levels of simplification of the required input data. Whereas the reference model uses numerical methods to simulate sound propagation, the engineering model builds on analytical and heuristic formulae. Moreover, the underlying data model will be more in line with the level of detail and the geometrical complexity that can be expected in noise mapping projects.

The Harmonoise engineering model does not provide a unique model for the prediction of road and railway noise but rather a modular "set" of "building blocks" covering the following aspects of sound production and propagation:

- An individual vehicle is modelled in terms of a set of equivalent point sources. These point sources are physically described in terms of sound power and directivity, which, in turn, are related to relevant sound generating mechanisms (road/tyre or wheel/track interaction, engine and exhaust noise, aerodynamic noise,...).

- Sound emission of each sound generating mechanism is, as far as possible, expressed as a function of measurable characteristics of the vehicle and the infrastructure (track and wheel roughness, road surface temperature,...) and operating conditions (speed, acceleration, engine load, breaking settings,...).
- For the prediction of long term integrated sound levels, the sound emission of a large number of individual vehicles is combined together and expressed as an equivalent sound power level per unit length along the vehicles' trajectories. This combination may account for the statistical variations of the vehicle characteristics, operating conditions and meteorological parameters. Depending on the level of accuracy one wants to obtain, input data may be accounted for using either larger or more detailed classifications. As an outcome of this process, the flow of vehicles is assimilated to a limited set of "source lines" parallel to each driving lane and/or track. In principle, the sources do not need to be straight lines, not even to be subdivided in straight segments.
- The resulting sound level at any given receiver position is expressed as a line integral along the source line. Numerical implementation requires the source lines to be broken down in smaller segments. The contributions of segment are calculated and summed up. Depending on preferred technological choices different segmentation/integration methods may be used by different software providers when implementing the Harmonoise methods in their respective software products, thus allowing for different compromises between acceptable computational efforts and achievable accuracy.
- The propagation from each elementary segment to the chosen receiver point is thought to take place in vertical planes: the so-called *propagation planes*. Different propagation planes may be constructed to represent direct propagation from the source to the receiver, sound reflected from vertical obstacles and sound diffracted around vertical edges (corners of buildings, sharp edges of screens). It is obvious that this approach does not account for the full three-dimensional complexity of sound propagation. However this approximation is generally found sufficiently accurate for most outdoor noise problems where propagation distances are mostly much larger than the average height of the sound rays above the ground. On the other hand, this "2D½" approach greatly reduced the required computational efforts, making the methods suitable even for use in large noise mapping projects.
- In each propagation plane, the excess attenuation of sound is estimated taking into account the terrain profile, the presence of blocking obstacles (screens, earth walls, hills, buildings...) and the nature of the ground... In more physical terms, excess attenuation is a combination of reflections on the ground and diffraction by blocking obstacles. Specific meteorological conditions are taken into account by means of a constant gradient of the equivalent sound speed (representing atmospheric refraction) and a variable amount of coherency loss (due to atmospheric turbulence and scattering).
- Yearly averaged L_{den} and L_{night} values are obtained by combining together sound levels under a limited set of representative meteorological conditions taking into account the relative frequency of occurrence of such conditions during a climatologic "normal" year.

Unlike the reference model, the engineering model is not intended to take into account the full complexity of propagation through an inhomogeneous atmosphere. The aim of the engineering model is to predict the sound propagation under a limited set of prototypical meteorological conditions (e.g. up/down wind, with/without thermal inversion). Within the Harmonoise project, prototypical meteorological conditions were related to a single parameter used as input into the propagation model i.e. the equivalent constant sound speed gradient.

Noise predictions under specific meteorological conditions may be carried out by relating standard weather observations to values of this single parameter. Long-term averaged noise indicators can then be obtained from climatologic relevant statistics of such meteorological

conditions; e.g. for validation purposes, the Harmonoise project used 8 wind directions, 3 wind speeds and 5 stability classes, resulting in 120 calculations.

For the time being, the linking of meteorological data to equivalent linear sound speed gradients is based on a highly simplified model of the lower atmosphere, valid only over sufficient large open areas. As it is, the model ignores most effects of local topography and the presence of obstacles (e.g. buildings, screens, forests). This problem was also recognised in Imagine WP7 and some heuristic corrections have been proposed there.

Long-time averaging can probably be made more efficient by means of a classification of the meteorological conditions according to the single parameter (see Figure 3) . First experiments tend to show that 3 to 5 propagation classes may be sufficient to predict the yearly averaged noise indicators L_{den} and L_{night} without loss of accuracy but due to lack of time, this was not further investigated within the Harmonoise project. Neither is further work on this topic mentioned in the description of work of the Imagine project.

