FRONTEX
EUROPEAN BORDER AND COAST GUARD AGENCY

TECHNOLOGY FORESIGHT ON BIOMETRICS FOR THE FUTURE OF TRAVEL

Research Study

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

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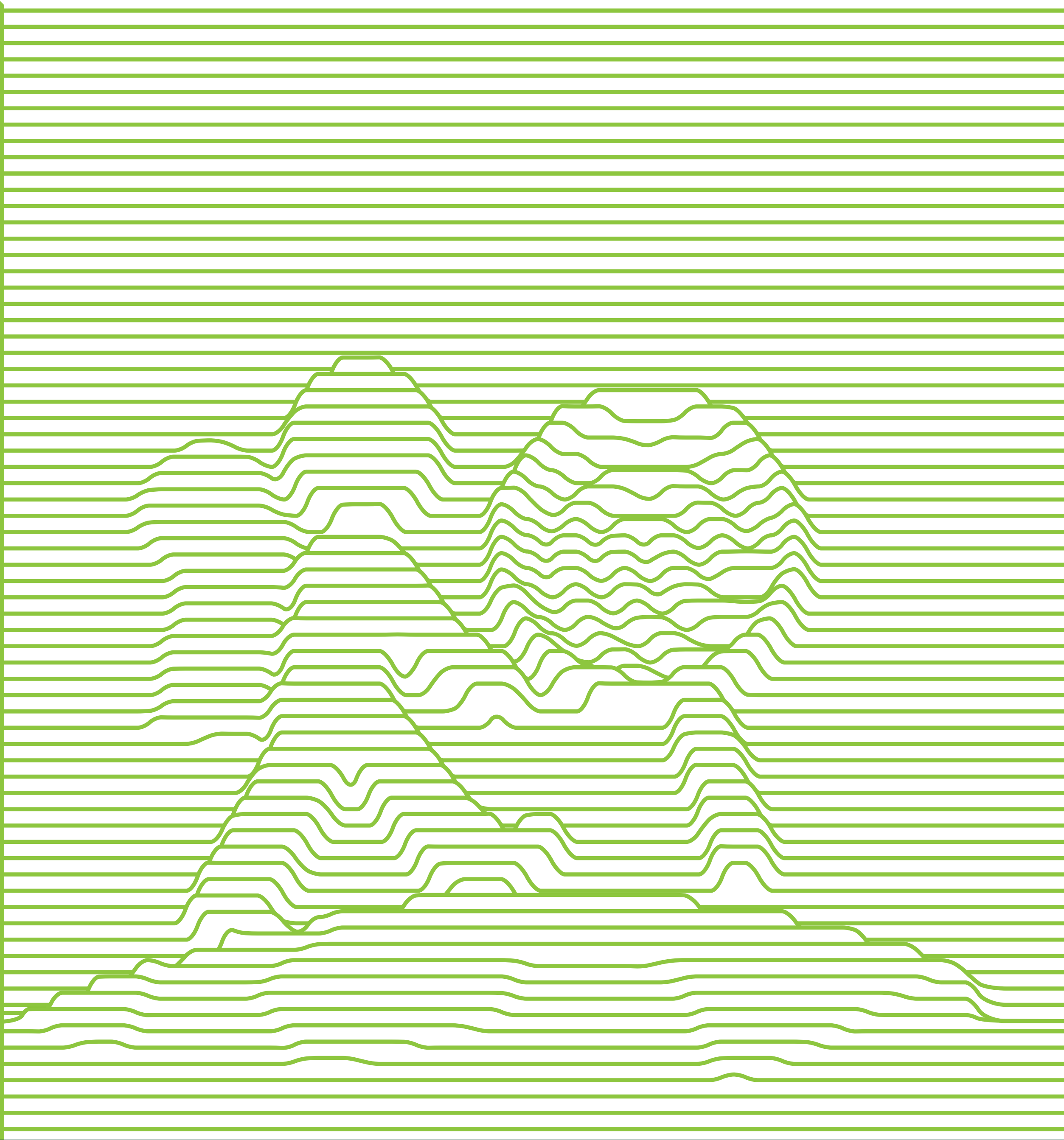

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Warsaw, September 2021

Foreword by the Executive Director of Frontex

In the coming years, emerging technologies will fundamentally change border management, creating significant opportunities for making the journey of travellers to Europe easier, safer and hassle-free, in a word "seamless". In particular, biometric technologies have a strong potential to pave the way to the long-dreamed objective of having secure and "transparent" external EU borders, ensuring the free movement of persons within the Union as the fundamental component of the Schengen area of freedom, security and justice.

Frontex implements research and innovation as one of the horizontal components of the European integrated border management, continuously striving to facilitate an enabling environment for innovation and remaining abreast of the latest developments in technologies for border management. In this context, the *Technology Foresight on Biometrics for the Future of Travel* is an example of how Frontex, the European Border and Coast (EBCG) community, scientists, engineers and government officials can work hand in hand, complement their knowledge and experience to unlock insights in the area of biometrics. The guiding idea behind this project was to make a first step towards a paradigm shift from reactive to predictive research and innovation, exploring and anticipating the future of biometrics using collective intelligence, which we hope led to the most comprehensive foresight result.

The focus of the report has been on the large-scale application of biometrics in border checks. The first part of the study presents current knowledge in the form of an up-to-date taxonomy for biometric technologies, analysis of patents, large volumes of scientific data and EU-funded projects in the area of biometrics. In the second part, selected technology foresight methods have been utilized to embrace uncertainty and consider the range of future developmental pathways. This, on the other hand, helped to design a customised set of scenarios to future-proof potential new technologies and roadmaps to monitor the development paths. All these results connect known, new, or emerging issues that could significantly impact biometric technologies.

I would like to particularly draw your attention to the roadmaps for the key biometric technological clusters by 2040. These are strategic options in preparing border checks for the future by taking advantage of opportunities, confronting challenges and mitigating risks proactively. The roadmaps represent a "rich picture" and are a perfect example of capturing knowledge and experience from a wide range of perspectives. They can be used to provide context and broad direction. The roadmaps enable a consistent language and approach to be developed in terms of understanding the relationships between specific technology areas, system performance and industry drivers.

The roadmaps described above were accompanied and supplemented with a capability mapping exercise, the last phase of the research study. This exercise identified the existing capabilities for the key technologies in biometrics, 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.

I invite you to read and reflect on how the findings link to your national technical expertise and developments in the area of biometrics. This will lay the foundation for the next challenge which again requires our collective effort: strengthening the required capabilities and deploying resources in the best way possible. I hope that this research study will guide us in this journey contributing to the creation of a common forward-looking vision for the European Border and Coast Guard and providing clear, independent and up-to-date knowledge.

Aija Kalnaja
Executive Director of Frontex (ad interim)

Table of Contents

Figures and Tables

Abbreviations and Acronyms

Abbreviation / Acronym	Definition
2D	Bi-dimensional
3D	Three-dimensional
ABC	Automated Border Control
AI	Artificial Intelligence
BCP	Border Crossing Point
CNN	Convolutional Neural Networks
CORDIS	Community Research and Development Information Service
DG TAXUD	European Commission's Directorate-General for Taxation and Customs Union
DG HOME	European Commission's Directorate-General for Migration and Home Affairs
DL	Deep Learning
DNA	Deoxyribonucleic acid
DOCDB	DOCument DataBase DOCDB is the European Patent Office's master documentation database with worldwide coverage. It contains bibliographic data, abstracts, citations and the DOCDB simple patent family, but no full text or images The DOCDB simple patent family is defined by the European Patent Office as "*a collection of patent documents that are considered to cover a single invention. The technical content covered by the applications is considered to be identical*" (https://www.epo.org/searching-for-patents/helpful-resources/first-time-here/patent-families/docdb.html)
EBCG	European Border and Coast Guard
EBCG community	Frontex; the national authorities of Member States responsible for border management, including coast guards to the extent that they carry out border control tasks; and the national authorities responsible for return, as indicated in Regulation (EU) 2019/1896 of the European Parliament and of the Council of 13 November 2019 on the European Border and Coast Guard – Article 4
EBCG regulation	Regulation (EU) 2019/1896 of the European Parliament and of the Council of 13 November 2019 on the European Border and Coast Guard (OJ L 295, 14.11.2019, p. 1)
EC	European Commission
EES	Entry-Exit System Currently under development, the EES will electronically register the time and place of the entry and exit from the EU of third country nationals as well as calculate the duration of their authorised stay. It will replace the obligation to stamp the passports of third country nationals. Established by Regulation (EU) 2017/2226
EPO	European Patent Office
ETIAS	European Travel Information and Authorisation System Currently under development, the ETIAS will be a pre-travel authorisation system for visa-exempt travellers. Its key function is to verify whether a third country national meets entry requirements before travelling to the Schengen Area Established by Regulations (EU) 2018/1240 and (EU) 2018/1241
ETM	Earliest Time to Mainstream (not to be confused with Estimated Time to Mainstream)

Abbreviation / Acronym	Definition
EU	European Union
Frontex	The European Border and Coast Guard Agency Governed by Regulation (EU) 2019/1896
Frontex Representatives	Frontex staff who participated in the *Tech Foresight on Biometrics*
GDPR	General Data Protection Regulation
Group of Experts	Subject-matter experts representative of stakeholders selected to participate in the consultation and collective intelligence activities conducted within the framework of the *Tech Foresight on Biometrics*, such as the workshops and the *Delphi Survey*. This also included members of the Research Team and Frontex Representatives
IATA NEXTT	International Air Transport Association New Experience Travel Technologies
ICAO	International Civil Aviation Organization
ICAO NTWG	ICAO New Technologies Working Group
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
JRC	European Commission's Directorate-General Joint Research Centre
KTC	Key Technological Cluster
LEA	Law Enforcement Agency
LWIR	Long-Wavelength Infrared; electromagnetic radiation with 8-15 μm wavelength
MECE	Mutually exclusive and collectively exhaustive
ML	Machine Learning
MS	Member State
MWIR	Medium-Wavelength Infrared; electromagnetic radiation with 3-8 μm wavelength
NIR	Near-Infrared; electromagnetic radiation with 0.78-1.0 μm wavelength
OEM	Original Equipment Manufacturer
OpenAIRE	Open Access Infrastructure for Research in Europe (https://www.openaire.eu/)
PAD	Presentation attack detection
R&D	Research and Development
R&I	Research and Innovation
RA	Relative Advantage
Research Team	Employees of the of the Contractor selected by Frontex to conduct the *Technology Foresight on Biometrics for the Future of Travel* (Steinbeis 2i GmbH) and its Subcontractors (4CF Sp. z o.o., Erre Quadro S.r.l. and the Instytut Optoelektroniki – Wojskowa Akademia Techniczna), who jointly provided expertise in the following fields: • Project Management • Strategic Technology Foresight • Biometrics for border control systems • Smart and Autonomous Systems • Systems Engineering for border control

