FRONTEX
EUROPEAN BORDER AND COAST GUARD AGENCY

TECHNOLOGY FORESIGHT ON BIOMETRICS FOR THE FUTURE OF TRAVEL

Executive Summary

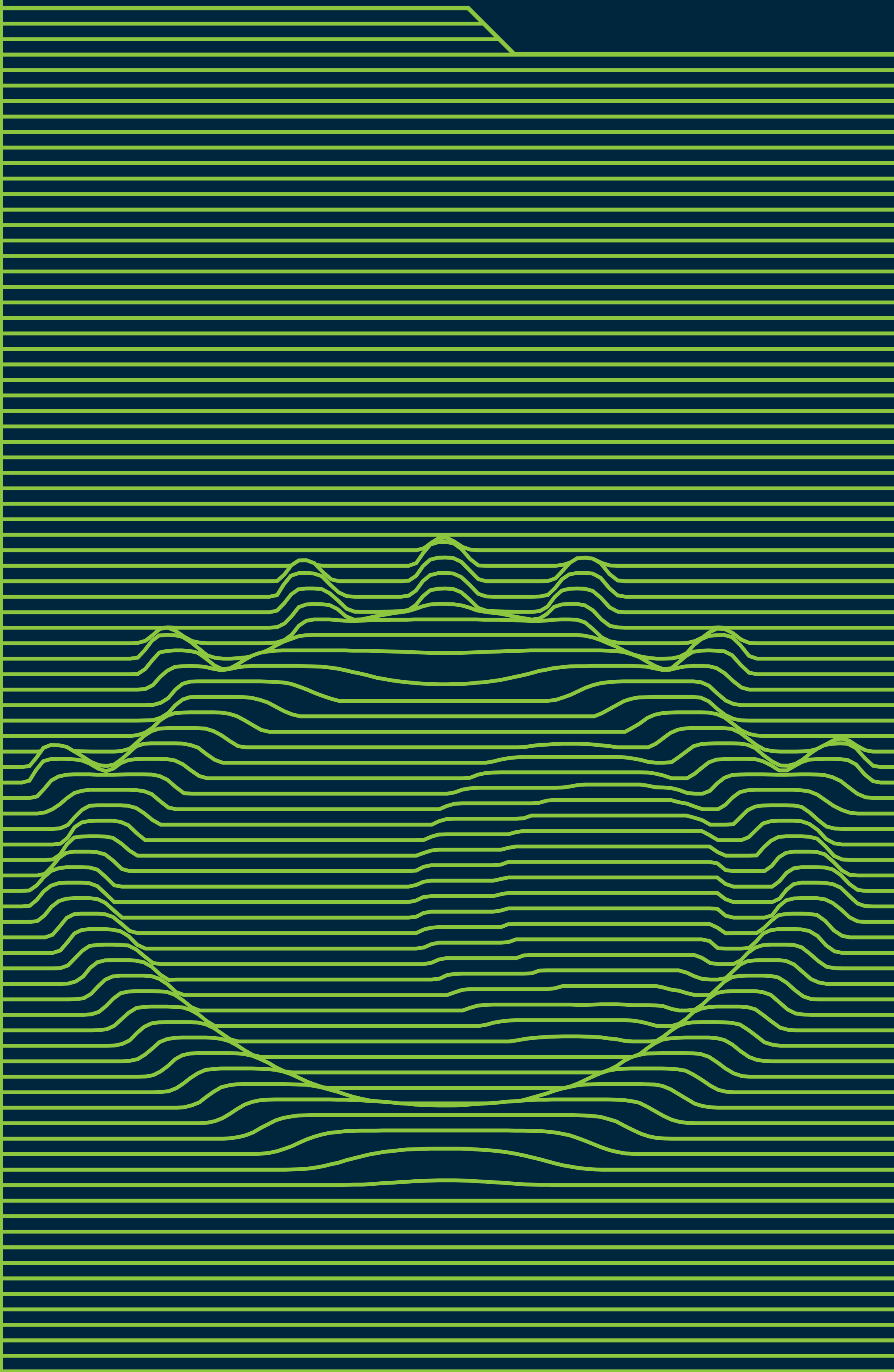
Executive Summary

Research Study

Annex I: Technology Foresight Manual

Annex II: Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems

Annex III: Patentometric and Bibliometric Analyses of Biometric Technologies

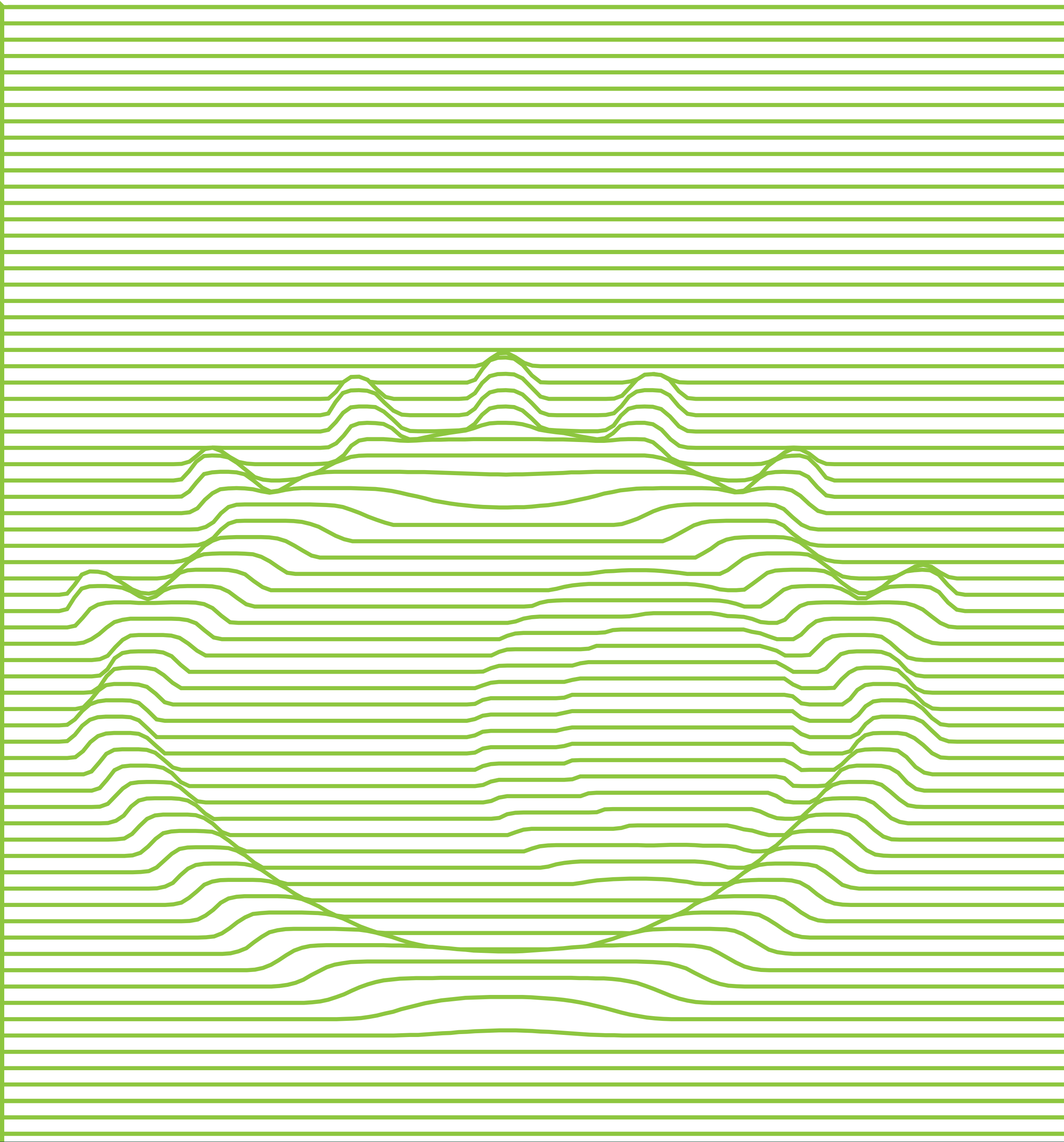


FRONTEX

EUROPEAN BORDER AND
COAST GUARD AGENCY

TECHNOLOGY FORESIGHT ON BIOMETRICS
FOR THE FUTURE OF TRAVEL

Executive Summary



Legal Disclaimer

This document has been produced under a contract with the European Border and Coast Guard Agency (Frontex). The information and views set out in this document are those of the author(s) and do not necessarily reflect the official opinion of any institution or body of the European Union, including Frontex. Frontex does not guarantee the accuracy of the data included in this document.