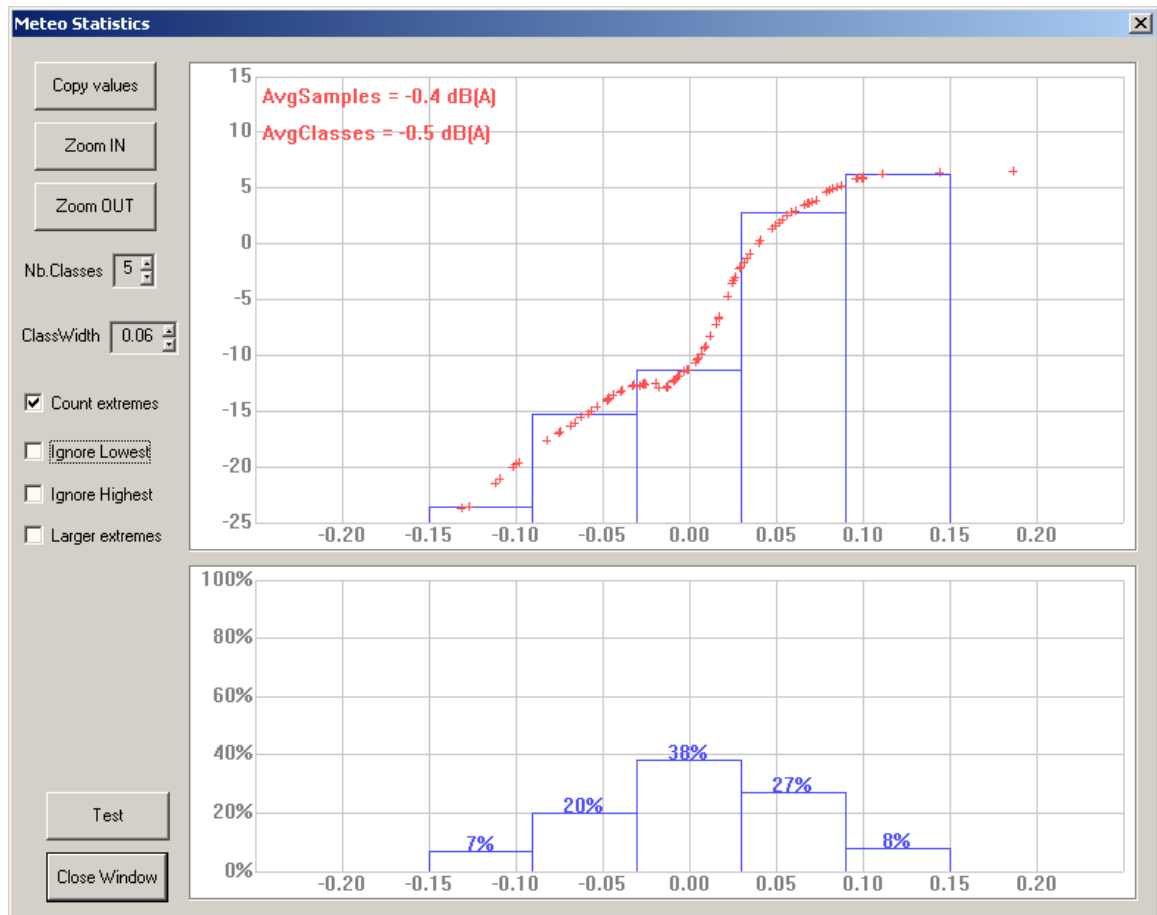


Figure 3 - Variation of sound level as a function of equivalent linear sound speed gradient. The long-term averaged sound levels were calculated using 1) the average over 100 randomly generated samples and 2) using 5 classes with a width of 0.06 s^{-1} each. The frequency of occurrence of samples in each class is shown in the graph below

3.5 Application to aircraft noise

Although the engineering model uses a “simplified” propagation model, it may share its input data and source modelling with the reference model. However, even using such detailed input data it will not be able to predict individual events at the same level of accuracy as the reference models.

E.g. the engineering model may not distinguish between downwind conditions and thermal inversions if both lead to identical values for the single parameter. Results obtained with the engineering model must always be interpreted as representative values over larger sets of “similar” meteorological condition, where similar must be interpreted as “leading to similar acoustical results”.

In order to comply with the generic modelling scheme of Harmonoise, aircraft sound sources shall be described in terms of equivalent source lines. Each of these source lines will then be described in terms of spectral sound power output and directivity. As for the other source line models in Harmonoise, the sound power per unit length will be directly related to the sound power for each “vehicle” operating on a specific flight path and the speed at which it operates. The actual sound power associated with the moving “vehicle” will be determined in terms of aircraft categories, number of operations, thrust setting and aircraft configuration. Special attention shall be paid to the fact that sound power and speed may vary along the trajectories (e.g. acceleration and deceleration cannot be ignored for take-off and landing stages).