Abbreviation / Acronym	Definition
Research Team Experts	Members of the Research Team who provided subject-matter expertise in the following disciplines: • Biometrics for border control systems • Smart and Autonomous Systems • Systems Engineering for border control
RTDI	Research, Technology Development and Innovation
SAC	Schengen Associated Country
Schengen Borders Code	Regulation (EC) No 562/2006 of the European Parliament and of the Council of 15 March 2006 establishing a Community Code on the rules governing the movement of persons across borders
SEWS	Strategic Early Warning System
SPIE	Society of Photo-Optical Instrumentation Engineers
SSI	Self-sovereign identity
SWIR	Short-Wavelength Infrared; electromagnetic radiation with 1-3 μm wavelength
TC	Technological Cluster. TCs represent a level of abstraction of the biometric technologies included in the Taxonomy of biometric technology, which was defined in order to enable *Patentometric and Bibliometric Analyses* and to ensure the usability of the taxonomy in the different phases of the *Tech Foresight on Biometrics*. See Annex III – Patentometric and Bibliometric Analyses of Biometric Technologies.
Tech Foresight on Biometrics	Technology Foresight on Biometrics for the Future of Travel
TF	Technology Foresight
TFP	Technology Foresight Process
TRIZ	From Russian "*Teoriya Resheniya Izobretatelskikh Zadatch*", which may be translated as "*Theory of Inventive Problem Solving*"
TRL	Technology Readiness Level

Preface

This Research Study is the final document delivered within the framework of the *Technology Foresight on Biometrics for the Future of Travel*, commissioned by Frontex, the European Border and Coast Guard Agency. The project was conducted between January and September 2021 by Steinbeis 2i GmbH (S2i), which has extensive expertise in the implementation of Technology Foresight activities, policy advice, EU-funded RTDI projects and technology transfer. S2i was strongly supported by 4CF, Erre Quadro and Wojskowa Akademia Techniczna.

The Research and Innovation at Frontex coordinates horizon scanning of available science and technological developments, making them available to MS/SAC and Third Countries. It serves as an EBCG knowledge hub and observatory of border management research, innovation and technological developments, supporting future-oriented research and fostering innovative approaches and applications.

Biometric technologies are expected to be of increasing importance for EU external border management, as they could potentially increase the efficiency and strength of border checks and enable seamless travel, thus helping smooth the travel of bona-fide passengers crossing EU external borders while simultaneously safeguarding a high level of security. Therefore, Frontex's Research and Innovation decided to commission this *Technology Foresight on Biometrics*, with the following aims: a) to provide a comprehensive foresight methodology tailor-made to Frontex's needs, and b) to implement this methodology using quantitative, qualitative and participatory approaches to identify biometric technologies of high relevance to future applications in border checks.

This document outlines the approach and outcomes of the research. The authors believe the study provides relevant input for Frontex's strategic decision-making processes and generates useful anticipatory intelligence. In addition, it is expected that the entire EBCG community can take stock of the results and identify potential paths of action concerning the development and implementation of biometric technologies for border checks. Finally, the findings can be used by public organisations, research and industrial entities in Europe to identify areas of strategic interest and to take action towards strengthening European strategic autonomy.

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Note on Fundamental Rights

When biometric technologies and biometrics-enabled technological systems are investigated and considered for the purpose of border control, special consideration must be given to the fundamental rights implications of collecting, storing and using biometric data. Under the EU data protection acquis, biometric data are sensitive personal data. As such, EU law provides for enhanced protection of biometric data, and more stringent requirements and additional safeguards apply compared to other personal data (see Article 9 (2) (g) of the General Data Protection Regulation[1] and Article 10 of the Law Enforcement Directive).[2] Moreover, fundamental rights are an integral and cross-cutting component in the implementation of European Integrated Border Management as stipulated in Article 3 of the European Border and Coast Guard Regulation.[3]

In light of the constantly developing technology, infringements on fundamental rights are not easy to predict in a foresight exercise. However, this study acknowledges that fundamental rights considerations – which are legally binding requirements – should be assessed case-by-case if any biometric technologies identified by the study are deployed.

The processing of biometric data by new technologies deployed at the EU external borders may potentially bring opportunities, but also risks for fundamental rights. These can affect a wide range of fundamental rights, as enshrined in the EU Charter of Fundamental Rights and the European Convention on Human Rights, including the right to privacy, the right to data protection, as well as human dignity, the prohibition of discrimination, the right to a good administration, the rights of the child and the right to an effective remedy. Hence, the necessity and proportionality of potential infringements on these rights triggered by the deployment of new technologies must be assessed case-by-case.

Recent reports published by the European Union Agency for Fundamental Rights (FRA) on the potential impacts of the use of biometric technologies in large-scale IT systems on fundamental rights[4, 5] highlight the importance of respect for human dignity when processing biometric data. FRA has further analysed the potential discriminatory impact of certain biometric technologies, particularly those that are AI driven, such as facial recognition technology.[5] The Agency has also raised potential issues with respect to

1 Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation), OJ 2016 L 119/1.

2 Directive (EU) 2016/680 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data by competent authorities for the purposes of the prevention, investigation, detection or prosecution of criminal offences or the execution of criminal penalties, and on the free movement of such data, and repealing Council Framework Decision 2008/977/JHA (Law Enforcement Directive), OJ 2016 L 119/89.

3 Regulation (EU) 2019/1896 of the European Parliament and of the Council of 13 November 2019 on the European Border and Coast Guard and repealing Regulations (EU) No 1052/2013 and (EU) 2016/1624.

4 European Union Agency for Fundamental Rights, "Under watchful eyes: biometrics, EU IT systems and fundamental rights", Luxembourg, Publications Office of the European Union, 2018.

5 European Union Agency for Fundamental Rights, "Facial recognition technology: fundamental rights considerations in the context of law enforcement", Vienna, 2020.

the reliability of stored biometric data, as well as the possibilities for persons to access, correct and delete their own data, and the risk of unlawful access.[4] Strong independent oversight mechanisms and effective remedies should be in place to monitor and address any misuse or negative impact of such technologies on fundamental rights.[5] FRA also indicates that when designing new technological solutions, the industry and the scientific research community can play an important role in promoting respect for fundamental rights, including the protection of personal data, by embedding data protection in the technology by design and by default.[4]

Furthermore, we acknowledge the need to also have robust fundamental rights impact assessment frameworks as an essential pre-requisite before the large-scale deployment of future biometric technologies for border checks. Fundamental rights impact assessments are key to ascertaining the extent to which the adoption of novel biometric technologies affects different fundamental rights, and to reducing the negative impacts.[6] Also, although biometric technologies that can enable fully-automated seamless border check systems are the main target in this study, the 'human in the loop' factor is considered essential to guarantee human review and thus full respect for fundamental rights and, ultimately, social acceptance of even the most accurate and sophisticated biometric technological solutions. The role of border guards is foreseen to remain essential to directly supervise the systems and for intervening in exceptional cases.

In light of the above, the Research Team and Frontex, whenever possible during the course of the study, especially during the expert consultation events, did their utmost to highlight the need to envisage future challenges and opportunities for fundamental rights entailed by biometric technologies, and the strict relationship of these with social acceptance of novel technological solutions in the future. Considering the prevalent focus of this research endeavour towards anticipating future technological developments of biometrics, studied under different socioeconomic and geopolitical hypothetical future scenarios with legal frameworks potentially different from today's, as well as the major collective intelligence component needed to carry out a Technology Foresight exercise, those opportunities and challenges were reflected directly or indirectly mainly in the outcomes of specific project activities such as needs analysis, scenario building, security assessment, prioritisation of biometric technologies, roadmapping and capability mapping, as can be seen in the following chapters.

6 A detailed discussion of fundamental rights impact assessment as a practical tool for protecting fundamental rights can be found in: European Union Agency for Fundamental Rights, "Getting the future right. Artificial intelligence and fundamental rights", Luxembourg, Publications Office of the European Union, 2020.

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. A complete list of all the organisations that participated in the project can be found in Appendix 3.

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, needs-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.

Introduction

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.

This Research Study comprehensively outlines the approach followed for implementing the *Technology Foresight on Biometrics for the Future of Travel* as well as its outcomes.

Objectives of the Research Study

The study analysed future trends to provide technology-related insights on biometric solutions and, thus, to identify the most promising technologies and explore their future applications in border checks. The main aims of the study were twofold:

a) to provide a comprehensive foresight methodology, tailor-made to Frontex's needs, and

b) to implement this methodology using quantitative, qualitative and participatory approaches to identify biometric technologies of high relevance to future applications in border checks.

The outcomes of the exercise shall provide Frontex with the practical knowledge required for further TF studies in other technological fields and research areas, as well as supplying 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.

A good definition of the scope of the study was essential. It 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 border surveillance as well as emotion and behaviour detection.

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 through 2040;
- Identification of biometric technology accelerators, including the main actors and R&D initiatives.

On an 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 the present Research Study to encourage joint initiatives, the development of a shared vision and strengthened capability development.

