HAQT deliverable 6-1: AQ network utilization roadmap based on HAQT results

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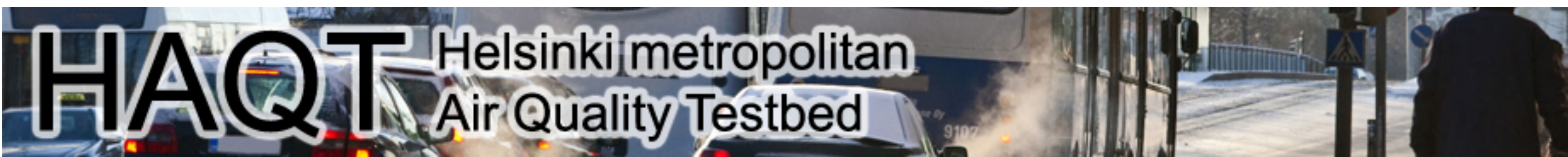

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1. Introduction

Air quality is one of the grand challenges that the society faces at the moment (Gimeno, 2013, Lappalainen et al. 2014, Kulmala et al. 2016, Arnold et al. 2016). The problem arises from a suite of anthropogenic activities including industrial and emissions of pollution gases and particulate matter and associated land use changes (e.g. Foley et al. 2005, Baklanov et al. 2016). Furthermore, the air quality deteriorates via atmospheric chemical reactions producing harmful gas phase pollutants, such as ozone (Zhang et al. 2004) and secondary particulate matter (Chu et al. 2018). Meteorology governs the dispersion of pollutants, both vertically and horizontally (e.g. He et al. 2017). Various feedback mechanisms can deteriorate the local air quality within cities even further (e.g. Petäjä et al. 2016, Ding et al. 2016). Regulations have already improved the air quality regionally and globally (Crippa et al. 2016), but more targeted restrictions and support from observations are needed to further tackle the air quality in the future (Zheng et al. 2018).

Traditionally, the air quality in the urban environment is monitored with a network of in-situ observations of key gas phase pollutants (O_3, NO_x, CO and SO_2) and particulate mass below 2.5 µm or 10 µm (PM2.5 and PM10, respectively). The regulatory network is constructed to represent different urban environments (kerbside, urban background, rural) and the air quality conditions at these sites are reported and taken as representatives for similar urban environments (e.g. Duyzer et al. 2015, Rohde and Müller, 2015).

Recently, this traditional view has been improved by implementing more numerous supplementary air quality observations (e.g. Popoola et al. 2018), combining this dense observation network with more comprehensive benchmarking supersites and integrating the observed air quality situation and prediction with spatially and temporally high resolution models. In Helsinki region, the observations from two supersites – one representing urban background and the other an urban street canyon – and a regulatory network are extended with supplementary observations with Vaisala AQT420 sensors (2017 Release). The observations are integrated with a fusion modeling framework (FMI-ENFUSER) to provide spatially representative air pollution fields that take into account in-situ observations, spatiotemporal variability of pollution sources (e.g. traffic, industry) and meteorological situation.

The aim of this report is to provide insights into development of air quality observations based on work performed in HAQT and related projects. We summarize these insights in the sections below.

2. Recommendations to improve air quality observations

2.1 Use of hierarchal networks

The principal idea of a hierarchal network is described in Figure 1. In HAQT and other air quality projects in Helsinki metropolitan area, we have developed a hierarchal network of AQ instruments with different precision levels. This network includes currently two supersites, which are research stations with comprehensive state-of-the-art instrumentation for air quality and meteorology observations, regulatory network, which contains precise instrumentation for official AQ measures, and sensor network, which increase the spatial coverage of the regulatory network. In future, even denser network of stationary and mobile low-cost sensors will be implemented in the area. Full benefit of a hierarchal network is achieved by applying e.g. a fusion model to interpolate and validate the sensor data and use them for predicting the upcoming AQ situation (see Section 2.2). Based on the experience gained in HAQT, we recommend establishment of similar networks and modelling frameworks in other cities that wish to efficiently monitor and improve the AQ situation.