Considering the reduced sensitivity of the engineering model with respect to individual events, it is questionable whether the engineering model should share the full complexity of the reference source models. When carrying out noise mapping projects using the engineering model, the effort needed for the preparation of the input data is usually large compared to the computation effort. It may therefore be useful to consider simplifications of the source description, as compared to the source description of the reference model, in order to make the engineering prediction model more pragmatic to use.

Basically, the Reference Model considers each flight operation an individual event and averaging is carried out explicitly. In order to increase efficiency, the Engineering Model tends to predict averaged values directly for larger sets of “similar” events. In this sense, some guidance must be given as to the definition of “similar” events that can be combined into a single source line. Simplification of the input data may include:

- Grouping of flight paths per aircraft category, with or without sub-tracks to simulate the lateral and vertical dispersion with respect to the base flight paths.
- Grouping of aircrafts in larger categories
- Grouping of aircrafts on similar flight paths regardless of aircraft types

Such simplifications can easily be checked by means of numerical experiments without needs for actual data collection. In order to cover the full range of variability of the input data it is preferable to rely on the higher sensitivity of the Reference Model for the prediction of the individual events.

More advanced (and highly efficient) modelling solutions may be considered by taking into account the almost statistical distribution of actual flight paths. More flexible ATM rules introduced in the past decennia make it more difficult to assign aircraft to ground tracks and to relate actual operations to prototypical procedure. This greatly reduced the accuracy (and public acceptance) of the “deterministic” prediction model intrinsically based on an accurate description of actual or supposed flight paths and operating conditions. A work around in deterministic models is to introduce higher dispersions (and more sub-tracks), leading to increased computational efforts.

For the prediction of long tem averaged noise indicators, a more statistical description may be more appropriate, more efficient and more in accordance to the unpredictable nature of the actual

problem. This may be achieved by combining together larger sets of flight paths into a single volume source. The estimation of 3D sound power distributions is not more complex than in the deterministic source line model. The segmentation and propagation models can be adapted to take into account such extended sources in an efficient and accurate way.

3.6 Base-line engineering model

- Construction of long-term averages based on
 - A set of representative flight paths (based on simulation/radar data)
 - A statistical distribution of aircraft operations over the different flight paths
 - A limited number of representative meteorological conditions

The modelling of flight paths and their statistical distribution will not be a subject in the engineering model development. These parts of the method may be copied from current aircraft noise prediction models and may be adapted to the needs of the users.
- Input data
 - Source description
 - Based on the following flight parameters:
 - Estimate of speed along the flight path
 - Appropriate estimate of engine thrust setting
 - For landing phase:
 - Flap settings, Landing gear settings
 - Effect of airspeed on source strength
 - Taking directivity into account
 - Based on parameterised directivities
 - Meteorology
 - Described by a single parameter (equivalent constant gradient)
 - Simplified model relating actual meteorological conditions to values of the single parameter
 - Topography
 - Large-scale topological elements fully taken into account
 - Terrain profile taken into account by a number of straight-line profiles (analogous to the Nord2000 procedure)
 - Ground impedance/resistivity (based on standardised values for a limited number of ground types)
- Propagation model
 - Based on source line segmentation and integration
 - Based on a ray-tracing prediction scheme
 - Semi-analytic model to estimate the effects of equivalent constant sound speed gradients on the sound propagation

4 Practical implementation of base-line modelling principles

This chapter discusses a proposal for the development of noise impact modelling methods for air traffic noise in analogy with the implementation of the noise impact modelling principles in the Harmonoise project. These principles are based on a functional separation of the description of the sound emission at the source and the modelling of the propagation phenomena. The sound emission is described in terms of the sound power and its directivity. Furthermore in the description of the sound emission of road and railway vehicles a distinction between the various sound generating mechanisms was introduced.

For the modelling of sound propagation the main development was focussed on the engineering models that are intended for large scale routine applications for noise mapping purposes, while the reference model was primarily developed as a 'calibration' tool for the engineering model.

This calibration tool was intensively used during the development period, but remains available to solve future disputes about the correct noise impact values in difficult cases. The engineering model is based on (analytical) curved ray modelling, in which the meteorological influences are incorporated by a distance related ray curvature. The reference model uses an approximation of the wave equation, in which the propagation is simulated in stepwise finite difference approach.

This approach allows the input of actual meteorological profiles with arbitrary complexity.

Both models are used in combination with the same source description to yield a proper noise impact value.