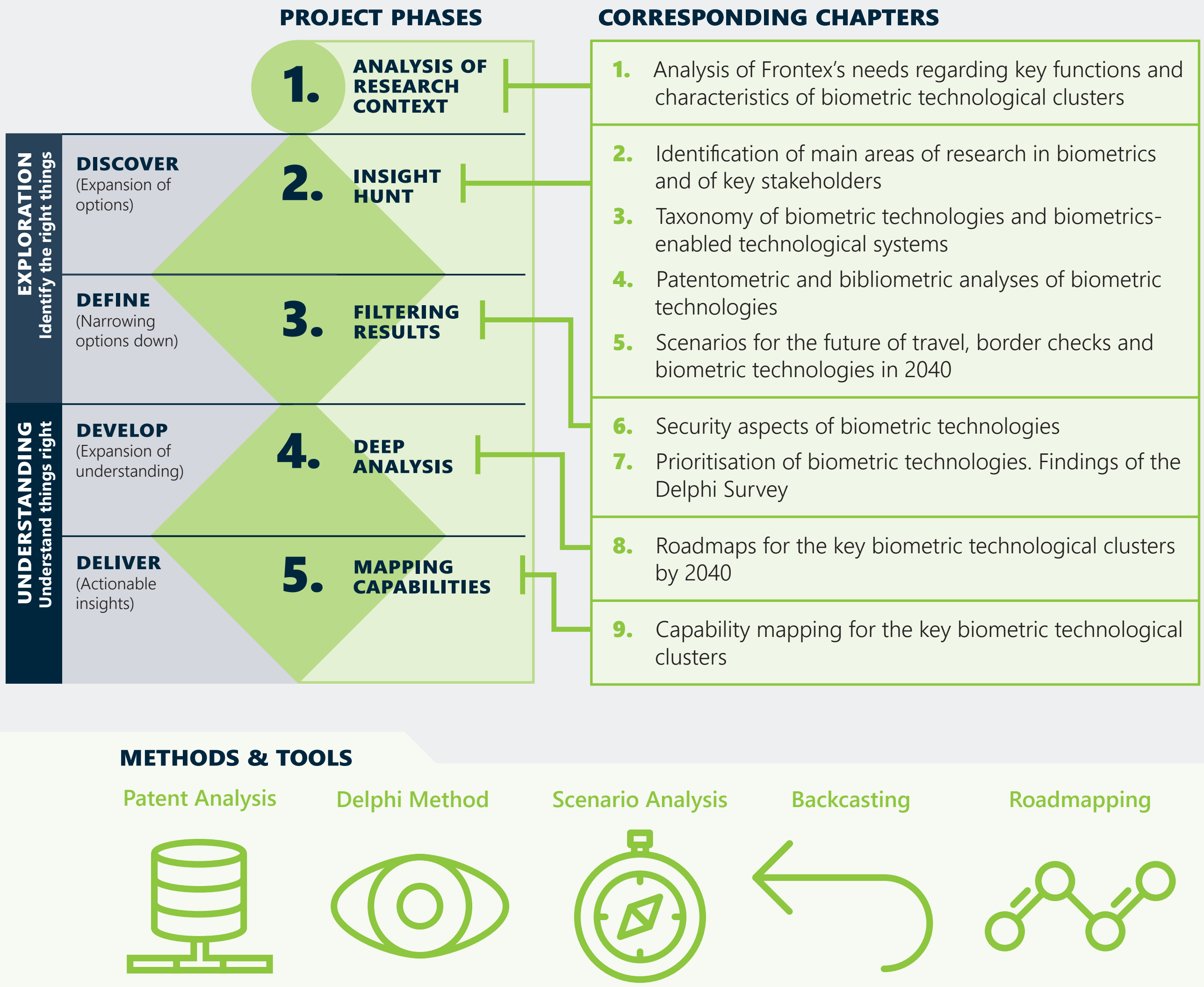


Figure 1: *Overview of the project phases, corresponding Research Study chapters, as well as the main methods used within the project.*

Structure of the Research Study

The Research Study was structured in five phases, as depicted in Figure 1. In the following chapters (linked to project phases as in Figure 1), both the approach adopted to implement the specific phases and the results are outlined.

The first phase defined the overall methodology and framed the context according to the needs expressed by Frontex. The subsequent phases were depicted as two diamonds: each begins by opening the horizon and broadening the knowledge, eventually narrowing down the insights obtained and, thus, identifying the targeted outcomes. The main methods used throughout the project are listed in the same figure and are briefly described in Table 1. The methods are not directly linked to chapters or phases due to their diversified use. The methodological approach is discussed in the respective chapters.

Table 1: *Brief description of the main methods used within the project.*

Patent Analysis	Patent literature — published official documents containing details about inventions — is a unique source of technical information. Studies have shown that about 80% of the technical information contained in patent documents is not available elsewhere. Thus, a patentometric analysis was conducted within the project to map state-of-the-art biometric technologies and outline the technological landscape in this area of research. The patentometric analysis was supplemented with a scientific literature analysis as well as an examination of EU-funded projects. The results were used to compile a list of biometric technologies potentially important for the EBCG community.
Delphi Method	The Delphi method was originally developed in the 1950s and 1960s in the United States by the RAND Corporation to assess the impact of contemporary technologies in the military domain and support decision-making. It is now an essential tool widely used in strategic foresight and strategic management. It allows expert groups to find a consensus on an issue within a short time. The results of *Delphi Surveys* are relatively unaffected by psychological, rhetorical or sociological factors that usually have a negative impact on group discussion. We used a next-generation real-time Delphi platform, *4CF HalnyX*, to identify and assess the most promising biometric technologies and solutions.
Scenario Analysis	Scenarios, a cornerstone of most foresight exercises, aim to reframe visions of the future in order to challenge them. Hence, they indicate previously unidentified threats and opportunities. There are many methods for the development and employment of scenarios, but they all take advantage of the fact that the "*future is a safe conceptual space allowing for experimentation of different perspectives to understand the context of current decisions*".[7] *Scenario Analysis* was used to assess how specific biometric solutions would perform in the stress conditions of alternative futures, as well as in roadmapping and capability mapping.
Backcasting	The backcasting technique is used for determining the steps that could lead to a particular vision of the future, represented by a *snapshot scenario*, describing the world many years from now. It consists in the identification of the sequence of events that would need to occur between that future and the present for that particular vision to occur. The analysis is conducted by going backwards from the envisioned future state, hence the name. Backcasting helped deepen the understanding of particular scenarios for the future of travel, border checks and biometrics in 2040.
Roadmapping	Technology roadmapping is a planning method successfully applied by a broad range of public and private organisations to identify potential development pathways in the short, medium and long term, e.g. for technology and product development and evolution. Roadmaps reveal how a set of inputs (including, e.g. scientific research, technological trends and policy interventions) might combine over time to shape future developments. Roadmapping was an important part of the *Deep Analysis* phase of this project, as it provided a vision of the potential development paths for promising biometric technologies.

Following this introduction, Chapter 1 describes the *Identification of Needs* regarding the key functions of biometric technologies and systems. This phase aimed to specify the scope of the process and to set goals for the study. The results were used as the first filter for narrowing down the area of further analysis to the technologies and systems of greatest potential importance to Frontex.

Chapter 2 outlines how the main areas of research in biometric technologies and the key stakeholders in this field were identified. In total, the analysis revealed 43 main directions of research. Over 200 relevant players were identified within the area of interest.

7 R. Ramirez and A. Wilkinson, "Strategic Reframing: The Oxford Scenario Planning Approach", Oxford University Press, 2016.

The resulting list enabled outreach to key stakeholders and ensured their involvement in subsequent phases of the project.

Chapters 3 and 4 review the results of the development of the taxonomies of biometric technologies and biometrics-enabled technological systems as well as the comprehensive patentometric and bibliometric analyses, together with an analysis of EU-funded projects covering relevant topics.

Another cornerstone of the project is described in Chapter 5, which outlines the approach to scenario development and its outcome: visions of what the future of travel, border checks and related biometric technology-based applications might look like between now and 2040. This activity was built on the first participatory *Technology Foresight Workshop*, conducted in April 2021.

The security aspects of the biometric technologies deemed of greatest importance within the framework of this study are analysed in Chapter 6.

Chapter 7 details the approach adopted to prioritise the identified biometric technologies by way of a *Delphi Survey* conducted with the support of the Group of Experts in May 2021.

Chapter 8 presents the results of the roadmapping exercise, which was used to determine the turning points, challenges and opportunities in the further development of five key biometric technological clusters. The exercise was conducted within the framework of the second participatory *Technology Foresight Workshop*. It considered potential developments in the functions of technologies, as well as products and application areas in the short, medium and long term.

The roadmapping analysis was followed by and supplemented with a capability mapping exercise, described in Chapter 9. It aimed to identify both the existing capabilities of biometric technologies within the EU and the projected development of those capabilities up to 2040. The resulting capability landscape provides a good foundation for strategic decision-making regarding key technological clusters since it highlights present and future opportunities and gaps.

The Research Study ends with conclusions drawn from the implementation of the foresight project and insights that can serve as the basis for future strategic decision-making.

Lastly, the Research Study is accompanied by three Annexes:

- **Annex I – Technology Foresight Manual**, which provides a thorough description of the Technology Foresight process, methods and tools adopted to conduct this study.
- **Annex II – Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems**, which reports the results of the categorisation analysis conducted on the selected biometric technologies and biometrics-enabled systems, and the corresponding methodological approach.
- **Annex III – Patentometric and Bibliometric Analyses of Biometric Technologies**, which contains the details regarding the analyses conducted on patents, scientific literature and EU-funded projects, and the adopted methodology.

1. Analysis of Frontex's needs regarding key functions and characteristics of biometric technological clusters

The identification of needs regarding key functions and characteristics of biometric technologies and biometrics-enabled technological systems was of the first steps of the TFP. It aimed to specify the scope of the process and to set goals for the study. The results of this step constituted the first filter for narrowing the area of further analysis to the technologies and technological systems of greatest potential importance to Frontex.