Neither Frontex nor any person acting on behalf of Frontex (including the authors) may be held responsible for the use which may be made of the information contained herein. In particular, the information in this document is provided "as is" and the authors give no guarantee or warranty that the information is fit for any particular purpose other than the performance of the contract with Frontex. The referenced contractor and subcontractors shall have no liability for damages of any kind, including without limitation direct, special, indirect or consequential damages that may result from the use of these materials, subject to any liability which is mandatory due to applicable law.

Frontex – European Border and Coast Guard Agency
Plac Europejski 6
00-844 Warsaw, Poland
T +48 22 205 95 00
F +48 22 205 95 01

frontex@frontex.europa.eu
www.frontex.europa.eu

Warsaw, September 2021

Acknowledgements

This Research Study and the underlying research project were conducted by Steinbeis 2i GmbH, strongly supported by 4CF, Erre Quadro and the Instytut Optoelektroniki – Wojskowa Akademia Techniczna. The following Research Team members dedicated considerable time and effort to successfully completing this study: Sabine Hafner-Zimmermann, Melanie Gralow, Norbert Kołos, Anna Sacio-Szymańska, Maciej Jagaciak, Kacper Nosarzewski, Giovanni Pianigiani, Giovanni de Santis, Tommaso Pavanello, Dario Brugnoli, Donata Gabelloni, Riccardo Apreda, Marcin Kowalski and Norbert Pałka.

The Research Team would like to particularly thank Raffaele Bruno and Martin George for their continuous support, constructive comments and knowledgeable feedback at various stages of the project.

The Research Team also gratefully acknowledges the trust and invaluable support received from the members of the Border Security Observatory at Frontex, without whom this Research Study would not have been possible. Furthermore, the study took stock of the numerous and highly valuable contributions of all stakeholders' experts who actively participated in the two Technology Foresight Workshops and the Delphi Survey. The Research Team and Frontex express their particular gratitude to all participants of these activities, who generously shared their time and expertise.

About Frontex

Frontex, the European Border and Coast Guard Agency, promotes, coordinates and develops European border management in line with the EU fundamental rights charter and the concept of Integrated Border Management. The Agency also plays a key role in analysing and defining the capability needs in border control and in supporting the Member States in the development of these capacities. Furthermore, it provides qualified expertise to support the EU policy development process in the area of border control.

The Border Security Observatory, within the Frontex Research and Innovation Unit, is responsible for leading and conducting transformational, need-driven research with academia, EU institutions and Agencies, international organisations and industries to stimulate and support innovation. The ultimate goal is to consistently enhance the capabilities of the European Border and Coast Guard in line with the Capabilities Development Plan, which includes those of the Member States and of the Agency itself.

1. Motivation and goals

In December 2020, Frontex awarded a tender to conduct the study *Technology Foresight on Biometrics for the Future of Travel*. The project was implemented between January and September 2021 by Steinbeis 2i GmbH (S2i), strongly supported by 4CF Sp. z o.o. (4CF), Erre Quadro S.r.l. (R2) and the Instytut Optoelektroniki – Wojskowa Akademia Techniczna (WAT). The Research Study, the ultimate output of the project, depicts the individual stages of the Technology Foresight (TF) process and describes the results in detail. This Executive Summary aims to provide a concise and comprehensive outline of the approach, implementation and outcomes of the research.

The primary goal of the Research Study was to provide technology-related insights on the future of biometrics for its implementation in border check systems that could be utilised by the European Border and Coast Guard (EBCG) community in the short- (2022-2027), medium- (2028-2033) and long-term (2034-2040) perspectives. Secondly, Frontex wished to raise awareness about the relevance and applicability of foresight for forward-looking decision-making within its organisation and to acquire the related know-how. Finally, the study provides a comprehensive foresight methodology, tailor-made to Frontex's needs and outlines the implementation of this methodology using quantitative, qualitative and participatory approaches to identify biometric technologies of high relevance to future applications in border checks.

A good definition of the scope of the study was essential. The study was limited to biometric technologies and biometrics-enabled technological systems that could find applications in border checks, biometric recognition and access control. Additional constraints were imposed by disregarding the applications of biometrics in border surveillance as well as emotion and behaviour detection.[1]

The outcomes of the exercise will provide Frontex with the practical knowledge required for further TF studies in other technological fields and research areas. They will also supply in-depth information to underpin future strategic decisions on the application of biometric technologies in the context of border checks, e.g. with regard to future priorities, research directions and investment decisions.

More specifically, the following objectives were defined for the study in the context of border checks:

On a global scale:

- Identification of the current implementation status and future development pathways of biometric technologies by 2040;
- Identification of biometric technology accelerators, including the main actors and key Research and Development (R&D) initiatives.

1 Behaviour detection was considered within the general scope of the Research Study only within the context of detection of people in need of assistance or special care (e.g. not moving for a long period of time, disoriented children or elderly people) and only in a certain phase of the study (i.e. Roadmapping).

On a European Union (EU) scale:

- Identification of future opportunities in terms of biometric technologies that could support EU external border management, e.g. facilitating seamless travel;
- Identification of biometrics-enabled technological solutions to future operational problems within the EBCG community;
- Analysis of legal, ethical and technological limitations intended to minimise the risks associated with applications of biometric technologies;
- Assessment of the impact of biometric technology trends on border checks and identification of future research needs.

Within the EBCG community:

- Providing know-how on the implementation of TF projects;
- Raising awareness about the relevance and applicability of TF for forward-looking and evidence-based decision-making;
- Disseminating the results of this Research Study to encourage joint initiatives, the development of a shared vision and strengthened capability development.

2. Background

Millions of travellers cross the EU's external borders every year and their numbers will likely increase even further. Thus, border checks will need to undergo significant transformations, both to safeguard the EU's external borders and to improve the border crossing experience for travellers, e.g. by enabling seamless or near-seamless travel. Innovative technological solutions will play an essential role in the transformation of border checks; biometrics is one of the fields expected to enhance the security of border checks while at the same time facilitating seamless travel. However, additional research is required to identify the most useful and relevant biometric technologies as well as to find a path of actions that leads to the attainment of these goals. Since Frontex proactively monitors and contributes to research and innovation initiatives relevant to European integrated border management, including those for the adoption of advanced border control technologies, this *Technology Foresight on Biometrics for the Future of Travel* was commissioned to gain additional insights into the potential of biometric technologies that could serve as a foundation for future-oriented decision-making.