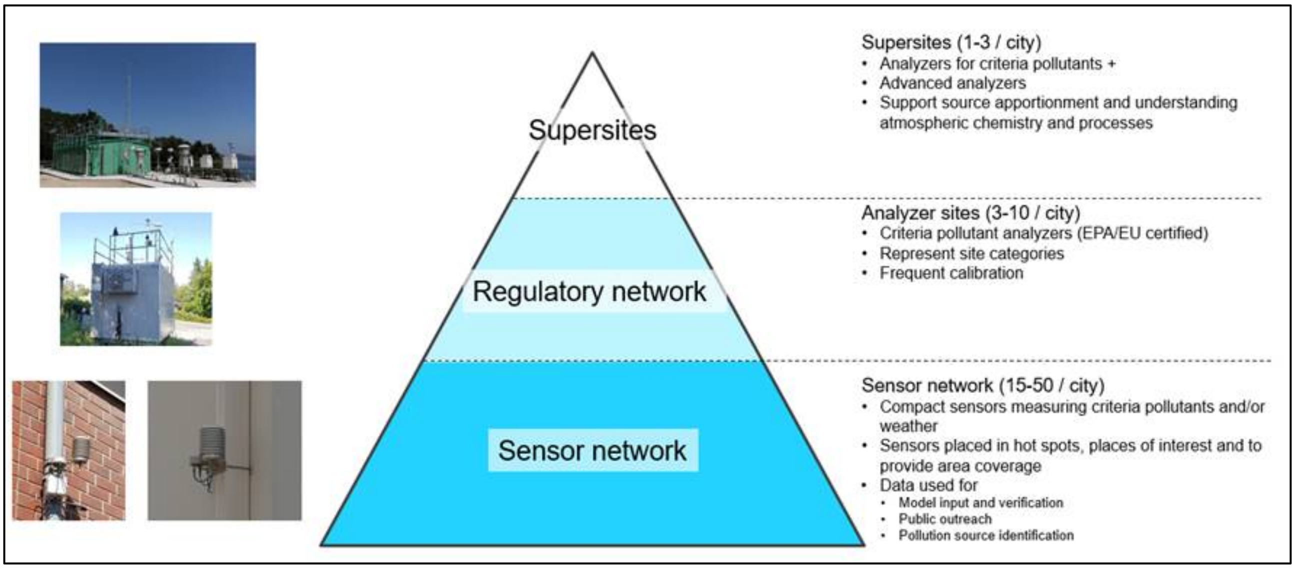

Figure 1. Principal idea of three-level hierarchal network for air quality monitoring.

Networks

The value from network data can be maximized if the sensor locations are chosen and categorized in such a way that they represent a certain type of environment in a city. The locations are typically classified according to location type (urban, suburban, rural) and to the dominant type and source of pollutants (traffic, industrial, background). Yet another commonly encountered location type is residential area, where domestic burning may be a significant pollution source. In coastal areas it is important to make distinction between sites that are inland versus those close to the watershed.

Pertinent to reducing negative health effects, it is obvious that emphasis should be put on areas with high pollution levels, but at the same time it is important to note that also background locations are needed in order to understand for example the roles of regional background and long range transport in air quality. In choosing the location for the regional background station, the prevailing winds and the nature of regional emissions are important to consider for truly representative results.

The regulatory network and sensor network, as applied in Helsinki during HAQT, is presented in Figure 1. After HAQT, the networks are maintained, but locations of some sensors have been changed.