The initially adopted quantitative approaches to the identification of needs were discontinued in favour of a qualitative approach, deemed more practical and better suited to the requirements of the study. A list of qualitative "must-haves" was therefore prepared through collaboration between Frontex and the Research Team. At this stage of the analysis, the Research Team had already identified the main areas of interest within biometrics as well as the key stakeholders (see Chapter 2). The taxonomies of biometric technologies and biometrics-enabled technological systems (see Chapter 3) were also constructed. A cursory analysis of those initial results revealed that the number of identified biometric technologies was too large for reasonable use in further phases of the TFP as designed. Therefore, they were grouped into clusters of related technologies — technological clusters (TCs).

The initial list of qualitative "must-haves" was reviewed to select parameters suitable for assessing technological clusters and for the needs of further research. Some parameters were not applicable to technological clusters (e.g. it is impossible to determine the Technology Readiness Level of an entire cluster of technologies; this can be done only for a specific technology). An essential factor in the final selection of qualitative parameters was the assessment of TCs in terms of the *Earliest Time to Mainstream* (ETM) metric – not to be confused with *Estimated Time to Mainstream* (see Section 7.1 for more details). The parameter inherently assumes that a technology from a given technological cluster will enter the mainstream at some point in the future. This rendered many identified parameters redundant (e.g. it is difficult to imagine a biometric technology in widespread use despite its inaccuracy in identification and verification). The results of this analysis are included in Table 2, where the initial list of qualitative parameters is presented, along with suitability for the assessment of technological clusters.

Table 2 : *List of qualitative parameters regarding biometric technologies and biometrics-enabled technological systems used in future border check systems, including determination of suitability for the assessment of technological clusters.*

Qualitative parameters ("must-haves")	Suitability for assessment of technological clusters
Technology demonstrated in operational environment (TRL≥7)	
High quality of biometric data achievable	
High accuracy in identification and verification	
Low vulnerability to adversary attacks	**Yes**
Highly reliable	
Highly durable	
Significantly reduced traveller crossing time at BCPs	
Capable of contactless operation (short distance)	
Capable of stand-off operation (medium/long distances)	
Suitable for seamless border checks	**Yes**
Smooth human-machine interaction	
Potential for improved border crossing experience for travellers	
Innovative (potential for carrying out border check functions through a novel approach)	
Highly scalable	
Simple operational implementation at BCPs	
Compatible with European Smart Borders requirements[8]	
Compatible with Entry/Exit System requirements[8]	
Potential to support virtual identity schemes (e.g. Digital Travel Credentials)	
Compatible with policies and measures taken in case of pandemics (e.g. use of personal protection devices such as face masks, social distancing, measures to reduce the risks of biological contamination, disinfection)	**Yes**
Compliant with EU general legal requirements	**Yes** (Merged into one parameter: "Compliant with EU regulations and values")
Compliant with EU requirements for fundamental rights protection	
Compliant with EU data protection regulations	
Compliant with EU ethical requirements	
Potential for political and public acceptance	
Cost-effective (competitive cost to acquire, operate and maintain the system)	
Limited additional infrastructure required	
Technological components available in the EU supply chain (e.g. no export restrictions, European suppliers available)	

8 European Union, Regulation (EU) 2017/2226 of the European Parliament and of the Council of 30 November 2017 establishing an Entry/Exit System (EES), 2017.

As a result, four parameters were selected for use in later phases of the project. The other factors remained a useful point of reference for assessing and cross-checking how technologies fulfil the specified needs. The four selected "must-haves" included:

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

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

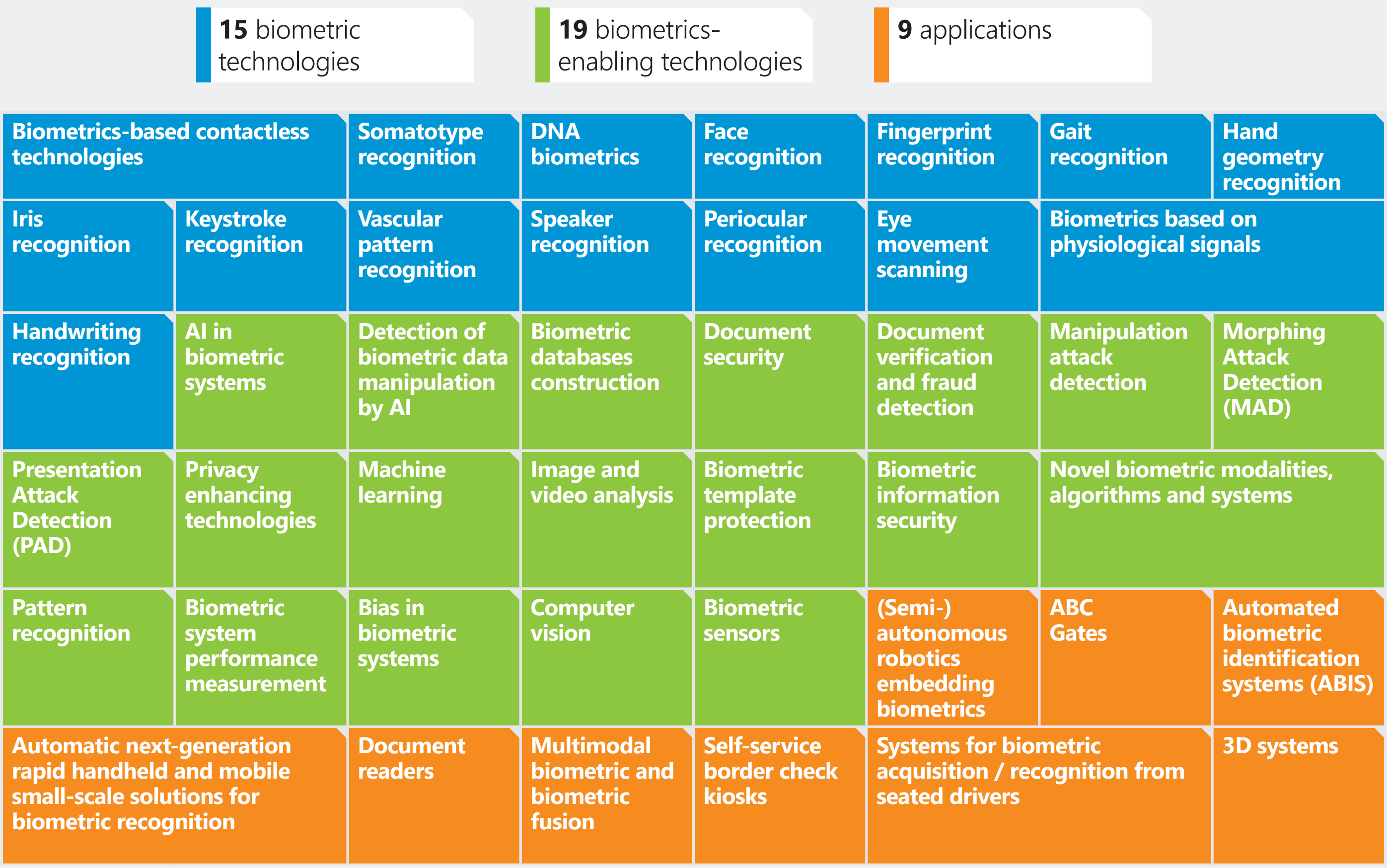
2.1. Main areas of research in biometrics

To identify the primary areas of interest concerning the usage of biometrics for border checks, the Research Team conducted desk research. In total, the analysis revealed 43 key directions of research within the field of interest (Figure 2). They were grouped into three categories: *biometric technologies*, *biometrics-enabling technologies* and *applications*.

The assessment further included an initial estimation of the Technology Readiness Level (TRL) for the 15 identified biometric technologies and an indication of potential applications in border checks, where possible (see Appendix 1 – List of main areas of research in biometrics).

The identification of the 43 key research areas was a point of departure for the development of a structured system of analysis. The preliminary results were further refined and amended through the construction of taxonomies (see Chapter 3), patentometric and bibliometric analyses (see Chapter 4) and input from the *Delphi Survey* (see Chapter 7).

Figure 2: *Main directions of research related to biometric technologies.*



2.2. Key stakeholders in this Research Study

In every Technology Foresight project, it is crucial to obtain a good overview of relevant stakeholders in the primary research areas early on, so their feedback can be taken into account and their needs can be considered. This, in turn, paves the way for successful implementation within the EBCG community.

After the identification of relevant stakeholders, a broad group of them was contacted and became involved in the project. A participatory approach was used to pursue a better understanding of the importance of TF in biometric technologies, particularly within, but not restricted to, the EBCG community. Hence, the identified stakeholders represent not only the field of biometric technologies but also relevant organisations within the EBCG community. More specifically, the following categories of stakeholders were distinguished: EBCG community (Frontex and Border and Coast Guard National Authorities), EU institutions, international organisations, extra-EU border management authorities, EU-funded R&I projects, industrial producers of systems and components, academic institutions, research and technology organisations, civil society and trade associations, consultants.