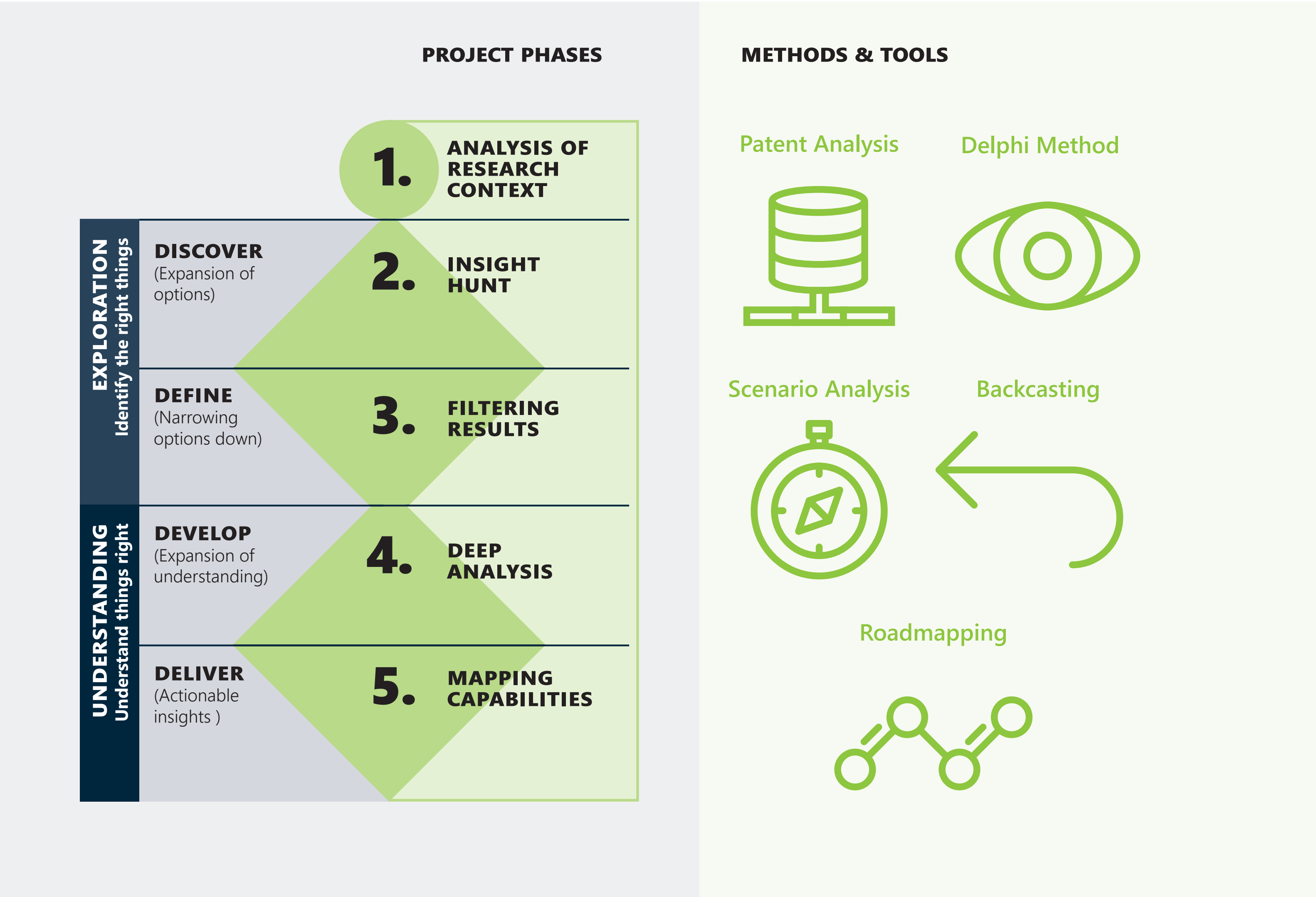
Biometric technologies were identified, and their possible future evolution paths studied, using Technology Foresight, a method that provides anticipatory intelligence which can successfully support evidence-based decision-making, strategy development and capacity building in both public and private organisations. In short, Technology Foresight is an approach that delivers strategic insights by analysing possible future technological development paths. However, there is no single recipe for conducting a foresight exercise: each study needs to be tailored to the specific context, requirements and fields of interest, as well as to the assets and data sources available. The benefits of foresight analyses are numerous and include identifying threats and opportunities, stress-testing long-term strategies, uncovering vulnerable assumptions regarding the future and detecting potentially disruptive technologies and events.

Therefore, a tailor-made foresight process was developed for the purposes of the *Technology Foresight on Biometrics for the Future of Travel* and described in detail to provide Frontex with general insights into the development and implementation of foresight exercises.

3. Structure and implementation of the study

The Research Study was structured in five phases, as shown in Figure 1. The first phase defined the overall methodology and framed the context according to the needs expressed by Frontex. The subsequent phases were dedicated to putting this methodological framework into practice. They can be depicted as two diamonds: each begins by opening up the horizon and broadening the knowledge, eventually narrowing down the obtained insights and thus, identifying the targeted outcomes. Figure 1 also provides a selection of the methods used throughout the project.

Figure 1: *Overview of the project set-up, as well as of the main methods used within the project.*



3.1. Analysis of Research Context

Definition of the methodological framework

An important objective of the project was to develop a comprehensive foresight methodology. To this end, a Technology Foresight Manual was developed, published as Annex I to the Research Study. The TF Manual outlines the overarching methodological framework developed for this project and the methods and tools used for its implementation in considerable detail. Thus, the first part of the TF Manual describes the 5 phases of the Technology Foresight process (TFP), the second part provides the reader with key information about the foresight methods used in the TFP and the third part lists the tools used to implement the TF methodology and describes each tool, its respective features, property rights, its application in the TFP and possible alternative tools. The methodological approach adopted in each phase of the project is also detailed in the respective chapters of the Research Study.

Analysis of Frontex needs regarding key functions and characteristics of biometric technological clusters

The identification of Frontex's needs regarding key functions and characteristics of biometric technologies and related systems was the first step of the Technology Foresight process. It aimed to specify the field and scope of the TFP and to set goals for the study, which in turn were used to tailor the TFP to Frontex-specific needs. The results of this step constituted the first filter for narrowing the area of further analysis to the technologies and technological systems of the greatest potential importance to Frontex.

As a result of the needs analysis, four "must-haves" were identified for reference in later phases of the project:

- low vulnerability to adversary attacks,
- seamlessness,
- applicability within pandemic-specific restrictions,
- compliance with fundamental EU values and regulations.

3.2. Insight Hunt

Identification of main areas of research in biometrics and of key stakeholders

The Research Study spans the operational fields of interest of the EBCG community in relation to border checks. To navigate the vast field of biometrics, 43 preliminary directions of analysis were defined. They included biometric technologies as well as biometrics-enabling technologies and applications.

Gaining further insights into stakeholders was another essential part of this phase, as the active involvement of stakeholders was a prerequisite for the study. This facilitated the dissemination and communication of project results within the EBCG community throughout the project, as well as ensuring that valuable insights from diverse fields of expertise were collected and could serve as the core input to the analyses. In total, over 200 stakeholders were initially identified, with more than 40 selected to participate in the study by way of three participatory activities (two *Technology Foresight Workshops* and a *Delphi Survey*).

Taxonomy of biometric technologies and biometrics-enabled technological systems

The field of biometrics is highly heterogeneous and complex. Thus, a systematic categorisation was needed to identify the technologies and systems with potential for finding applications in the operational fields associated with border checks. This step aimed to enhance the Research Team's comprehension of how the area of research in biometrics is structured and how the technologies relate to one another. For this purpose, the Research Team developed two taxonomies[2] to map *biometric technologies* and *biometrics-enabled technological systems*. Two distinct design approaches, differing in thoroughness and complexity, were followed to construct the taxonomies. The taxonomy of biometric technologies, which used the preliminarily identified main areas of research for initial guidance, was developed through an iterative process based on an analysis of patents and scientific literature with the employment of Natural Language Processing (NLP) automatic tools. This approach led to the creation of a three-level taxonomy.

A set of technological systems of potential interest to Frontex served as the initial input for creating the taxonomy of biometrics-enabled technological systems. The set was later expanded and consolidated by the Research Team to construct a two-level taxonomy.