The same basic philosophy will be followed for the development of air traffic noise impact models.

4.1 Aircraft sound source description

Within Imagine one single source description for aircraft sound sources will be developed. This description will be such that it may be used with different levels of detail and of accuracy. This means that for some parameters a specific or a more generalized assessment can be made. If sufficient information is available a specific value for a specific case can be used as input. If not the case a more generally estimated value can be used as a default that will result in an acceptable accuracy of the modelling output for average cases.

In this way the user can choose between ease of input data preparation or optimised accuracy, depending on the type of application.

For the first approach the basic assumption is that an aircraft will be modelled as a point source, in which the sound emission of the various sound generating mechanisms is assumed to be concentrated. In most current aircraft noise data bases no discrimination is being made between for instance engine noise and airframe noise. This means that all types of sound are summed into a single sound emission value that is normally presented as a sound (reception) level as a function of distance and of engine thrust setting (Noise–Power–Distance tables). Because of the dependency of various other parameters the tables must be produced for a large number of flight operations for each type of aircraft that uses the airspace involved in a certain noise mapping area. This leads to a vary large number of tables that are necessary to build up a complete noise emission database. In Annex A a proposal is elaborated that could lead to a different and possibly less extensive way of dealing with the complexity of aircraft sound emission. It is expected that this proposal cannot be implemented within the constraints of the Imagine project, but it could be accommodated as a future development.

For the first development of the European aircraft noise impact models the traditional approach will be followed, which means that the sound emission will be described in tables giving the sound emission for each type of aircraft and for each type of flight condition as a function of engine thrust setting. Contrary to the current practice these values will not be given as sound reception levels as a function of distance, but as sound power levels with additional information about the directivity. In view of the importance of longitudinal as well as lateral directivity the directivity will be given in a full 3D-description,

The flight conditions will be characterised by a short categorial designation and defined by a specification of input data and input-preparation data. The direct input parameters for the determination of the sound emission are:

- engine thrust setting;
- flap and slat settings;
- landing gear setting;
- radiation angle relative to the aircraft orientation

For the assessment of these input parameters the following input preparation parameters are relevant:

- take-off or landing weight;
- ground speed;
- true air speed;
- altitude;
- climb angle;
- angles of pitch, roll and yaw;
- wind speed;
- air temperature;
- air pressure.

If accuracy allows it or if proper information is lacking the above parameters may be clustered or set at a default value to produce less specific, more generic categories of flight conditions.

In general, less specific data sets may be used in combination with the Engineering propagation model (EENIMAT; see 4.4) for the purpose of estimating yearly averaged L_{DEN} values in large mapping projects (e.g. like the ones required by the END). The Reference model (RENIMAT; see 4.5) is specially suited to use the fully detailed sound emission data and will utilize its full accuracy potential only in that case. Fully detailed sound emission data combined with the Reference propagation model may be used for validation purposes (e.g. on a few receiver points corresponding to installed monitoring stations), for the assessment of uncertainties in the engineering model, for impact studies (action planning) concerning specific aircraft types and/or specific procedures. It is clear that the latter models will also require more detailed input data concerning actual flight paths, take-off masses and flight procedures.

In principle, both the Reference model and the Engineering model can handle directional sound sources, but the implementation of an aircraft as a directional point source in the Reference model requires a dedicated study.

4.2 Aircraft sound emission measurement methods

The sound emission data should apply to normal operation of aircraft in the vicinity of airports, because these are the conditions that are relevant for noise mapping purposes. As sound measurements are carried nowadays out on a regular basis around many airports, the results of

noise mapping computations should not deviate significantly from sound measurement results in order to avoid ambiguities and public questioning of computation methods.

This implies that the sound emission input data for noise mapping computations should be determined during normal aircraft operations around airports or, if they are measured under different circumstances, that they are equivalent with the data for normal operations. Two measurement methods for operations around airports have been developed: the FLULA method in Switzerland and a draft measurement regulation in the Netherlands.

The proposal is to use these two examples to develop a harmonised European method for the assessment of aircraft sound emission in normal operation. An English translation of the Dutch method will be supplied to the WP 4 team by TNO.

This harmonised European method for in field conditions should be consistent with the ICAO noise certification measurement procedures. This does not mean that the actual values resulting from the application of these two measurement procedures have to be equal. It means that both methods should give the same results within the confidence intervals caused by measurement uncertainty, if the operational conditions of the aircraft and the propagation conditions (including ground impedance and atmospheric parameters) are equal. If this equivalence can be demonstrated it may be inferred that any differences between sound emission during normal operations around airports and during noise certification measurements are caused by actually existing differences in conditions and not by discrepancies between measurement procedures.