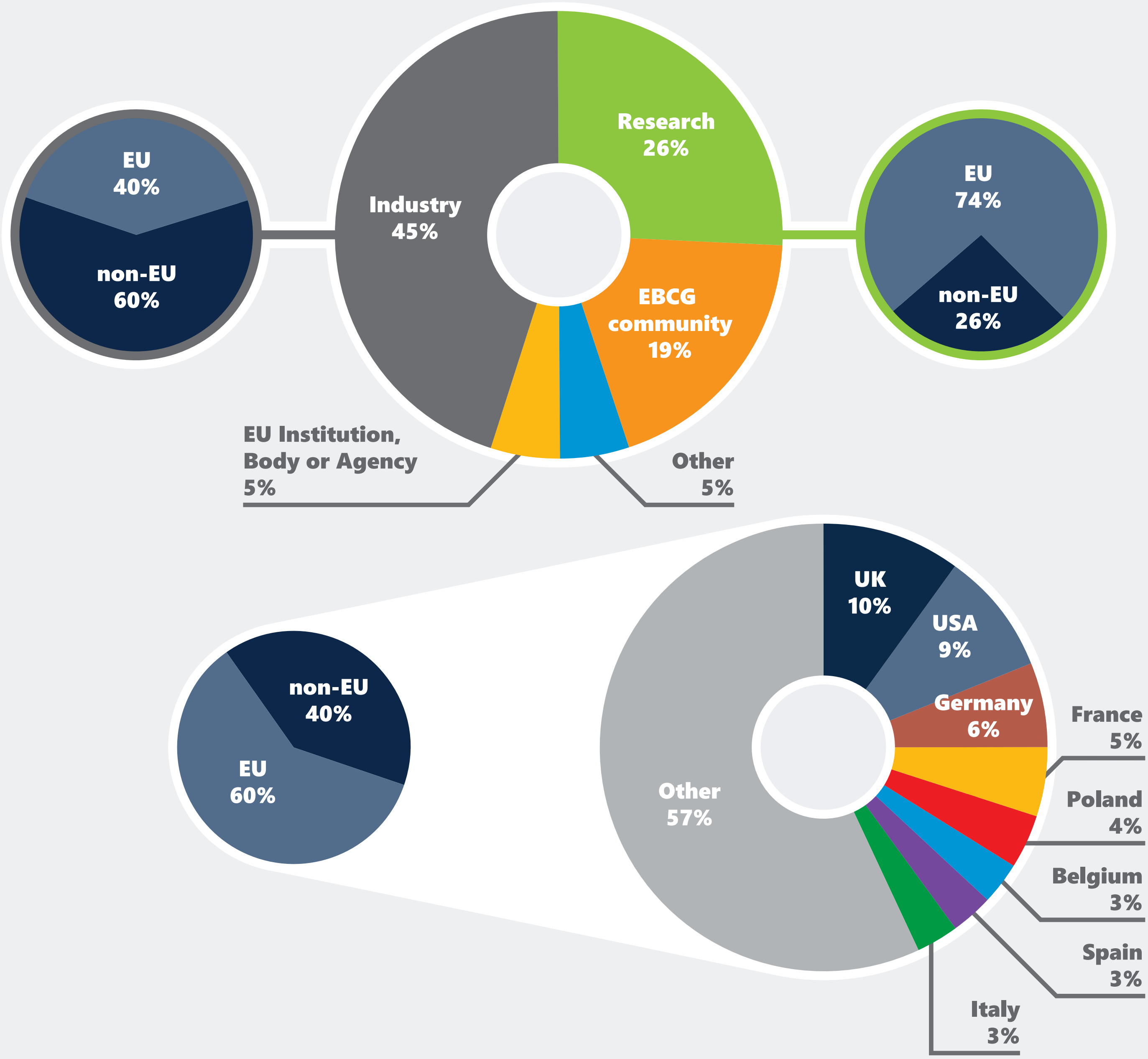
In total, over 200 stakeholders were initially identified (see Appendix 2), over 40 of whom were actively involved in the project through participation in two TF workshops and a *Delphi Survey* (refer to Appendix 3). The diagrams in Figure 3 show the allocation to the defined stakeholder categories and geographic distribution. It should be noted that the data presented in this chapter is only based on the initial list of stakeholders (Appendix 2) compiled through desk research and building on the expertise of the Research Team. Later in the project, this information was supplemented with stakeholders identified through the patentometric and bibliometric analyses. Detailed information about these analyses is provided in Chapter 4.

Industry (Industrial producers of systems and components) represents the largest group among the stakeholders (45%), followed by research (academic institutions, research and technology organisations, EU-funded R&I projects) with 26%. The EBCG community has a share of almost 20%.

While about three-quarters of the identified research representatives are located within the EU, indicating EU dominance in biometrics research, 60% of the industrial producers[9] are primarily located outside the EU.

The UK (10%), the USA (9%), Germany (6%) and France (5%) are the stakeholders' dominant countries of origin. Most of the relevant players are located within the EU (60%).

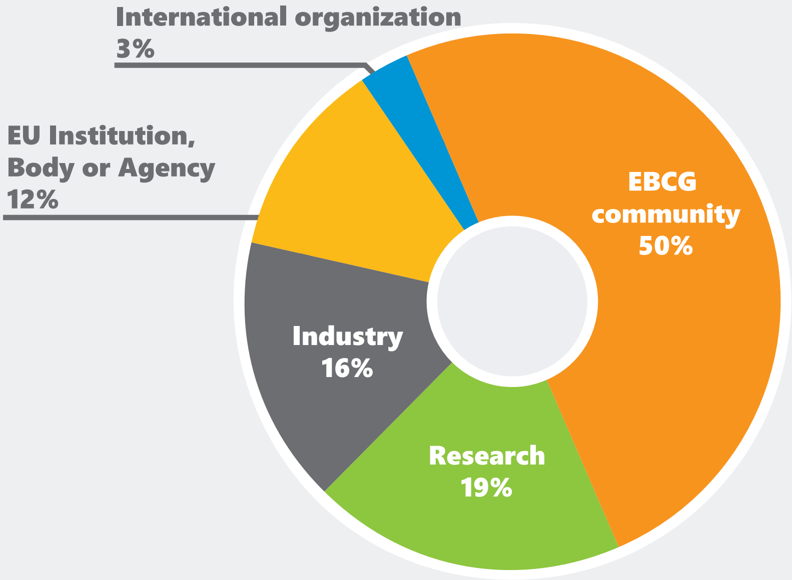
9 Disclaimer: There is no commercial interest in citing industrial producers. Furthermore, the authors do not claim that the list is exhaustive; some relevant players might be unlisted. The list represents the results of desk research produced to the best knowledge of the Research Team.

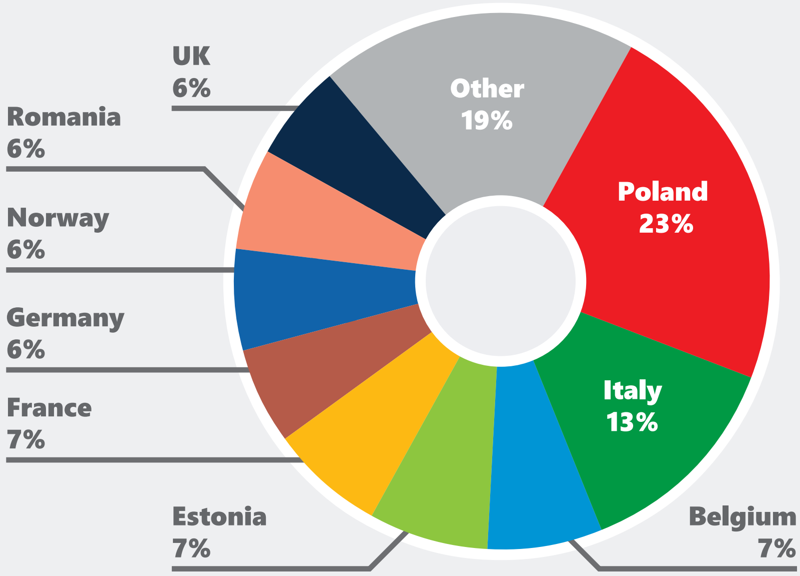


Data source: *List of identified stakeholders (Appendix 2).*

Figure 3: *Identified stakeholders' categories and geographic distribution.*

The expertise of the stakeholders included in the Group of Experts and their evaluations provided the core input for this study. The composition of those who participated in at least two out of the three experts' consultation activities (*First* and *Second Technology Foresight Workshop* and *Delphi Survey*) is displayed in Figure 4. A well-balanced representation of stakeholder groups was the key factor in the selection of participants, with particular focus being placed on stakeholders within the EU. The complete list of stakeholders who were included in the Group of Experts and participated in the activities can be found in Appendix 3. The prevalence of Poland within the geographic distribution is linked to the percentage of participants from Frontex headquarters located in Poland.





Data Source: *Appendix 3. Only participants who participated in at least two out of the three events are included.*

Figure 4: *Categories (top) and geographic distribution (bottom) of stakeholders who participated in at least two out of the three experts' consultation activities conducted within the Research Study (First and Second Technology Foresight Workshop and Delphi Survey).*

As shown in Figure 4, the participants were a well-balanced representation of research (academic institutions, research and technology organisations and representatives of EU projects), industry, EU institutions, bodies or agencies, and international organisations. Jointly, these categories of stakeholders constituted about 50% of the participant group. Representatives of the EBCG community (Frontex and Border and Coast Guard National Authorities) comprised the remaining 50% of the participants. Even though the members of the Group of Experts represented specific stakeholder categories and locations, they were asked to express only their personal views and opinions based on their individual expertise.

3. Taxonomy of biometric technologies and biometrics-enabled technological systems

The research proceeded with the construction of two taxonomies, a *taxonomy of biometric technologies* and a *taxonomy of biometrics-enabled technological systems*. The two taxonomies were developed following two different approaches:

1. The methodology used to develop the *taxonomy of biometric technologies*[10] focused on the analysis of patents and scientific papers, which were assumed to contain all necessary knowledge. Given the significant volume of literature on biometric technologies, automatic tools[11] were used to (a) analyse the textual content of patents and scientific papers, respectively retrieved from the patent database[12] and the *OpenAIRE*[13] database and (b) collect suitable terminology for creating the taxonomy. The Research Team Experts were tasked with amending and validating the information gathered.
2. The taxonomy of biometrics-enabled technological systems[14] was developed primarily through desk research conducted by the Research Team Experts.