The reference document (Annex II to the Research Study) detailing the process of taxonomy development and the two taxonomies themselves is a fundamental outcome of this Research Study and can serve the EBCG community as a starting point for future investigations into relevant areas of innovation. Together, the two taxonomies constituted an essential building block for the study:

- The taxonomy of biometric technologies was used to extract a set of *technological clusters* (TCs, shown in Table 1) required for the subsequent phases of the project.
- The taxonomy of biometrics-enabled technological systems played an essential role in guiding the development of technological roadmaps (see Section 3.4).

2 Both available in the Research Study, in Appendix 4 and 5.

Table 1: *Description of the examined biometric technological clusters*[3].

Technological clusters	Description
DNA biometrics	Biometric technologies that rely on the recognition of human DNA. These technologies find easier applications in forensic science, however, applications in biometric recognition have also been proposed. Although these systems are still unsuitable for applications in border checks, advances are being made to expedite the analysis process. This technological cluster includes DNA phenotyping, DNA profiling and DNA sequencing.
Infrared face recognition	Technologies for the recognition of human faces using infrared (IR) imaging, commonly subdivided into: near-infrared (NIR, 0.78-1.0 μm in wavelength) imaging; short-wavelength infrared (SWIR, 1-3 μm) imaging; mid-wavelength infrared (MWIR, 3-8 μm) imaging; long-wavelength infrared (LWIR, 8-15 μm) imaging. NIR and SWIR are sometimes called "reflected infrared", while passive MWIR and LWIR techniques are sometimes referred to as "thermal infrared". This cluster is formed by two biometric technologies: thermal infrared face recognition and near-infrared face recognition.
2D face recognition in the visible spectrum	This technological cluster deals with the automated recognition of individuals through the matching of a face — from a digital image or a video frame acquired in the visible spectrum of light — against a database of face images or a specified biometric reference image. It encompasses video-based face recognition and image-based face recognition.
3D face recognition	Solutions aimed at recognising an individual by the three-dimensional (3D) features of their facial components. Once the 3D geometry of the human face is acquired, it is used to extract distinctive features on its surfaces. 3D face recognition is claimed to have the potential to achieve better accuracy than its 2D counterpart.
Infrared friction ridge recognition	The skin on the palms of hands, fingers, soles and toes is known as *friction ridge skin* in the biometric and forensic communities. This technological cluster includes biometric recognition modalities (such as *Fingerprint recognition*, *Palmprint recognition*, *Footprint recognition* and *Finger-knuckle-print recognition*) implemented through thermal imaging or near-infrared imaging of friction ridge skin.
3D friction ridge recognition	Biometric modalities capable of acquiring the frictional ridges of one or multiple body parts (e.g. fingers, palms, feet or finger-knuckles) and producing three-dimensional representations in order to recognise an individual. For example, extracted features from 3D palmprint data usually include depth and curvature of the palm lines and wrinkles on the palm surface.
Contactless friction ridge recognition	Biometric technologies in which the friction ridge mark signature of a finger, palm, foot or finger-knuckle is acquired without direct contact of the relevant body part with a sensing surface, mostly employing video or image acquisition.
Contact-based friction ridge recognition	Biometric technologies in which the friction ridge mark signature of a finger, palm, foot or finger-knuckle is acquired through the contact of the relevant body part with an acquiring surface. For example, contact-based palmprint capture may be performed by asking users to put their hands on a planar surface where their fingers are typically restricted by pegs.
Iris recognition in the NIR spectrum	The iris is a thin, circular structure in the eye that controls the diameter and size of the pupils. Its back surface is covered by a layer of pigmented epithelial tissue, which gives an eye its distinctive colour. *Iris recognition in the NIR spectrum* is the field of biometrics that deals with the recognition of individuals through images of the textural features of the iris captured using near-infrared illumination.

3 For more detailed definitions please refer to Annex II to the Research Study, Chapters 2 and 3.

Technological clusters	Description
Iris recognition in the visible spectrum	This cluster includes iris recognition technologies based on images of the iris captured in the visible spectrum of light. This presents many challenging aspects, especially in the case of individuals with dark irises (caused by higher melanin pigmentation and collagen fibrils) because the unique pattern of the iris is not clearly observable under visible light.
Iris recognition at a distance	*Iris recognition at a distance* (metres away from the subject) might be implemented even for a person walking, thus enhancing travellers' experience at border checks by reducing the need for user cooperation and achieving low intrusiveness, high acceptance and transparency.
Eye vein recognition	In general, vein (or vascular) pattern recognition uses a light source (usually near-infrared light) to acquire images of blood vessels. In the case of *Eye vein recognition*, scanners typically use low-energy lasers and users are typically asked to put their eyes in front of the scanner, as eyes must be very close to the sensors for the vein patterns to be acquired. This cluster encompasses retina recognition and sclera/episclera recognition technologies.
Hand vein recognition	Recognition of individuals through images of the complex structure of larger blood vessels near the skin surface in human hands. These may be captured from hand surfaces as well as from fingers and wrist, using non-invasive and safe imaging techniques. This technological cluster includes finger, palm, back-of-hand and wrist vein recognition.
Heart signal recognition	Heart signals belong to the wider group of physiological characteristics of an individual, i.e. signals that can be acquired and monitored to assess a person's clinical state. This technological cluster includes biometric recognition technologies based on the detection and acquisition of heart-rate variability (HRV), electrocardiographic (ECG) signals, phonocardiographic (PCG) signals and photoplethysmographic (PPG) signals.
Hand geometry recognition	Hand geometry readers take measurements of an individual's hand — including height, width, deviation and angle — and compare those measurements to a reference sample. This cluster is formed by two biometric technologies: contact-based hand geometry recognition and contactless hand geometry recognition.
Periocular recognition	The region around the eye, including the *sclera, eyelids, lashes, brows and skin*, is known as the *periocular region* and can be acquired non-intrusively and used as a biometric characteristic. *Periocular recognition* offers advantages over face recognition as it is least affected by expression variations, ageing effects and facial hair.
Keystroke recognition	Keystroke dynamics is a behavioural biometric characteristic that describes the unique timing pattern used by a person to type on the keyboard of a digital device, derived mainly from the two events that make up a keystroke: Key-Down and Key-Up. *Keystroke recognition* utilises off-the-shelf computer keyboards or virtual keyboards. This technological cluster includes static keystroke recognition and dynamic keystroke recognition.
Gait recognition	Gait is a behavioural biometric characteristic used to recognise individuals by their walking style and pace. Gait has several advantages compared to other biometric characteristics: in most modalities, *Gait recognition* is non-intrusive, does not require cooperation from the individual and can function at moderate distances from the subject. This technological cluster is formed by *Gait recognition* technologies based on video sensors, radar sensors, floor sensors and wearable sensors.
Handwriting recognition	*Handwriting recognition* is the process of recognising the author of a text from their handwriting style; it can be applied to a generic text or to a specific predefined text (usually a signature) and implemented according to two main modalities: dynamic and static.
Speaker recognition	Group of biometric technologies that use information extracted from a person's speech to perform biometric operations such as speaker identification and verification. It is based on the extraction of acoustic features of speech that differentiate individuals. This technological cluster includes text-dependent and text-independent recognition.

Patentometric and bibliometric analyses of biometric technologies

Patentometric and bibliometric analyses were conducted to identify and analyse patents and scientific literature related to the 20 TCs outlined above, and to obtain insights into global R&D activities in the identified biometric TCs.

EU-funded research and innovation projects on topics revolving around the TCs were also analysed to outline the priorities of the European research, technology development and innovation (RTDI) community within the biometrics domain. This analysis supplemented the picture of the technological landscape of biometrics by providing an overview of the EU's investments in R&D projects and by indicating where the highest levels of knowledge and expertise may be found within Europe.