The final deliverable of this development should be a method for sound emission measurements of aircraft under operational conditions giving results that are consistent with the results of noise certification measurements.

4.3 Conversion method for sound emission data

The future harmonised input data for noise mapping computation will be expressed as sound spectral power levels in function of the radiation direction.

Most currently available data sets of aircraft sound emission are not expressed in this way and cannot directly be used with the future harmonised noise mapping methods. Over time new data bases will be built that comply with the basic principles of the noise impact models, but for the short term the use of currently available data is essential.

Therefore a method should be developed that converts the current Noise-Power-Distance tables into Spectral Sound power-Directivity tables. Of course an exact transformation is impossible, but using some basic assumptions about generic directivity characteristics, it should be possible to convert the current datasets into the new structure, without losing too much accuracy.

When such converted data are fed back into the noise impact model and calculations are carried out under compatible propagation conditions, the results should be as close as possible to the initial values from which they were derived. The compatibility of such results is an essential step towards a large acceptance of the new methods.

4.4 Engineering European Noise Impact Model for Air Traffic (EENIMAT)

The actual noise mapping of air traffic noise will be carried out with a modified version of the Harmonise Engineering model. This model was developed and tuned for optimal accuracy and computation speed for low source positions (< 4 m) for road and railway vehicles in combination with receiver distances up to 1 km.

In mathematical terms, the engineering model described the contribution of a source line as a line integral: For numerical implementation (calculation by hand has not been considered), the source line is broken into segments corresponding to “homogeneous propagation sectors” as seen from a specific receiver position. Different sectors may be constructed to account for direct and (multiple) reflected propagation paths. In the end all contributions from all direct and reflected propagation paths are summed in order to predict the total noise level at the receiver. Whereas the construction of propagation sectors is mostly done by hand in the Reference model, it will be done automatically by software implementations of the engineering model. The Harmonoise team decided it was not possible to provide a standard segmentation algorithm.

The contribution of each segment to the sound level at receiver is expressed as:

$$L_p = L_{p,free} + \Delta L_{air} + \Delta L_{refl} + \Delta L_{excess}$$

Where $L_{p,free}$ is the free field contribution of the segment to the receiver, ΔL_{refl} includes corrections for reflections from vertical walls, ΔL_{air} accounts for atmospheric absorption and ΔL_{excess} is the excess attenuation due to diffraction and reflection on the ground.

The excess attenuation is calculated using the engineering propagation model for an equivalent point source located at the center of the segment. This approach is valid if the excess attenuation is a slowly varying function of the position along the trajectory, i.e. if the segment represents a sector with almost homogeneous propagation conditions.

Note: Within the Harmonoise project it was found save to ignore lateral diffraction around vertical edges. This assumption will be revised in Imagine WP7. The proposal worked out by WP7 is to include lateral diffraction in the ΔL_{refl} correction term and to estimate its value from 2D analysis (in the horizontal plane) of the propagation paths.

Because air absorption is a function of propagation distance it will impose further restrictions on the maximum angle of view of the segments. For ground based sound sources, segmentation is most often determined by the presence of diffracting and reflecting obstacles. In absence of such obstacles, large angle segmentation very efficiently provides accurate approximations. For aircraft noise, and as longer propagation distances are involved, the air absorption may become the dominant criterion for source allowable line source segmentation.

Existing aircraft noise models are generally classified into two extremes, called “simulation” or “segmentation” methods. The generalised integration techniques proposed by Harmonoise seem well adapted to aircraft noise while allowing for more flexible compromises between accuracy and computation effort.

The proposed segmentation / integration method seems to be well adapted to aircraft noise. Implementation details will depend on the complexity and layout of the source directivity model.

Within the Harmonoise project, the engineering propagation model has been developed and fine-tuned for source close to the ground (dominant sources for road and railway noise are located below 0.5 m) and for propagation distances up to 1000m. The extension of the model to aircraft

sources clearly will require some adaptations to include larger propagation distances and higher sources.

The basic propagation model describes sound propagation in a homogeneous atmosphere; i.e. without sound speed gradients. The model is derived from geometrical acoustics with heuristic corrections for almost grazing incidence. As the source moves up the basic assumptions of geometrical acoustics are more easily fulfilled and there seems to be little need to adapt the proposed model to these situations.

In the Harmonoise engineering model the meteorological influences were taken into account by assuming curved sound rays that are substituted by a curved ground surface. This substitution enables the computation with straight rays, which are easier to handle in case of diffraction around obstacles and of ground reflections. Simulations carried out by the ImagineWP7 team tend to show that the initial curved ground model produced by the Harmonoise project may lead to incorrect results for sources higher above ground and/or for wind speeds higher than 3 m/s. Such situations have not been validated in the Harmonoise project and the current model must be adapted and extended to give more accurate results in these situations. Some overlap with work carried out in WP7 will occur at this point.