Taxonomy is a compound word formed by the Greek terms τάξις (*taxis*, meaning 'order' or 'arrangement') and *νόμος* (*nomos*, meaning 'law' or 'science') and may be defined as the practice and science of categorisation or classification.[15] The categorisation analysis needed to construct the requested taxonomies was performed as part of the *State-of-the-Art Review* within the *Insight Hunt* phase of the TFP.[16] The 43 key research areas introduced in Section 2.1 served as a starting point for the categorisation analysis, and thus for the development of the taxonomies.

A biometric technology was considered within the scope of interest if and only if at least one reference to its application in at least one of the applicative fields mentioned in the Introduction (border checks, biometric recognition and access control) was found during the automated analysis of patents and/or papers. A technology was also taken into consideration if a single "in-scope" application was known to the Research Team Experts.

10 See Annex II – Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems – Part 1.

11 Erre Quadro's proprietary tools, named Domain Terminology Extractor, Smart Ranker and Weighted Clusterer. For more information, see Annex I – Technology Foresight Manual.

12 Erre Quadro's proprietary patent database based on the Patstat Service provided by the European Patent Office, see Annex II – Chapter 1, and Annex III – Section 3.1.

13 OpenAIRE (Open Access Infrastructure for Research in Europe 2020, https://www.openaire.eu/) is a European platform whose mission is to provide unlimited, barrier free and open access to research outputs financed by public funding in Europe.

14 See Annex II – Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems – Part 2.

15 M. Schatten, M. Baca and K. Rabuzin, "A Taxonomy of Biometric Methods", 30th International Conference on Information Technology Interfaces, 2008.

16 See Annex I – Technology Foresight Manual for more details.

To limit the complexity of the taxonomy and of the entire Research Study, the cross-cutting scientific and technological fields listed below were not included in the taxonomical categorisation:

- artificial intelligence in biometric systems,
- privacy-preserving and privacy-enhancement solutions for the security of identity,
- techniques for biometric database construction,
- manipulation attack detection and protection against attempts/techniques to falsify biometrics.

These fields represent vast technological areas and can improve the operational performance of almost all known biometric modalities. For example, any biometric technology may exploit novel algorithms based on artificial intelligence as well as on privacy-preserving and privacy-enhancing technologies since they are based on algorithms for biometric feature extraction and matching. Algorithms for the detection of morphing and presentation attacks are yet another example of the extraction and matching of specific types of features gleaned from the data set. In all cases, AI requires a large collection of both training and probe data for the development phase. Detection of other types of fraud and attack, including novel and sophisticated attacks on systems, is also considered out of scope since it would rely on investigating a wide range of signal and image acquisition techniques, database construction, processing algorithms and decision algorithms. Without undertaking an in-depth analysis of these additional areas of technology, the study would risk superficial and misleading assessments of the same areas. Moreover, since EU legislation limits patents for software and algorithms, a patent analysis might not identify all the relevant information regarding these areas. Therefore, the Research Team (in cooperation with Frontex) decided not to perform a taxonomical analysis of the cross-cutting technological fields.

The development processes that led to the creation of the two taxonomies and their outcome are briefly described below. The reader is referred to Annex II – Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems for a complete description of the methodology, the elements forming the two taxonomies and the major findings.

3.1. Taxonomy of biometric technologies

The construction of the taxonomy of biometric technologies started once the preliminary list of research areas introduced in Section 2.1 was completed. This enabled the creation of the necessary prior knowledge and terminology for querying databases of patents and papers. The search queries were then used to collect preliminary sets of patents and papers. The *Domain Terminology Extractor* tool[17] was subsequently applied to expand and validate the list of search keywords as well as to extract the terms that could be used to define and describe biometric technologies, techniques and modalities. Concurrently with the extraction of patents and papers, brief desk research in industrial literature, online sources and scientific publications was performed to find additional terminology and omitted biometric technologies. Whenever an additional

17 See Annex I – Technology Foresight Manual – Chapter 19.

biometric technology was extracted, a validation step followed: patent and scientific literature were searched for at least one application within the scope of the Research Study. Suitable technologies were classified to form a preliminary taxonomy. An iterative approach was applied to integrate the taxonomy further, leading to multiple additions and reclassifications. Finally, the taxonomy of biometric technologies was reviewed and validated in close collaboration with Frontex.

The set of biometric technologies retrieved was categorised on the three-level taxonomy tree[18] shown in Appendix 4 having:

1. the ***first level***, consisting of three macro-areas: biomolecular biometrics, morphological biometrics and behavioural biometrics;
2. the ***second level***, including 14 technological fields;
3. the ***third level***, comprising 57 specific biometric recognition or acquisition technologies and modalities (hereinafter also referred to as *third-level technologies*).

Morphological biometrics was the most copious group of biometric technologies pertinent to the investigated application domains of border checks, biometric recognition and access control. *Biomolecular biometrics*, mostly formed by DNA-related technologies, made up the narrowest macro-area. Even though among the various possible biometric technologies suitable for recognising individuals, DNA-related ones produce the most reliable results, they are still characterised by highly invasive and low-efficiency sample capture and processing. Therefore, these technologies find applications in forensic science rather than in border checks and/or access control.

Patents proved to be a suitable source of information for taxonomy design. They allowed the Research Team to retrieve less-known technologies, such as:

- Hand bacteria identification,
- Encephalographic signals,
- Acoustic properties of the ear canal,
- Dental biometrics,
- Tongueprint recognition,
- Cranial suture scanning,
- Rugoscopy (patterns within the palate structure of the human mouth),
- Complex eye movement patterns (eye-tracking),
- Oculomotor plant characteristics.

On the other hand, scientific literature and the knowledge of the Research Team Experts represented the most reliable sources of information for validating and describing the technologies included in the taxonomy.

After the taxonomy of biometric technologies was developed, the third-level technologies were grouped into 20 technological clusters, defined to provide input for patentometric and bibliometric analyses as well as to ensure the usability of the taxonomy in the subsequent phases of the Research Study. Preliminary identification of clusters was performed with the use of the *Weighted Clusterer tool*.[19] The tool uses an ML algorithm

18 The reader is referred to Annex II – Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems – Part 1 for a complete description of all levels of the taxonomy.

19 See Annex I – Technology Foresight Manual – Chapter 21.

to interpret the content of document sets and to support tasks that require the categorisation of documents as well as technologies and technological applications[20]. The final identification of clusters was based on the size of the associated document sets (patents and scientific publications), the technological affinity between third-level technologies and the relevance in target applications (border checks, biometric recognition and access control). Table 3 lists the final 20 technological clusters and corresponding third-level biometric technologies[21].

Table 3: *List of 20 technological clusters and corresponding third-level biometric technologies considered for conducting patentometric and bibliometric analyses (see Chapter 4) and used in further phases of the Tech Foresight on Biometrics.*

#	Technological Clusters	Third-level biometric technologies included in each technological cluster
1	DNA biometrics	1.1.1 DNA phenotyping
		1.1.2 DNA profiling
		1.1.3 DNA sequencing
2	Infrared face recognition	2.1.1 Thermal Infrared face recognition
		2.1.2 Near-Infrared face recognition
3	2D face recognition in the visible spectrum	2.1.3 Video-based face recognition
		2.1.4 Image-based face recognition
4	3D face recognition	2.1.5 3D face recognition
5	Infrared friction ridge recognition	2.2.1 Thermal friction ridge recognition
		2.2.2 Near-Infrared friction ridge recognition
		2.2.6 Fingerprint recognition 2.2.7 Palmprint recognition 2.2.8 Footprint recognition 2.2.9 Finger-knuckle-print recognition
6	3D friction ridge recognition	2.2.3 3D friction ridge recognition
		2.2.6 Fingerprint recognition 2.2.7 Palmprint recognition 2.2.8 Footprint recognition 2.2.9 Finger-knuckle-print recognition

Continued on pg.36

20 For more details, please refer to Annex III – Patentometric and Bibliometric Analyses of Biometric Technologies.

21 See Annex II – Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems – Chapter 3 for a complete description of technological clusters.

Continued from pg.35

#	Technological Clusters	Third-level biometric technologies included in each technological cluster
7	**Contactless friction ridge recognition**	2.2.4 Contactless friction ridge recognition
		2.2.6 Fingerprint recognition 2.2.7 Palmprint recognition 2.2.8 Footprint recognition 2.2.9 Finger-knuckle-print recognition
8	**Contact-based friction ridge recognition**	2.2.5. Contact-based friction ridge recognition
		2.2.6 Fingerprint recognition 2.2.7 Palmprint recognition 2.2.8 Footprint recognition 2.2.9 Finger-knuckle-print recognition
9	**Iris recognition in the NIR spectrum**	2.3.1 Iris recognition in the NIR spectrum
10	**Iris recognition in the visible spectrum**	2.3.2 Iris recognition in the visible spectrum
11	**Iris recognition at a distance**	2.3.3 Iris recognition at a distance
12	**Eye vein recognition**	2.4.1 Retina recognition
		2.4.2 Sclera/episclera recognition
13	**Hand vein recognition**	2.4.3 Finger vein recognition
		2.4.4 Palm vein recognition
		2.4.5 Back-of-hand vascular pattern recognition
		2.4.6 Wrist vein recognition
14	**Heart signal recognition**	2.5.1 Heart-rate variability
		2.5.2 Electrocardiographic signals
		2.5.3 Phonocardiographic signals
		2.5.4 Photoplethysmographic signals
15	**Hand geometry recognition**	2.6.1 Contact-based Hand geometry recognition
		2.6.2 Contactless Hand geometry recognition
16	**Periocular recognition**	2.7.4 Periocular recognition
17	**Keystroke recognition**	3.1.1 Dynamic Keystroke recognition
		3.1.2 Static Keystroke recognition
18	**Gait recognition**	3.2.1 Gait recognition based on video sensors
		3.2.2 Gait recognition based on radar sensors
		3.2.3 Gait recognition based on floor sensors
		3.2.4 Gait recognition based on wearable sensors
19	**Handwriting recognition**	3.3.1 Dynamic Handwriting recognition
		3.3.2 Static Handwriting recognition
20	**Speaker recognition**	3.4.1 Text-dependent Speaker recognition
		3.4.2 Text-independent Speaker recognition

3.2. Taxonomy of biometrics-enabled technological systems

As previously mentioned, a taxonomy of biometrics-enabled technological systems (e.g. ABC gates, wearable devices, etc.) was also created, but a different process was used for its development. The Research Team considered the system aspects and use cases which these various biometric technologies may be applied to, as well as how the individual traveller would interact with them. A traveller's end-to-end journey was considered, from booking the travel to arrival and passing control at the destination. The taxonomy of biometrics-enabled technological systems was constructed based on the Research Team's expertise regarding existing and projected systems worldwide as well as on sources such as IATA *NEXTT*[22] – *Building the journey of the future* or the World Economic Forum's[23] project on *Shaping the Future of Security in Travel*[24].