Through the patentometric and bibliometric analyses, the clusters' technological lifecycles were analysed following Altshuller's *Theory of Inventive Problem Solving*, according to which a technology's evolution over time follows distinctive patterns that can be assessed by observing the trend in the number of inventions. Such an assessment helps identify the current stage of a technology's lifecycle and can provide a basis for projections of its future evolution. As a result of the analysis, the TCs were categorised as follows:

- Childhood stage: 2 TCs (*Periocular recognition* and *Gait recognition*);
- Growth stage: 5 TCs (*Infrared friction ridge recognition*, *3D friction ridge recognition*, *Iris recognition in the visible spectrum*, *Iris recognition at a distance* and *Heart signal recognition*);
- Maturity stage: 10 TCs (*Infrared face recognition*, *2D face recognition in the visible spectrum*, *3D face recognition*, *Contactless friction ridge recognition*, *Contact-based friction ridge recognition*, *Iris recognition in the NIR spectrum*, *Eye vein recognition*, *Hand vein recognition*, *Handwriting recognition* and *Speaker recognition*);
- Maturity stage (but of minor relevance[4]): 3 TCs (*DNA biometrics*, *Hand geometry recognition* and *Keystroke recognition*).

The patenting activity related to the TCs appears to be located primarily in the United States. Europe and China alternate as the second most common location. This indicates that R&D, commercial and manufacturing activities are performed on a large scale in these three regions. Germany and the United Kingdom represent the dominant European regions for patenting activity.

The bibliometric analysis further revealed that the Institute of Electrical and Electronics Engineers (IEEE) dominates the editorial activity that concerns the biometric field. It is the most prolific publisher for 19 out of the 20 TCs, making it a key source for monitoring developments in biometrics.

The analysis of EU-funded projects showed that five technological fields (*Face recognition*, *Friction ridge recognition*, *Vascular pattern recognition*, *Periocular recognition* and *Speaker recognition*) are of particular interest for co-funded industrial and academic

4 The temporal distributions of patenting and publishing activities regarding these clusters showed poor similarity with the theoretical pattern proposed by the Theory of Inventive Problem-Solving. These clusters are likely to be characterised by low efficiency in biometric recognition processes. The long-time and low volumes of inventive activities suggest that no growth is foreseen.

research in the EU; *Face recognition* and *Friction ridge recognition* seem to be dominating. Contrastingly, *Heart signal recognition* and *Handwriting recognition* are presumably of minor relevance to the EU.

The results also indicate that British, German, Spanish and French organisations are likely to possess the highest levels of knowledge and capability required to implement these technologies, as they participated in the largest number of EU-funded projects related to the considered TCs.

Scenarios for the future of travel, border checks and biometric technologies in 2040

Parallel to the patentometric and bibliometric analyses, we conducted scenario development. Scenario Analysis is one of the most widely used methods in strategic foresight. Its primary focus is on assessing how various futures might influence the subject of the analysis. The method involves stress-testing strategies, insights and solutions to verify the extent to which they can be considered "future-proof". The scenarios developed in the framework of this project were based on those presented in *The Future of Customs in the EU 2040: A foresight project for EU policy*.[5] During an experts' consultation workshop, they were challenged and adapted to incorporate aspects relevant to the travel and border check context. An overview of the adapted scenarios in a 2x2 matrix is presented in Figure 2.

Clusters found especially vulnerable to future scenarios include *Handwriting recognition*, *Keystroke recognition*, *Eye vein recognition*, *Heart signal recognition*, *DNA biometrics* and *Hand geometry recognition*, primarily because of the challenges associated with the seamless acquisition of biometric data using these technologies. The analysis of technological clusters' compatibility with scenarios serves as a warning, especially in the case of clusters that received low compatibility ratings in some or all the analysed future realities. Futureproofing some of these clusters may be impossible due to fundamental incompatibilities with specific scenarios. This does not mean that they cannot be pursued, but such cases require a more detailed risk assessment and, preferably, also the introduction of a Strategic Early Warning System (SEWS) to indicate the emergence of unfavourable scenarios.

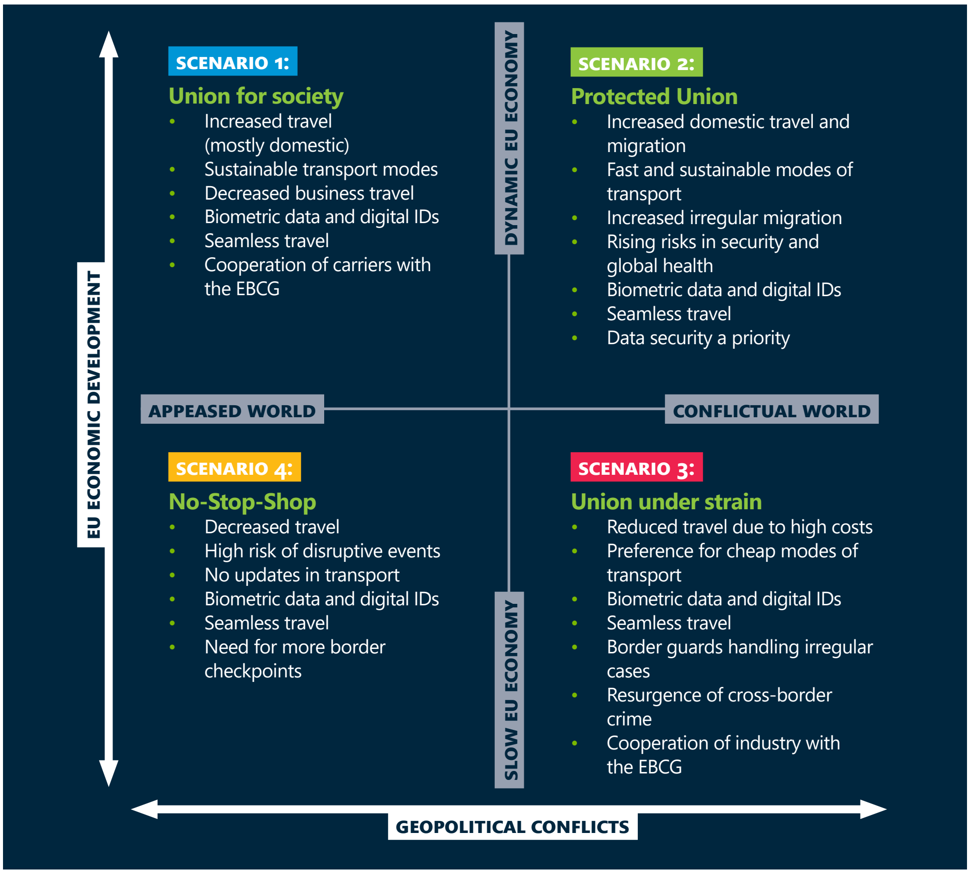
3.3. Filtering the Results

Security aspects of biometric technologies

The security analysis helped filter the 20 biometric TCs, focusing on their comparative inherent vulnerability to adversary attacks. Only attacks at user-level (presentation attacks) and morphing attacks (in the case of face recognition) were considered. The lowest level of vulnerability was assigned to *DNA biometrics*, which is, at least at the current level of technological development, far from seamless and highly intrusive. On the other hand,

5 This study was published in 2020 by the European Commission's Joint Research Centre (JRC) and conducted in collaboration with the Directorate-General for Taxation and Customs Union (DG TAXUD). The scenarios were constructed using a 2x2 Matrix technique, wherein 2 important factors were selected and placed on 2 axes, thus forming 4 quadrants. The chosen factors were geopolitical conflicts (with a peaceful world at one end of the spectrum and a world in conflict on the other) and EU economic development (slow vs dynamic EU economy).

Figure 2: *An overview of scenarios on the future of travel, border checks and biometric technologies used in this study – 2x2 scenario matrix.*



it is highly secure. *DNA biometrics* is closely followed by *Infrared face recognition* and *Eye vein recognition*, which display relatively low vulnerability to adversary attacks. At the other end of the scale is *2D face recognition in the visible spectrum*, which is intrinsically highly vulnerable to presentation attacks (such as artefacts and make-up) and morphing attacks, but has a remarkably high level of social acceptance and — contrary to DNA biometrics — a simple acquisition process. The outcomes of the security analysis were used as an additional filter in the subsequent prioritisation of biometric technologies.