Adaptation and fine-tuning of the engineering propagation model has already started in WP7 for typical situations occurring in industrial noise (propagation distances up to 1000 m, source heights up to 20 m) so that readily available reference models can be used to validate the proposed modifications. The task will continue in WP4 and solutions will be sought for larger propagation distances (up to ??? km) and higher sources. Modelling solutions, validation and fine-tuning will depend on the availability of the adapted Reference Model.

For sound sources near the ground, sound propagation is influenced by the atmospheric state of the lower atmosphere, below a few tenths of meters height. It is expected that the simplified meteorological classification and particularly the determination of equivalent constant gradients will require some adaptations to correctly represent the atmosphere in the higher layers. Development of the reference model will involve accurate characterisation of the atmosphere. The results of this work will provide insight and guidance for the adaptation of the engineering model.

When considering sources in higher layers of the atmosphere, temperature variations will not only result in sound speed gradients but will also affect the atmospheric absorption that can no longer be considered constant along the propagation path. Particularly, the Harmonoise deliverable D18 recommends the use of ISO 9613-1 for the estimation of atmospheric absorption whereas aircraft traditionally rely on SAE-AIR.... The ISO standard has a large range of application (up to 20 km above sea level) and annexe C provides guidelines for its application to a stratified atmosphere.

4.5 Reference European Noise Impact Model for Air Traffic (RENIMAT)

During its development the Harmonoise Engineering model was repeatedly calibrated against and tuned to the results of the Harmonoise Reference model. The latter model was primarily developed for this purpose, but may also be used as a reference in case of dispute about the correct noise impact determination, e.g. when the propagation parameters show a high degree of (physical) complexity.

The basis for the Reference model is found in the mathematical-physical modelling method PE (Parabolic Equation). This is an approximate solution of the wave equation, which is extrapolated numerically over a vertical propagation plane, starting from the source. Computation is carried out in finite steps over the propagation plane, which enables to vary the speed of sound over the numerical computation grid. By describing the speed of sound as a function of wind speed and temperature, the influence of atmospheric inhomogeneities can be incorporated in the propagation computation in a very flexible way. The large variation in wind and temperature gradients is classified into 25 meteorological profiles that correlate with 25 sound speed profiles. In case of propagation over barriers or other obstacles the disturbance of the wind field by the obstacle is taken into account by using a range dependent sound speed profile that changes with the distance from the barrier.

In the case of road and railway traffic noise modelling, the PE model is not always capable of dealing with the complex shapes of noise barriers and other obstacles in the source region. To deal with these propagation elements the PE model may be combined with either a BEM (Boundary Element Model) or a straight ray model. The transition from the BEM or straight ray model to the PE model is accomplished by using complex sound pressure computation results from one model as input to the next model. The intermediate sound pressure values are normally computed for a vertical stack of receiver points at 1m behind the obstacle.

The principles of this Reference model can also be used for the computation of aircraft sound propagation, but the implementation of the method will have to be revised to make it suitable. The most important limitation of the current Reference model is that the PE model approximation assumes essentially horizontal propagation. None of the three PE model versions can handle a greater angle of propagation than 60 degrees deviation from horizontal. This limitation is not acceptable for over-head aircraft passages, so adaptations to the basic propagation model are necessary.

A possible approach could be to use a (curved) ray model for higher elevation angles and the standard PE approach for lower elevations. Since the meteorological gradients are moderate and in most cases not very complex in shape at higher altitudes, aircraft passages at higher elevation angles may be treated with a relatively unsophisticated model without serious loss of accuracy. On the other hand the propagation for lower elevation angles will be more susceptible to meteorological influences and effects of ground reflection and shielding of sound. This makes it attractive to maintain the PE model for lower elevations and use a (curved) ray model for the higher elevations. An alternative for the use of ray models for the higher elevation may be the use of the Fast Fourier Program (FFP) for the higher elevations. This model is very well suited for a layered atmosphere, which may be a reasonable assumption in aircraft sound propagation situations.

Further study should be carried out to investigate the considerations given above, to make a choice between the ray model or the FFP solution and to develop a suitable transition between the two areas of elevation angles to guarantee a continuous and smooth transition.

For both modelling methods the meteorological classification has to be re-developed in order to take into account the higher propagation paths involved in air traffic noise and to adapt to the characteristic meteorological profiles that occur in at higher atmospheric layers.