The retrieved set of biometrics-enabled technological systems was categorised into the two-level taxonomy[25] shown in Appendix 5, with:

1. ***The first level*** consisting of seven groups;
2. ***The second level*** including 31 categories.

The proposed taxonomy of biometrics-enabled technological systems provides Frontex with a foundation for the development of future strategies related to the employment of biometrics, along with a systematic classification of systems and sub-systems that use biometric data for more efficient management of border control. Three key aspects are suggested to be considered when implementing future biometrics-enabled technological systems:

1. Ways in which individual travellers, including those with differing levels of ability and understanding, are likely to interact with and react to the systems and processes they encounter or are presented with;
2. The progress of technology and its capabilities within the various categories identified in the taxonomy, taking into account how the sub-systems might interact with and complement each other;
3. The progress of legislation related to the employment and ethics of biometrics as well as the balance between protecting fundamental rights and maintaining the security and integrity of external borders.

22 https://www.nextt.aero/en/

23 https://www.weforum.org/

24 https://www.weforum.org/videos/shaping-the-future-of-security-in-travel

25 The reader is referred to Annex II – Taxonomy of Biometric Technologies and Biometrics-Enabled Technological Systems – Chapter 6 for a complete description of all levels of the taxonomy.

4. Patentometric and bibliometric analyses of biometric technologies

After creating the taxonomy of biometric technologies, the Research Study proceeded with an analysis of patents, scientific literature and projects funded under EU framework programmes for R&I,[26] performed considering the needs of Frontex regarding the assessment of the biometric technology landscape.

The patentometric and bibliometric analyses focused on the 20 technological clusters listed in Table 3. The analyses aimed to extract the results of global research and development in technological clusters and consisted of the following:

1. Analysis of patent literature — obtained data:
   a) Temporal distribution of inventive activity displayed by the production of patent literature, which is analysed to evaluate a technological field's lifecycle evolution.[27]
   a) Most prolific patent assignees.[28] This information provides an overview of the most prominent inventors as regards the clusters and shows what share of inventive activity they account for.
   b) Geographic distribution of inventive activity, which provides an overview of the primary locations of R&D activity and where patents are filed for commercial or manufacturing purposes.
2. Analysis of scientific literature — obtained data:
   a) Temporal distribution of scientific publications, useful to supplement the information retrieved from patents to refine the assessment of technological lifecycles.
   b) Most prolific authors. This information provides an overview of researchers who study the clusters and their share of publication activity.
   c) Most prolific publishers and their share of editorial activity.
3. Analysis of projects funded under EU framework programmes for R&I — obtained data:
   a) List of EU-funded projects covering topics of relevance for the analysed clusters.
   b) Total EU investments in research projects, which is considered an indirect measure of EU interest in the analysed clusters.
   c) Temporal distribution of EU investments in research projects, which is used to determine how the interests and efforts of the EU have evolved over time and whether interest in a field is growing or decreasing.

26 The results of this analysis are extensively described in Annex III – Patentometric and Bibliometric Analyses of Biometric Technologies. In addition to the databases of patents and scientific publications mentioned in Chapter 3, the Research Team used the CORDIS database (https://cordis.europa.eu/about/en) to search for relevant projects funded under EU framework programmes for R&I.

27 The reader is referred to Annex III – Section 4.2 for an exhaustive introduction.

28 See Annex III – Section 3.1, for the definition.

d) Actors involved in EU-funded projects and their geographic distribution. The output was used to obtain an overview of countries and entities most engaged in the analysed projects.

As regards Point 2 of the above list, it must be stressed that the OpenAIRE database provided access only to the authors, titles and abstracts of scientific publications, not to the full text. Thus, the significance of the bibliometric analysis was reduced. Given the limitations of the data source, it was not possible to:

- implement a proper technology lifecycle analysis based solely on scientific literature;
- retrieve data regarding the authors' affiliation and country of publication. Consequently, the analysis of the geographic distribution of research and experimental activity was not possible.

Given the above, and to compensate for the limitations of bibliometric data, the Research Team decided to utilise the bibliometric analysis to supplement and integrate the results of the patentometric analysis.

Concerning Point 1.a. of the above list, Altshuller's *Theory of Inventive Problem Solving (TRIZ)*[29] was used to analyse the clusters' technological lifecycles by examining the temporal distribution of patent families.[30] According to the theory (developed also by Mann[31]), the typical lifecycle of technology incorporates the following five stages:

1. ***Birth***: when a new product is created via radical innovation.
2. ***Childhood***: the first cycle of incremental innovation, characterised by slow development due to lack of profits.
3. ***Growth***: the stage when the benefits of the product are recognised, characterised by an increase in *performance*,[32] profits and R&D investments.
4. ***Maturity***: the stage denoted by high *profitability* but saturation in terms of opportunities for innovation and improvement.
5. ***Decline***: the stage when the limits of product evolution are achieved, *profitability* decreases and the technology is no longer necessary.

Altshuller proposed a theoretical pattern for a technology's lifecycle based on the number of inventions throughout its course. Adopting the number of patent families filed each year as an indicator of the number of inventions, the similarities between the temporal distribution of patent families associated with a given technology and Altshuller's theoretical pattern may be used to assess a technology's lifecycle. For example, Figure 5 shows a mature technology whose temporal distribution closely matches the theoretical pattern (shown in the upper left corner of the same figure).

29 See Annex III – Section 4.2 for more details on the theoretical framework used for the patentometric and bibliometric analyses.

30 Specifically, the Research Team considered DOCDB patent families, defined by EPO as: "a collection of patent documents that are considered to cover a single invention. The technical content covered by the applications is considered to be identical. Members of a simple patent family will all have exactly the same priorities." (https://www.epo.org/searching-for-patents/helpful-resources/first-time-here/patent-families/docdb.html).

31 D. Mann, "Using S-Curves and Trends of Evolution in R&D Strategy Planning", TRIZ Journal, 1999.

32 Performance represents the technical measure of how well a technology or product works. Together with the Number of Inventions, the Level of Inventions and the Profitability, it is one of the four metrics that can be used to assess a product or technology lifecycle, as defined by Mann. The reader is referred to Annex III – Section 4.2 for the complete definition of these terms.

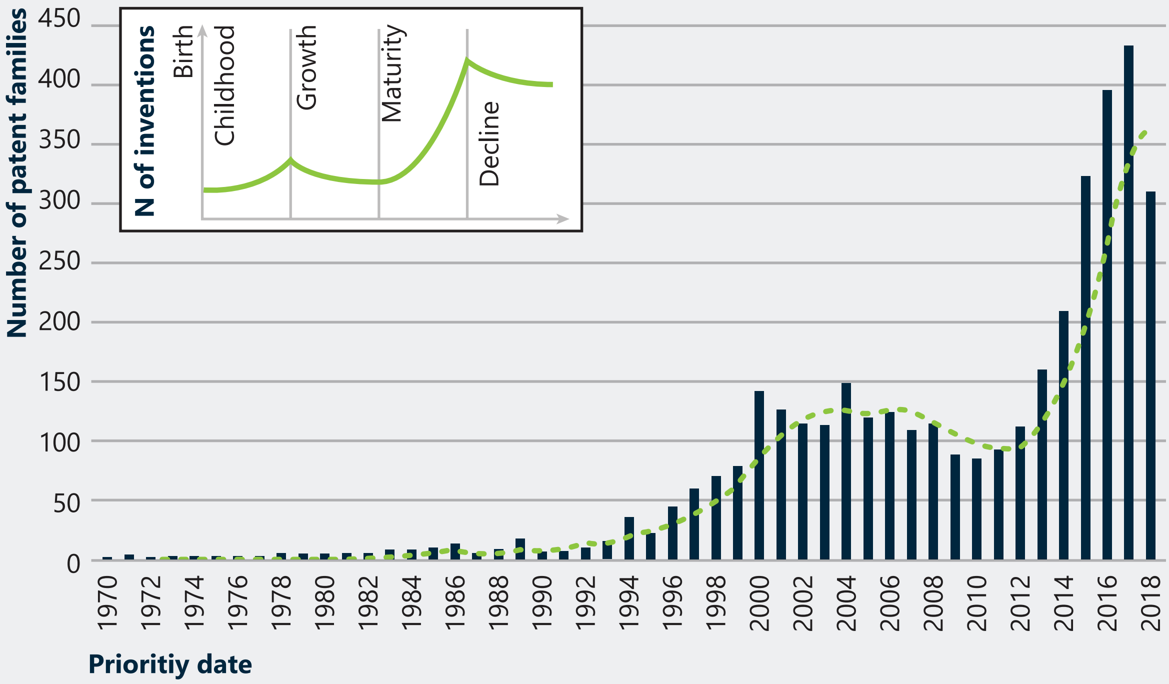


Figure 5: *Example of a temporal distribution of patent families filed each year (bar chart). A trendline representing a four-year moving average is shown to highlight similarities to the theoretical pattern[31] displayed in the upper left corner.*

By observing the temporal distribution of patents, the Research Team was able to formulate a set of hypotheses about the lifecycles of technological clusters, as summarised in Table 4.