Prioritisation of biometric technologies. Findings of the Delphi Survey

Before proceeding with an in-depth analysis of future technological developments, the initial list of 20 technological clusters needed to be narrowed to a shortlist of the most promising ones. The tool selected for this filtering phase of the project was the so-called *4CF Matrix*. To prepare a 4CF Matrix, hypothetical future technological solutions for border checks that would use each of the 20 TCs needed to be quantitatively evaluated in terms of two criteria:

- *Relative Advantage (RA)*: is the advantage that the envisaged technological solution would have over the best available contemporary solutions. RA is rated on a scale of 0-10, where:
    - 0 means that the envisaged solution would not provide any significant advantage over currently available best-in-class solutions or would be impossible to achieve;

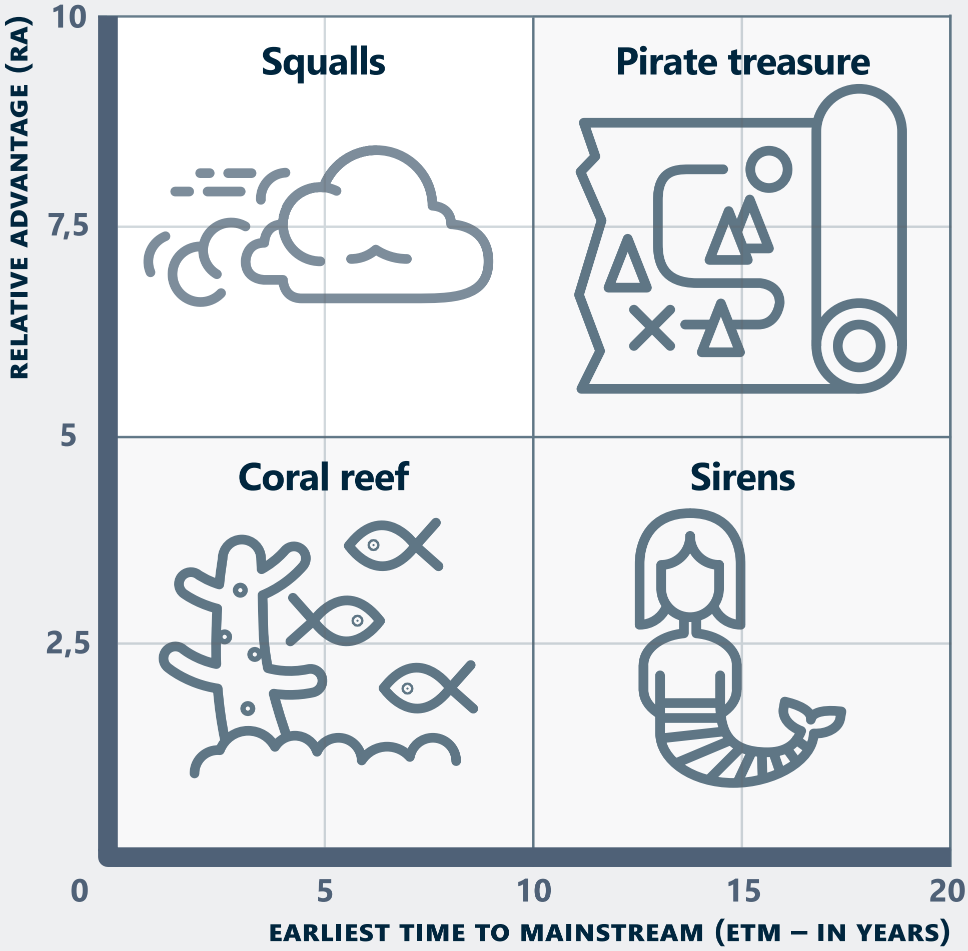


Figure 3: *Names of the 4 quadrants of the 4CF Matrix.*

   - 10 indicates a game-changer, i.e., a solution that would drastically improve travellers' border check experience.
- *Earliest Time to Mainstream (ETM)*: is the shortest time (from the present moment) required for the solution to become available on the market and widely adopted in border checks at external EU borders. In other words, ETM represents the shortest time necessary for the development, commercialisation and adoption of such a solution, taking into account not only the possible technological barriers, but also other relevant factors, including social, political and economic ones. ETM is assessed on a scale of 0-20 years, with:
   - 0 signifying that the envisaged technological solution is already available on the market and is widely adopted;
   - 20 indicating periods of 20 years and longer, including technological solutions which can never be realised.

To assess the 20 TCs according to these criteria with the support of a group of experts, a Delphi Survey was set up using an online real-time platform. Pre-selected stakeholders were invited to assess the 20 TCs.

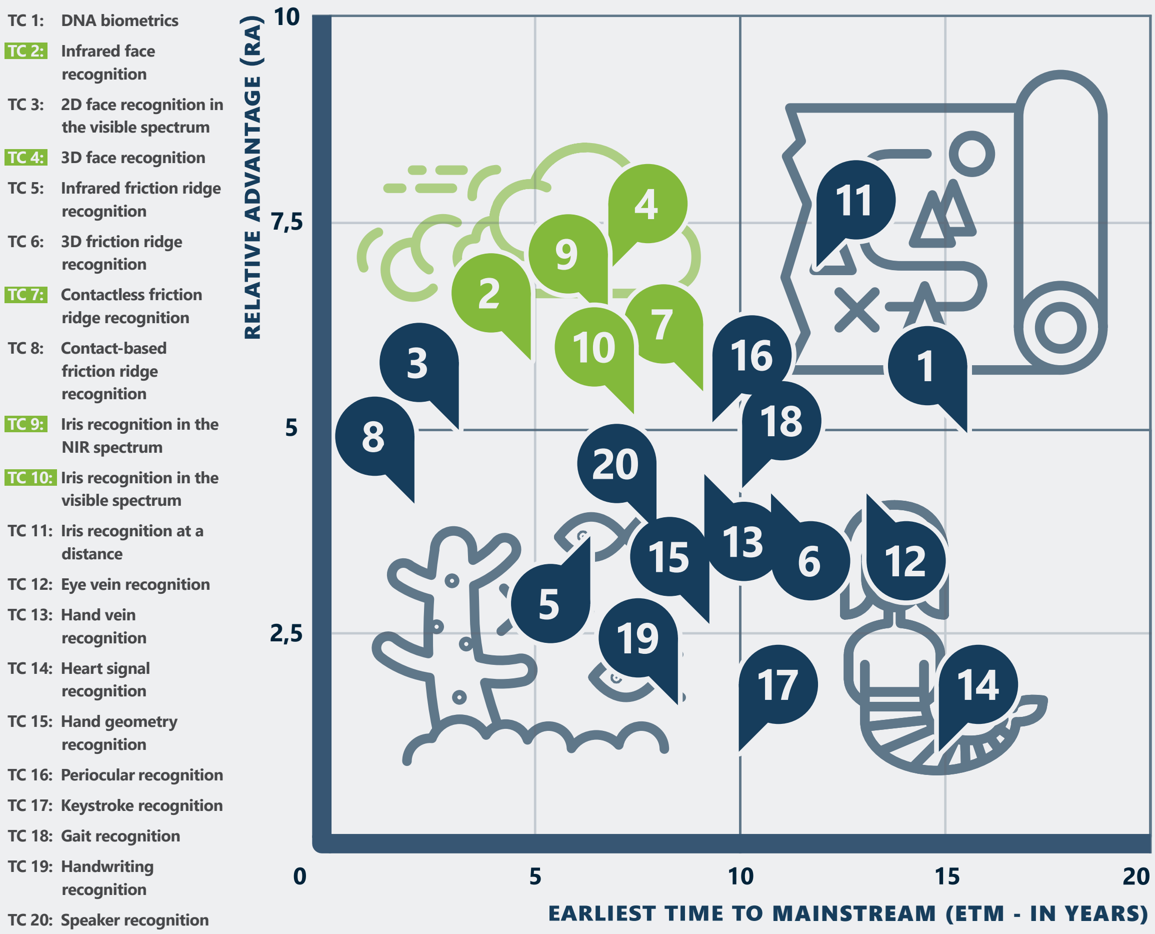


Figure 4: *4CF Matrix presenting the outcomes of the Delphi Survey. Assessment of the 20 biometric technological clusters in terms of their Relative Advantage and Earliest Time to Mainstream. The shortlisted KTCs are marked in green.*

Based on the assessments from the *Delphi Survey*, a 4CF Matrix was constructed, allowing the identification of technological clusters belonging to the 4 quadrants of the matrix (see Figure 3): from areas containing solutions that show little promise in terms of relative advantage but could be implemented quickly (*Coral reef*) to those that are very distant in time but contain ground-breaking solutions (*Pirate treasure*).