With respect to the source description the directivity of the sources will require special attention. In a ray model implementation the directivity can be handled relatively easy, as the sound power of the source can be taken as a function of the angle of radiation. The PE model, however, is strictly based on a monopole representation of the sources. Therefore a non-uniform directivity pattern has to be constructed with a combination of monopole sources. For each of these monopole sources the computations have to be carried out separately and the results summed at the receiving point. Under circumstances a more speedy alternative may be used by

implementing the directivity of the monopole combination directly in the starter function of the PE computation.

If the angle difference between the different radiation directions that contribute to the sound level in one single receiving point is small, the effects of directivity may possibly be neglected without a significant influence on the final result. In that case also in PE it will be easy to handle the effects of directivity.

In any case the various solutions will have to be studied and implemented for the specific characteristics of aircraft sound sources.

4.6 Validation of the noise impact models

In the Harmonoise project both the Engineering and the Reference model have been validated against measured data.

This validation has shown that the Reference model principles do have a broad validity in flat and hilly terrain, for all kinds of meteorological conditions. If, however, the principal lay-out of the model is going to be changed by adding a (curved) ray implementation and a transition part, a additional validation against measured data would be preferable.

The validation of the Engineering model in the Harmonoise project was less extensive and the results were less convincing in terms of general validity. Therefore a thorough validation of the modified version that will constitute the EENIMAT model may be important.

The measurements that are going to be carried out for the purpose of validation will have to deal with the validation of the source description as well as the propagation models. Therefore it is advisable to carry out measurements at various distances and to use the shortest distance primarily for the validation of the source power and directivity, while the longer distance data may be used for the validation of the propagation models.

Adequate registration of the flight condition parameters (see 4.1) is essential to obtain a complete validation of the models, including the source models.

When suitable data is available, the models may be validated on single flights recordings, using combined time/frequency analysis. Validation of the model as a whole (with all input data uncertainties and modelling simplifications taken into account) will require measurements over a sufficient long period so that the full variation of all relevant input parameters can be accounted for. Extrapolation of such long time measurements to yearly averaged L_{den} values is not truly part of the work of WP4 but should be discussed in cooperation with WP3. If no long time measurement campaigns are foreseen in this WP, data from existing monitoring systems may be used to validate the models. In the latter case, it is essential to seek contact with some airport authority willing to provide sufficiently detailed input data concerning numbers and types of aircrafts, actual flight paths, take-off masses, etc.

5 Knowledge gaps, missing modelling solutions and necessary activities

From the solutions and proposals discussed in Chapter 4 one may conclude that the basic knowledge to carry out the implementation of the proposed system of source and propagation modelling methods is available. Most of the problems described in Chapter 4 refer to the development of methods and modelling solutions for which the ideas are available but realisation is still the step to take.

As part of the realisation the topics that need further attention within the WP 4 work plan and the activities to be undertaken are described below.

5.1 Aircraft sound source description

- 5.1.1 Methods and format for modelling and classification of sound power levels;
- 5.1.2 Overview of occurring directivity characteristics and available data;
- 5.1.3 Study of necessity for 3D vs. 2D directivity modelling;
- 5.1.4 Method and format for modelling and classification of directivity;
- 5.1.5 Review of simplification possibilities and accuracy implications.

5.2 Aircraft sound emission measurement methods

- 5.2.1 Choice and elaboration of measurement method for normal operations;
- 5.2.2 Adaptation of current certification sound emission measurement method to comply with the method for normal operations;
- 5.2.3 Development of suitable data base structure.

5.3 Conversion method for sound emission data

- 5.3.1 Study of relationships between noise-power-distance data and sound power and directivity data;
- 5.3.2 Development of a generic conversion methodology;
- 5.3.3 Execution of data conversion;
- 5.3.4 Validation of converted data against initial values.

5.4 Development of Reference model RENIMAT

- 5.4.1 Development of Ray model for higher altitudes;
- 5.4.2 Development of Transition model between PE model and Ray model;
- 5.4.3 Implementation in PE of directional point source for aircraft
- 5.4.4 Assessment of suitable meteorological data for higher propagation altitudes;
- 5.4.5 Development of meteorological classification system;
- 5.4.6 Test computations with complete modelling set-up
- 5.4.7 Completion of first version of model;

- 5.4.8 Incorporation of validation results and adaptations to the model (after completion of task 5.6)

5.5 Development of EENIMAT

- 5.5.1 Test calculations with Harmonoise Engineering propagation module for air traffic noise situations;
- 5.5.2 Review and, if necessary, adapt curved ground methodology;
- 5.5.3 Compare results with and tune to RENIMAT computations;
- 5.5.4 Develop and implement connections to source database, flight path input data, topography input data, propagation path generation engine
- 5.5.5 Elaboration of classification system of wind speed and stability for EENIMAT, using data from 5.4.4 and 5.4.5
- 5.5.6 Test computation with complete model configuration;
- 5.5.7 Completion of first version of model
- 5.5.8 Incorporation of validation results and adaptations to the model (after completion of task 5.6).