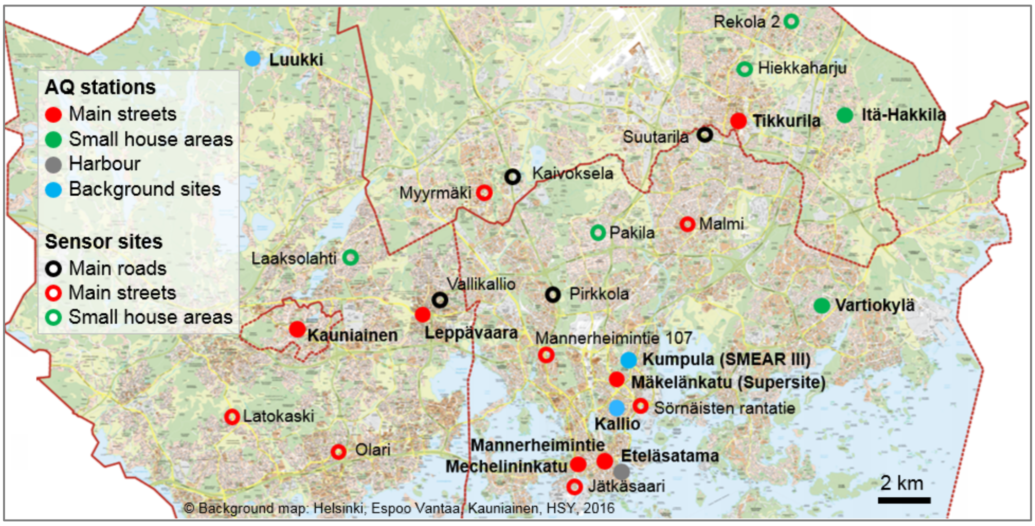

Figure 1 An example of a complementary air quality sensor network. Full circles represent the fixed regulatory network stations, open circles the sensor sites. Different colors indicate different location types.

The complementary sensors are placed in a way to efficiently improve the spatial coverage of air quality monitoring by the regulatory network. The sensor sites are located near major streets and roads as well as in small housing areas. Thus, the sites represent the main local pollutant sources, including traffic exhausts, street dust and emissions from small-scale wood combustion in the fire places and sauna stoves. The spatio-temporal variation is especially high for the emissions resulting from street dust and residential wood combustion, and therefore several measurement sites are needed to capture the local variation in air quality. Sensors were not placed at urban or rural background sites, since few air quality monitoring stations already exist in background areas. The spatial variation in pollutant concentration is much lower at background areas than at hotspot sites with poor air quality.

Public exposure is a product of pollutant levels, the number of people being exposed and the time of exposure. Therefore, air quality monitoring should preferably be established also in areas where large amounts of people are exposed to ambient, possibly polluted air. Another category of interest areas are locations where sensitive groups of people are exposed to polluted air, such as daycare centers, schools, hospitals or other types of healthcare facilities.

The sensors in the network should be maintained according to the manufacturers' recommendations. A sensor network should not be seen as a one-shot installation project. Taking advantage of the easy deployment of modern air quality sensors the network should be seen as a tool that is continuously evolving and expanding to address always the most significant air quality related issues in the area. Already at the planning stage of a new air quality sensor network a roadmap for further expansion and evolution of the network is useful to envisage. By adding in-situ meteorological sensing (WS, WD, rain, humidity, temperature) to air quality sensor location will in many ways help the interpretation of results.

Sensors in specific areas of interest

Areas of specific interest for air quality and sensor siting are those with permanently or occasionally elevated emissions, often referred to as hot spots. Examples of this type of areas are industrial areas, airports, ports or harbours, major landfills, major building sites etc. Any other or further information on emissions, emissions mapping etc should be used in considering network locations. For monitoring of point sources, the sensors should be placed downwind from prevailing winds. However, for network locations within complex urban structures such as street canyons, downwind is not necessarily optimal due to forming street canyon vortexes and there more detailed understanding of the local flow structures is required (see Section 2.3). For a more complete and reliable picture, several sensors can be placed in different directions from the point or area source.

Supersites

The spatial coverage provided by the network of stations should be complemented with state-of-the-art scientific stations. These stations can specifically address targeted scientific questions pertinent to air quality, provide location for calibrating the sensors and establishing correction factors to sensor data (see **HAQT deliverable 3.3**), as well as for developing proxies for derived AQ variables (see Sect 2.5). Supersites are also usevul in development of novel instrumentation and validation of model and satellite products. In Helsinki this approach is realized with two twin stations: SMEAR III site in Kumpula and Mäkelänkatu supersite. These research stations are described in more detail in **HAQT deliverable 3.1**.

Kumpula campus area of University of Helsinki represents urban background (SMEAR III, Järvi et al. 2009). Here the standard air quality observations are complemented with detailed aerosol observations and flux measurements The site complies with pan-European Aerosols, Clouds, and Trace Gases Research InfraStucture (ACTRIS) requirements and contributes to pan-European Integrated Carbon Observation System (ICOS).