The 33 participants in the *Delphi Survey* included representatives of selected stakeholders, Frontex representatives and the Research Team. Based on the results, a composite metric combining Relative Advantage and Earliest Time to Mainstream was calculated for each of the clusters to prioritise those closer to the top-left corner of the 4CF Matrix (those with a combination of high RA and low ETM).

After an additional cross-check that verified redundancy, ensured the inclusion of "must-haves" (identified in the needs assessment) and considered the inherent vulnerability to adversary attacks (rated in the security analysis), five key biometric technological clusters (KTCs) were selected for an in-depth analysis: *3D face recognition, Infrared face recognition, Iris recognition in the NIR spectrum, Iris recognition in the visible spectrum* and *Contactless friction ridge recognition*. These 5 clusters are marked green in Figure 4, which presents their placement on the 4CF Matrix.

The five key technological clusters are all located in the "Squalls" quadrant of the 4CF Matrix, a clear indication that their importance should be emphasised in strategic plans. However, the placement of the other 15 technological clusters on the 4CF Matrix is equally important, as detailed further in the Research Study.

3.4. Deep Analysis

Roadmaps for the key biometric technological clusters by 2040

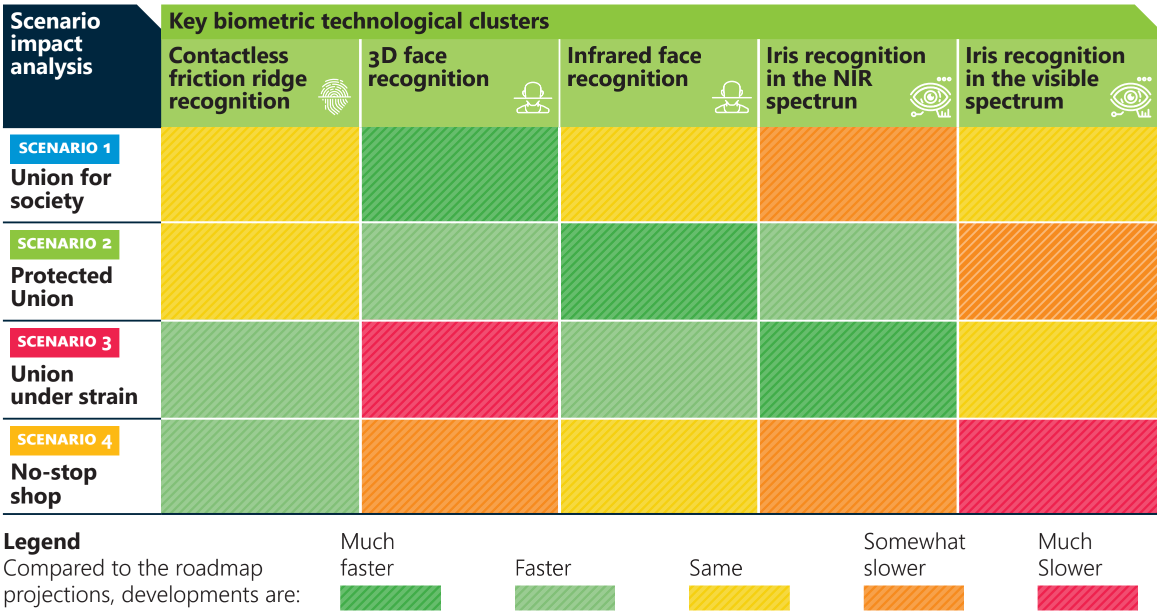
Within the *Deep Analysis* phase of the project, technology roadmapping was the planning method of choice. In general, it is applied to envision the short-, medium- and long-term paths in the development and evolution of technologies and products. The roadmapping approach aligns with technology-push and market-pull perspectives, thus supporting innovation and strategic planning at the level of an organisation, a sector or even a nation. Its role in the *Technology Foresight on Biometrics for the Future of Travel* was threefold: **(a)** to identify the development paths of the key biometric technological clusters in the 2021-2040 timeframe, **(b)** to determine key turning points in technological developments (factors delaying or accelerating the envisioned developments) and **(c)** to confront technology roadmaps with alternative scenarios regarding border-check processes and the future of travel. Each of the roadmaps for the five KTCs, which were created during a two-day participatory expert workshop, consists of three layers: application areas, functions and products or systems.

The roadmapping analysis, conducted under business-as-usual conditions, included an assessment of the opportunities (drivers) and challenges (bottlenecks) that could potentially affect the technological projections. It should be noted that the roadmaps should not be treated as a forecast but rather as an invitation to analyse the development paths of the technological clusters further, monitoring associated opportunities and threats and questioning the assumptions underlying strategic plans. Among the crucial takeaways are the identified key opportunities and challenges to the development of the KTCs in the 2021-2040 timeframe (Table 2) and the qualitative assessment of the impact of the four scenarios on the clusters' development (Table 3).

Table 2: *Key factors (opportunities and challenges) in the timeframe up to 2040 – a cross-cluster comparison*

Technology roadmap analysis		**Key biometric technological clusters**				
Key turning points	**Layers of the roadmap**	**Contactless ridge recognition**	**3D face recognition**	**Infrared face recognition**	**Iris recognition in the NIR spectrun**	**Iris recognition in the visible spectrum**
Opportunities	**APPLICATION AREAS**	Research aimed at the development and analysis of the quality of contactless fingerprint samples	Consumer market uptake (e.g. entertainment) would drive further development and reduce costs	Pilot programmes to compare wave-lengths and imple-ment sensor fusion	Low vulnerability to presentation attacks	Healthcare market uptake could increase under-standing that iris acquisition is eye-safe
	FUNCTIONS	Contactless biometrics is advantageous during pandemics	Adopting multi-modal biometric solutions which combine *3D face recognition* with other biometric modalities to achieve better accuracy	Use of thermal infrared cameras for temperature measurement, which can be an important feature in case of pandemics	NIR light sources (850, 905, 940 nm) are readily available	Research on the use of multi-spectral or hyperspectral iris imaging for the increased accuracy (spatial resolution)
	PRODUCTS AND SYSTEMS	Possibility of using existing sensors (e.g. cameras in smartphones)	Introduction of digital identity management schemes and novel algorithms for processing non-ideal images	Enabling acquisition (and processing) of IR images at different wave-length bands and effectively working at sensor fusion level via pilot projects	Integration of *Iris recognition in the NIR spectrum* into stand-off seamless systems for border checks would improve societal acceptance of this modality	Low technical bar-riers to implement digital identity wallets including Iris biometric reference data
Challenges	**APPLICATION AREAS**	Accuracy and security might be a challenge in mainstream use for border checks	Legal and ethical aspects (an agree-ment on what the biometric data might comprise)	Technology issues linked to IR illumination might require additional witness-based methods of recognition, which lowers seamlessness	Capturing biometric samples of such a small body part in motion and from a distance makes the technology difficult to develop and integrate into seamless systems	Functional limitations (stated below) might be a challenge for mainstream use in border checks
	FUNCTIONS	Extension of the distance and increase of the accuracy of the technology	Acquisition meth-ods for obtaining high-quality, reliable and interoperable data formats for 3D face images (especially for image acquisition at a distance)	Availability in the EU of foundries of affordable, accessible NIR-SWIR-LWIR image sensors	Eye safety issues when using IR illumination at wavelengths shorter than 1500 nm	Inclusivity (dark iris limitations) Suitable illuminators in visible light Iris image acquisition at a distance
	PRODUCTS AND SYSTEMS	Motion stability Interoperability Lack of harmonised regulations and standards for biometric data acquisition and exchange	The use of e-passports would require reading the passport and processing a large volume of data, which would rule out seamlessness	Development of EU regulations and standards for IR image acquisition	Introduction of enrolment via smartphone dependent on adoption of suitable solution by the mobile phone industry	Lack of harmon-ised guidelines and standards for the assessment of the operational performance of technological systems based on iris recognition