5.6 Validation of noise impact models

- 5.6.1 Development measurement procedures and choice of measurement quantities;
- 5.6.2 Selection of measurement sites;
- 5.6.3 Execution of measurements;
- 5.6.4 Elaboration of measured data;

As an alternative for the subtasks 5.6.1 through 5.6.4 the following may apply:

- 5.6.1 Definition of validation data requirements;
- 5.6.2 Enquiries concerning availability of data;
- 5.6.3 Collection of suitable validation data from available sources;
- 5.6.4 Elaboration of acquired data;
- 5.6.5 Validation computations EENIMAT;
- 5.6.6 Validation computations RENIMAT.

5.7 Reporting

- 5.7.1 Production of report on aircraft sound source description
- 5.7.2 Production of report on RENIMAT
- 5.7.3 Production of report on EENIMAT
- 5.7.4 Production of Guidelines for modelling

6 WP 4 Workplan

IMAGINE -- WP 4

Aircraft sound sources

Report: IMA41TR-040610-TNO 02.3

Task 4.1 - Modelling principles and lay-out

Chapter 6 - Work plan

Date: 12-7-2005

Task	Task description	Number of man days per partner							
		EURO- Control	AEA-T NL	Anotec	Boeing	CSTB	deBakom	EMPA	TNO
0	WP management								
1	Modelling principles and lay-out								
1.1	Production of State-of-the-Art report								
1.2	Production of Principles and Lay-out document								
2.1	Aircraft sound source description								
2.1.1	Methods and format for modelling and classification of sound power levels;								
2.1.2	Overview of occurring directivity characteristics;								
2.1.3	Study of necessity for 3D vs. 2D directivity modelling;								
2.1.4	Method and format for modelling and classification of directivity;								
2.1.5	Review of simplification possibilities and accuracy implications.								
2.2	Aircraft sound emission measurement methods								
2.2.1	Choice and elaboration of measurement method for normal operations;								
2.2.2	Adaptation of current certification sound emission measurement method to comply with the method for normal operations;								
2.2.3	Development of suitable data base structure.								
3	Conversion method for sound emission data								
3.1	Study of relationships between noise-power-distance data and sound power and directivity data;								
3.2	Development of a generic conversion methodology;								
3.3	Execution of data conversion								
3.4	Validation of converted data against initial values								

Task	Task description	Number of mandays per partner							
		EURO-Control	AEA-T NL	Anotec	Boeing	CSTB	deBakom	EMPA	TNO
4	Development of RENIMAT								
4.1	Development of Ray model for higher altitudes;								
4.2	Development of Transition model between PE model and Ray model;								
4.3	Implementation in PE of directional point source for aircraft								
4.4	Assessment of suitable meteorological data for higher propagation altitudes;								
4.5	Development of meteorological classification system								
4.6	Test computations with complete modelling set-up.								
4.7	Completion of first version of model								
4.8	Incorporation of validation results + adaptations to the model								
5	Development of EENIMAT								
5.1	Test calculations with Harmonoise Engineering model for air traffic noise situations;								
5.2	Review + adapt curved ground methodology								
5.3	Compare results with and tune to RENIMAT computations;								
5.4	Develop and implement connections to source database, flight path input data, topography input data, propagation path descriptions								
5.5	Elaboration of classification system of wind speed and stability for EENIMAT, using data from 4.4 and 4.5								
5.6	Test computations with complete modelling set-up								
5.7	Completion of first version of model								
5.8	Incorporation of validation results + adaptations to the model								
6	Validation of noise impact models								
6.1	Development measurement procedures and choice of measurement quantities <i>Alternative:</i> Definition of validation data requirements								
6.2	Selection of measurement sites <i>Alternative:</i> Enquiries concerning availability of data								
6.3	Execution of measurements <i>Alternative:</i> Collection of suitable validation data from available sources								
6.4	Elaboration of measured data <i>Alternative:</i> Elaboration of acquired data								

Task	Task description	Number of mandays per partner							
		EURO-Control	AEA-T NL	Anotec	Boeing	CSTB	deBakom	EMPA	TNO
6.5	Validation computations EENIMAT								
6.6	Validation computations RENIMAT								
7	Reporting								
7.1	Production of report on aircraft noise source description								
7.2	Production of report on RENIMAT								
7.3	Production of report on EENIMAT								
7.4	Production of Guidelines for Modelling								
TOTAL									

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