To contrast the urban background observed at SMEAR III, HSY has established a corresponding observation site in the urban street canyon in Mäkelänkatu, only one kilometer away from Kumpula. This site provides novel insights into micrometerological features at a site highly affected by traffic where the ventilation to the upper atmosphere is reduced due to nearby buildings. The observations include air quality parameters and aerosol number size distribution, chemical and optical properties as well as carbon dioxide measurements, that facilitate analysis of carbon dioxide and nanoparticle emission factors e.g. from traffic (Rönkkö et al. 2017).

2.2 Use of fusion modelling

The FMI-ENFUSER (Johansson et al. 2015) is an operational, adaptive local scale dispersion model used in Helsinki region as a part of HAQT project. The model utilizes real-time measurement data to fine tune emission factors and dispersion modelling parameters. The modelling system has been designed to predict hourly pollutant concentrations (SO_2, CO, NO, NO_2, O_3, PM2.5, and PM10) and air quality index (AQI) in the area with a spatial resolution of 13 x 13 meters. Due to the computational limitations that a real time operational AQ system presents, the dispersion modelling is performed with a combination of Gaussian puff and Gaussian plume dispersion modelling. In the hyper-local scale (0-300 m distance from the emission sources, Gaussian plume modelling is used while the local urban morphology is taken into account with simplistic corrections (e.g., buildings, street canyons, vegetation). For emission contributions originating farther away dispersion modelling is performed using Gaussian puff modelling, in which the individual emission puffs have been made to follow wind trajectories according to the available Numerical Weather Predition (NWP) data (given e.g. by HIRLAM, GFS or ECMWF). The long-range transportation of pollutants is taken into account by nesting the local dispersion modelling on regional scale chemical transport model FMI-SILAM. The details of the FMI-ENFUSER are described in HAQT deliverable 2.1 (Johansson et al. 2019).

During the HAQT the FMI-ENFUSER took the full use of air quality observations available from the regulatory network and supersites within Helsinki for the selected air quality compounds (SO_2, CO, NO, NO_2, O_3, PM2.5, and PM10). Including new observables, such as aerosol number concentration or lung deposited surface area (LDSA), black carbon or proxy variables developed within HAQT to the regional scale with the FMI-ENFUSER would expand the regional representation for these arising air quality parameters.

Furthermore, the FMI-ENFUSER model was used to determine ideal locations for the complementary sensors to enable maximum benefit from these new observables. This is a recommended way forward in further large-scale deployments of the cost-effective sensors that can improve the spatial representativeness of air quality conditions within the city.

2.3. Utilizing new observation and modelling platforms

Within HAQT, we have also applied novel observational methods to understand the local pollutant variations of particulate matter and gaseous pollutants in detail, and furthermore to provide evaluation data for high-resolution air quality modelling. In 2017, two 2-week measurement campaigns were performed in different prevailing meteorological conditions utilizing mobile van and drone observations. The measurement campaigns were conducted around the Helsinki Regional Environmental Services Authority (HSY) supersite located in a street canyon, about 3 km North-East from Helsinki city centre, on 5-16 Jun 2017 and 27 Nov-8 Dec 2017. During both campaigns, the Sniffer mobile laboratory was measuring particle number size distribution, particle mass (PM2.5/PM10), black carbon, and concentrations of O_3, NO_2 and NO during three 2-hour time slots (morning and afternoon rush hours and noon/evening) on workdays with suitable weather conditions (i.e. not too rainy). The mobile laboratory circled the main street and side roads in addition to measuring background air and standing still in the street canyon. On two days during both campaigns, the vertical distribution of air temperature, humidity, lung deposited particle surface area (LDSA), and concentrations of NO, NO_x and O_3, were measured using a drone during the same 2-hour slots.

The spatial observations show how the studied air pollutant concentrations are highly variable in space and time. Clearly, certain meteorology-dependent hotspots can form within the street canyon network.

The preliminary data analysis also shows how aerosol concentrations inside street canyons are mostly impacted by mean wind and turbulent mixing, while O_3 concentration influenced by air temperature.

The spatial observations are currently being applied to evaluate a novel high-resolution air quality model, which was developed by implementing an aerosol module and an online chemistry module to the large-eddy simulation (LES) model PALM (see Kurppa et al. 2019 for the aerosol part). The model provides the best tool for resolving pollutant transport and transformation in complex environments with a spatial resolution up to 1 m. High-resolution modelling supports urban planning by resolving the impact of individual buildings and vegetation on local air quality. Moreover, it produces unique information for selecting the best sensor locations for urban air quality observations. However, due to its high computational costs, the model is not in operational service at the moment, but case studies can be performed.