Table 3: *The impact of external realities described in the four scenarios on the technological developments envisaged in the roadmaps — a cross-cluster comparison.*



During the roadmapping analysis, the stakeholders' experts underlined that biometrics is a highly regulated environment. Therefore, advances are introduced gradually and external conditions (e.g. unfavourable economic standing or geopolitical situation) do not have a crucial impact on technological evolution. Nevertheless, examining developments of the key clusters in light of possible scenarios of EU development through 2040 revealed that the solutions are not entirely resistant to changes in the external environment.

3.5. Mapping the Capabilities

Capability mapping for the key biometric technological clusters

The roadmapping described above was accompanied and supplemented with a capability mapping exercise, the fifth and final phase of the Research Study. The exercise aimed to identify the existing capabilities for the five KTCs in the EU, as well as the expected development of capability readiness through 2040. The capability landscape shown by this exercise highlights opportunities and gaps associated with each of the technological clusters, providing a good foundation for strategic decision-making.

The outcomes of the capability mapping are presented in the form of heatmaps of capability readiness (defined as the degree to which cluster-specific capability-related needs are or will be met) for the five KTCs, distinguishing three timeframes (present, 2022-2027 and 2028-2033)[6] as well as the four customised scenarios. This analysis revealed that

6 It is assumed that once a biometric KTC has entered the mainstream, it will be available for implementation in border check systems and will not require any further capability development. Therefore, the long-term timeframe (2034-2040) was eliminated from the capability mapping exercise, as all five KTCs demonstrate an average ETM before 2033.

at present the majority of research, industrial and institutional overall capability readiness of any KTC is relatively low (with the exception of research capabilities for *Contactless friction ridge recognition*). Fortunately, most of those needs are expected to be met by 2027 or 2033 at the latest. *3D face recognition* and *Iris recognition in the NIR spectrum*, followed by *Iris recognition in the visible spectrum*, are expected to perform better than the other KTCs as they display good capability readiness from 2028 onwards.

One recommendation in the study is that any assumptions on future capability readiness levels should be closely monitored, both to track which scenario best matches the emerging trends and to track whether the assumptions themselves are still realistic. Adapting capability-based planning to the actual unfolding trends minimises the risk of missing the defined capability target for each KTC.

4. Conclusions

This Research Study provides an overview of the foreseen evolution and future applications of biometric technologies in border check systems that may prove useful for the EBCG community in the short- (2022-2027), medium- (2028-2033) and long-term (2034-2040) perspectives. Each of the phases of this complex study comes with its own set of insights meant to support the EBCG community in deciding about the adoption of novel biometric technological solutions and exploiting new opportunities while avoiding or mitigating associated threats. When transferring these insights into actionable recommendations, the context, as well as the process during which they were identified, should be considered. The outcomes of the prioritisation and roadmapping of emerging biometric technologies with the strongest potential to influence the future strategic development of Integrated Border Management deserve particular attention. The following were identified as the five KTCs:

- Contactless friction ridge recognition,
- 3D face recognition,
- Infrared face recognition,
- Iris recognition in the NIR spectrum,
- Iris recognition in the visible spectrum.

Due to the substantial amount of information provided and the participatory foresight approach adopted, the Research Study will directly contribute to an enhanced understanding of the relevance and applicability of foresight for forward-looking decision-making within the EBCG community. The Research Team believes that a thorough analysis of the output will reveal that its benefits extend far beyond the immediate value of the information. To leverage this value, however, further effort is needed to merge the results with additional sources of knowledge-based evidence and fuse them into the relevant streams of innovation management and strategy development, thus arriving at a well-grounded vision of the future with clear implementation pathways. The expected result of such an approach is the increased application of innovative biometric technologies in border checks, which will benefit both travellers and the EBCG community in the coming years.

This project resulted in a number of outcomes and deliverables described in detail in the respective chapters of the Research Study and its three Annexes. These are expected to provide essential insights for Frontex and the larger EBCG community regarding future research directions, strategic planning and decision-making:

- The **Technology Foresight Manual** (Annex I) provides a thorough explanation of the TF process, customised to the needs of the project with successive future implementations in mind, as well as the adopted methods and tools.
- The **taxonomy of biometric technologies and biometrics-enabled technological systems** (Annex II), produced for the purposes of the project, can be of great benefit to future research and innovation activities revolving around these subjects.
- The **analysis of patents, scientific literature and EU-funded projects** (Annex III) provides an overview of the global technological landscape and shows the evolution of EU interest in biometrics over time. The results can help focus future research initiatives.

- The **customised set of scenarios** can be used to future-proof any potential new technology as well as systems or products intended for use in the areas of travel and border checks (not limited to biometric technologies).
- The **4CF Matrix** of biometric technological clusters can serve as the groundwork for future strategic planning, decision-making, research and investments, allowing for the systematic comparison of new biometric technologies (not limited to the five KTCs identified in the Research Study) as well as tracking the impact of technological advancements and other factors on the placement of those technologies on the Matrix.
- The **set of roadmaps** developed for the key biometric technological clusters can be used as a starting point for further analysis of these technological clusters' development paths, monitoring associated opportunities and threats and questioning the assumptions of underlying strategic plans.
- The **capability readiness heatmaps** show a comprehensive overview of the extent to which cluster-specific needs are met or will be fulfilled in the future. They can be used by the EBCG community to identify the actions needed for strategic capability development.

In conclusion, the information obtained during this Technology Foresight project provides multiple opportunities for the further use of the findings in other contexts. Thus, the authors encourage everyone to read the full Research Study. Beyond Frontex, it is hoped that the entire EBCG community can take stock of the results and employ them for strategic planning to take more immediate actions regarding the development and implementation of biometric technologies for border checks. Furthermore, the Research Team believes that the findings can be used by public organisations, research and technology organisations, academia and industrial entities in Europe to identify areas of strategic interest and to make informed decisions about paths of future developments in biometrics, acting towards strengthening European strategic autonomy in the field of biometrics.

Plac Europejski 6, 00-844
Warsaw, Poland
T +48 22 205 95 00
F +48 22 205 95 01
frontex@frontex.europa.eu
www.frontex.europa.eu

PDF:
TT-07-22-484-EN-N
ISBN 978-92-9467-426-5
doi 10.2819/387848

Print:
TT-07-22-484-EN-C
ISBN 978-92-9467-425-8
doi 10.2819/605528

FPI 22.0058

EPUB:
TT-07-22-484-EN-E
ISBN 978-92-9467-506-4
doi 10.2819/821958

MOBI:
TT-07-22-484-EN-L
ISBN 978-92-9467-505-7
doi 10.2819/146278