2.4 Utilize new air quality parameters from new measurements

Epidemiological studies have shown strong correlation between mass-based PM exposure (i.e. PM2.5) and premature mortality, but the detailed processes governing the harmful health effects are still not fully understood. As a consequent, it has been hypothesized that surface related chemistry of particles may be a significant factor when assessing the harmfulness of PM. Toxic chemicals are attached to the surfaces of particles and transported to the deepest parts of human respiratory system via the particles. The surface area, and a so-called lung deposited surface area (LDSA) in particular, is therefore a parameter of interest. LDSA describes the computational surface area of particles depositing to the deepest parts (i.e. alveolar region) of human respiratory system and thus takes into account the potential of particle surface related chemistry.

LDSA concentrations are mainly driven by small (< 400 nm) particles as the alveolar deposition fraction of particles of this size is high, and they are typically present in high numbers, especially in urban areas. Anthropogenic sources such as vehicular exhaust emissions and residential wood combustion are typical sources of high LDSA concentrations as particles emitted from these sources are often in the ultrafine size range. Due to the small size of particles LDSA concentrations cannot be measured with optical methods.

Concentrations of LDSA are typically measured with a so-called diffusion charging-based technique where particles are charged using a unipolar corona charger. Formed ions are driven onto the surfaces of particles by diffusional forces, and a current signal, which is proportional to the number of ions attached to the surfaces of particles, can be measured by collecting the particles with a Faraday cup electrometer or by using a measurement of escaping current. This method enables measurement of ultrafine particles and, more specifically, the LDSA concentration with good accuracy and high temporal resolution (1 Hz). Currently, several different instruments are available on the markets which utilize the aforesaid technique as their operation principle.

Another emerging parameter in air quality – health interactions is aerosol number concentration. Typically the aerosol number concentration is dominated by ultra-fine aerosol particles (sizes below 100 nm) whereas the mass is dominated by larger particles (e.g. Petäjä et al. 2007). The emissions from traffic in terms of aerosol number is already now addressed by EURO-VI regulations by the European Commission. New technologies with a potential to be developed as more cost-effective are being developed and they could be deployed as a part of the existing air quality observation networks as they are already operated at the supersites (e.g. Järvi et al. 2009, Rönkkö et al. 2017).

Black carbon (BC) is strongly light-absorbing carbonaceous material that is emitted in the atmosphere as fine particles as a side product of incomplete combustion. It has been shown that combustion-derived particles are more relevant to the human health than aerosol particles from other sources (Janssen et al., 2011). Since BC is an indicator of combustion related aerosol particles, it gives additional information about the health effects of PM2.5, marking the importance of monitoring BC in addition to PM2.5. In Helsinki area, BC concentration is monitored at the supersites (SMEAR III and Mäkelänkatu) and in different types locations around the metropolitan area covering traffic sites, detached housing areas and background sites. Observing BC concentration in different surroundings, as well as estimating the concentrations with higher spatial resolution (see Sect. 2.5), is important for understanding the varying contribution of combustion aerosols on PM concentrations.

Continuous measurements of aerosol composition with particle ACSM (Aerosol Chemical Speciation Monitor, Ng et al. 2011) or AMS (Aerosol Mass Spectrometer) are important to conduct at least on the supersites. The chemical composition can be applied to determine the contributions of different sources on the aerosol concentrations with source apportionment methods.

The utilization of high resolution mass spectrometry (CI-APiTOF, Jokinen et al. 2016) at the supersites facilitate development of new proxy variables describing the atmospheric oxidation capacity and determination of acid compounds is possible. These can be connected to standard air quality parameters throughout the air quality network and to the modelled compounds. This facilitates upscaling to city or even sub-urban scale within the city. This increases the potential to perform targeted air quality improvement strategies.

Apart from pollutant measurements and basic meteorological quantities, an atmospheric parameter, which has great influence in ambient pollutant concentrations, is the mixing height. Mixing height effectively defines the air volume into which the pollutants from ground sources are diluted, and hence directly affects the ground concentrations (e.g. Petäjä et al. 2016). Combining continuous mixing height observations to any air quality observation network will bring important new information to air quality modelling and provide a new level of situational awareness for providing air quality forecasts and advisories.

2.5 Utilize new air quality parameters with proxies and combined effects of air quality

The new AQ parameters described above in Sect 2.4 are typically measured with expensive and/or large instruments. Thus, it is impossible to observe their concentrations with a dense observation networks in a similar manner than the traditional air pollutants are observed. Based on data observed at the well-equipped supersites and regulatory network, we developed in this project proxies for the new AQ parameters (BC, LDSA, N and SA). The proxies and their derivation are described in more detail in **HAQT Deliverable 4.2**. Since the proxies estimate the concentrations of the new AQ parameters with the information of the traditional pollutants and meteorological variables, the proxies make it possible to implement the new AQ variables in models such as FMI-ENFUSER in future. It is important to notice that the proxies cannot be applied alone for estimating the concentrations of the new AQ parameters in varying urban environments: since the sources of these pollutants are multiple, the proxies need to be determined separately for different cities and preferably also in different environments of the city in question for improving their accuracy. This can be done either by having instruments measuring the new AQ parameters simultaneously in different environments, as done for BC in this project, or by moving these instruments between different environments e.g. with a mobile platform.

The air quality situation is typically expressed in terms of Air Quality Index (AQI). There are varying threshold levels in different parts of the world for different index levels, but a common feature for all the AQI's is that the total index value is determined based on the single pollutant, which at the given moment induces the highest AQI level. E.g. if one pollutant induces AQI value 8 and the others any values below 8, the AQI is 8 regardless of the concentrations of other pollutants. With respect to health, this is not reasonable, since the health impacts of the other pollutants are not decreased due to one pollutant having high concentrations. On the contrary, there is evidence that simultaneous exposure to several air pollutants would be more harmful than exposure to similar levels of same pollutants separately (is it? reference!). Where the enhancement of exposure to multiple pollutants is still to be quantified, the cumulative health impact of different pollutants is reasonably straightforward. Such approach has been developed e.g. in Stockholm (Olstrup et al., 2019) and we propose to investigate further the use of this type of cumulative AQI in future studies.

3. Summary

The aim of this report was to provide insights into development of air quality observations based on work performed in HAQT and related projects.

The Helsinki Air Quality Testbed (HAQT) included a well-established and operated regulatory network for air quality observations with state-of-the-art urban observations. The measurement network was supplemented with denser sensor network within the region. The spatial representativeness was ensured by a wide utilization of FMI-ENFUSER air quality model that was able to digest the observations and to provide a synthesis. The data was used to develop novel variables and the we explored benefits for new air quality observables, such as aerosol number concentration, lung deposited surface area and black carbon.

Complementing a regulatory network with sensor network and fusion model provides added value to air quality management work and eventually to public health with a modest capital investment. Feeding significantly more in-situ observations to air quality models improves the reliability of modelling results and forecasts. More complete in-situ data and more reliable models will also contribute to better understanding of local atmospheric conditions and people's exposure to pollution. Finally, local measurements in communities may play a significant role in education and citizen outreach.

Including a supersite to regulatory network or combination of regulatory and sensor networks and fusion model increases the spatial representativeness of air quality assessment and provides novel tools to expand the air quality analysis to new, potentially health related parameters.

Overall, a tight collaboration between air quality researchers and authorities in charge of air quality monitoring will enable fast transfer of newest research results instruments and air quality models to routine air quality monitoring. In the Helsinki metropolitan area, e.g. FMI-ENFUSER air quality model developed by FMI researchers has been taken into the use by authorities (HSY) and is available for citizens in the address www.hsy.fi/ilmanlaatukartta (English web pages www.hsy.fi/airqualitymap) as well as in information screens in public transportation. Realtime air quality data and forecasts improve the awareness of citizens, enables targeted emission mitigation actions and benefits the Finnish society. For researchers the collaboration with authorities provides access to air quality measurement locations at variable environments and important reference data from air quality network. Also, tight collaboration enables targeted in-depth research campaigns and new research projects to resolve local air quality related problems found by authorities.

The partners in HAQT will continue to maintain and operate the observation networks. The infrastructure has already shown potential to be scaled up to answer specific air quality problems in China and India. This is shortly described in the follow-up HAQT deliverable 6.2.

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