A summary of conclusions based on the results of the patentometric and bibliometric analyses is provided in the sections of the present chapter, while the complete set of related information for each of the 20 clusters is contained in the dedicated Annex III to this Research Study, including:

- data-driven interpretations of how each technological cluster evolved over time and of possible future developments;
- overview of the geographic distribution of inventive and research activities;
- identification of the organisations and researchers that were/are most active within the clusters.

It should be noted that the interpretations do not refer to the technologies in and of themselves. Instead, they consider the development of the technologies in the context of applications defined for the purposes of this project (border checks, biometric recognition and access control).

4.1. Technology lifecycle of biometric technological clusters

The following results were obtained from the assessment of the technologies' lifecycles (a synoptic overview is shown in Table 4).

- **Childhood:** two clusters (*Periocular recognition* and *Gait recognition*) were categorised as still in the childhood stage of their technology lifecycle. In the case of these clusters, inventive and publishing activities are expected to develop, although their future impact on the sector is impossible to determine based on the data. The clusters contain technologies that might find applications in border checks but for which no *dominant design*[33] exists.
- **Growth:** five clusters (*Infrared friction ridge recognition, 3D friction ridge recognition,* Iris *recognition in the visible spectrum, Iris recognition at a distance, Heart signal recognition*) were categorised as in the growth stage of their lifecycle. These fields are currently facing a period of maximum growth in performance and profitability. A *dominant design* is supposed to be emerging in these technological fields, and they may be considered of interest for present and future applications in border checks.
- **Maturity:** 10 clusters were categorised as being in the maturity stage of their lifecycle (*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*). It must be highlighted that 'mature' implies neither 'old' nor 'obsolete.' These are fields with high technical performance (e.g. reliability, throughput, accuracy etc.) and high profitability, where a *dominant design* is presumed to exist. In other words, the technologies are ready for use. They do, however, display saturation in terms of room for innovation and improvement. These technologies can be used in systems that have been verified in operational environments.
- **Maturity – minor relevance:** The temporal distributions of patenting and publishing activities regarding three technological clusters (*DNA biometrics, Hand geometry recognition* and *Keystroke recognition*) showed poor similarity with the pattern suggested by the theoretical framework. These clusters are probably characterised by low efficiency in recognition processes. The long time-intervals and low volumes of inventive activities suggest that no growth in inventive activity is foreseen in the future.

33 A "dominant design" means a single architecture that establishes dominance in a product category. A *dominant design* is a concept that wins the allegiance of the marketplace, the one to which competitors and innovators must adhere if they hope to command a significant market.

Table 4: *Overview of the inferred stages of the technologies' lifecycles for the 20 analysed technological clusters.*

#	Technological clusters	Stage in technology lifecycle
1	DNA biometrics	Maturity – minor relevance
2	Infrared face recognition	Maturity
3	2D face recognition in the visible spectrum	Maturity
4	3D face recognition	Maturity
5	Infrared friction ridge recognition	Growth
6	3D friction ridge recognition	Growth
7	Contactless friction ridge recognition	Maturity
8	Contact-based friction ridge recognition	Maturity
9	Iris recognition in the NIR spectrum	Maturity
10	Iris recognition in the visible spectrum	Growth
11	Iris recognition at a distance	Growth
12	Eye vein recognition	Maturity
13	Hand vein recognition	Maturity
14	Heart signal recognition	Growth
15	Hand geometry recognition	Maturity – minor relevance
16	Periocular recognition	Childhood
17	Keystroke recognition	Maturity – minor relevance
18	Gait recognition	Childhood
19	Handwriting recognition	Maturity
20	Speaker recognition	Maturity

4.2. Geographic distribution of inventive activities

Patenting activity related to the 20 clusters seems to be located primarily in the United States, the leading country in terms of the number of filed priority patents for each of the clusters. This metric was used to understand where the R&D was mainly performed, because applications of priority patents are usually primarily submitted in the states or regions where research was performed. Europe and China alternate as the second most common location.

These three regions also represent the main areas of interest when considering the geographic distribution of all filed patents (not only the priority ones). This indicates that commercial and manufacturing activities are also performed on a large scale in these regions.

Germany and the United Kingdom are the only European countries among those with the largest number of patents filed. These two locations seem to represent the dominant European regions in terms of research, manufacturing and commercial activities regarding the 20 analysed technological clusters.

Countries where patents are also frequently filed for both R&D and commercial/manufacturing activities include Japan and South Korea.

Other countries (e.g. Canada, Australia, Taiwan, Brazil and Mexico) are "innovation importers" where R&D is performed at lower levels.

4.3. Main patenting organisations and concentration of inventive activity

The patentometric analysis led to the identification of the 15 most active assignees in terms of filed patent families for each technological cluster. This outcome was used to measure the *concentration of inventive activity*[34] within each cluster, defined as the percentage of patent families owned by the first 15 patenting organisations in the total number of patent families in a cluster.

Only two technological clusters (i.e. *Periocular recognition* and *Gait recognition*) showed a high level (over 60%) of inventive-activity concentration. The following nine technological clusters were assessed as having low concentration:

- DNA biometrics,
- Infrared face recognition,
- 2D face recognition in the visible spectrum,
- 3D face recognition,
- Contactless friction ridge recognition,
- Contact-based friction ridge recognition,
- Eye vein recognition,
- Keystroke recognition,
- Handwriting recognition.

All the others were found to be moderately concentrated.

The leading patenting organisations change from one cluster to another, resulting in a total of 154 different organisations, spanning from multinational corporations (e.g. Apple, Microsoft, Philips) to public organisations and universities (e.g. US Government, University of California, Chinese Academy of Sciences). The University of California and the Chinese Academy of Sciences are among the top patenting organisations for three technological clusters and are therefore the most active academic organisations in the field. On the other hand, 14 industrial producers appear among the 15 most active assignees for five or more technological clusters. They include primarily electronic and communication technology suppliers: American Express Travel Related Services Company, Apple, Fujitsu, Honeywell International, IBM, Intel Corporation, LG Electronics, Microsoft, NEC Corporation, Panasonic Corporation, Philips Electronics, Qualcomm, Samsung and Sony Corporation.

34 The following thresholds were used to assess the level of concentration of inventive activity, based on the percentage of total inventive activity owned by the first 15 patent assignees (here indicated with "x"):
x < 30%, low concentration,
30 % ≤ x < 60%, moderate concentration,
x ≥ 60%, high concentration.

4.4. Most prolific authors and publishers

The bibliometric analysis led to the identification of the 15 most prolific authors and publishers of scientific articles for each cluster. This was used to measure the *concentration of publishing activity* and the *concentration of editorial activity* within each cluster,[35] defined respectively as the percentage of published articles in a cluster contributed by the first 15 authors, and the percentage of articles in a cluster issued by the first 15 publishers.

Only the following four clusters were found to be *highly concentrated* in terms of publishing activity:

- One *mature* cluster: *Keystroke recognition*. This cluster was assessed as of *minor relevance* to the field of analysis. Therefore, the high concentration could result from the low number of authors who perform R&D activities within this cluster.
- One *growing* cluster: *3D friction ridge recognition*. This cluster has just advanced from the *childhood* stage of its lifecycle to an early *growth* stage. At this point of the lifecycle, there are generally still few researchers working on R&D. Consequently, the majority of publications are authored by a narrow group of researchers.
- Two clusters in the *childhood* stage of their lifecycles: *Periocular recognition* and *Gait recognition*. Research focused on such technologies is generally limited, and few researchers concentrate on them. Consequently, the majority of publications are authored by a narrow group of researchers.

The editorial activity turned out to be much more concentrated than the publishing activity. IEEE seems to dominate the biometric field in terms of the number of publications. It appears to be a key reference for monitoring present and future developments in the technological clusters analysed. The analysis revealed it to be the leading publisher for 19 out of the 20 clusters. *DNA biometrics* is the only cluster where IEEE is displaced as the leading publisher by Elsevier, another highly relevant entity. For most clusters, Elsevier, SPIE and Springer alternate as the second most prolific publisher.

35 To estimate the level of concentration of publishing activities (authors) and editorial activities (publishers), the following thresholds were used:
$x < 30\%$, low concentration,
$30\% \le x < 60\%$, moderate concentration,
$x \ge 60\%$, high concentration;
where "x" is the percentage of total papers published by the first 15 authors or publishers, respectively.

4.5. EU-funded projects

A total of 32 EU-funded research projects on subject matters of relevance to the 20 biometric technological clusters were extracted from the European Commission's primary public repository, CORDIS. Almost 91 M€ was granted to these projects by the European Commission.

Table 5: *Overview of the EU-funded projects. The colour scale in the column 'No. of projects' is proportionate to the number of funded projects.*

Technological field	Technological clusters	No. of projects	Overall budget [M€]	EU contribution [M€]	Percentage of EU contribution
DNA biometrics	DNA biometrics	2	2.16	2.16	100.0%
Face recognition	Infrared face recognition 2D face recognition in the visible spectrum 3D face recognition	16	45.99	38.28	83.2%
Friction ridge recognition	Infrared friction ridge recognition 3D friction ridge recognition Contactless friction ridge recognition Contact-based friction ridge recognition	10	27.88	23.52	84.4%
Iris recognition	Iris recognition in the NIR spectrum Iris recognition in the visible spectrum Iris recognition at a distance	4	20.82	16.49	79.2%
Vascular pattern recognition	Eye vein recognition Hand vein recognition	5	16.18	15.17	93.7%
Hand geometry recognition	Hand geometry recognition	1	2.50	2.20	100.0%
Heart signal recognition	Heart signal recognition	0	-	-	-
Periocular recognition	Periocular recognition	5	28.44	22.24	78.2%
Keystroke recognition	Keystroke recognition	1	0.84	0.59	70.0%
Gait recognition	Gait recognition	1	0.07	0.05	70.0%
Handwriting recognition	Handwriting recognition	0	-	-	-
Speaker recognition	Speaker recognition	6	38.67	30.19	78.0%

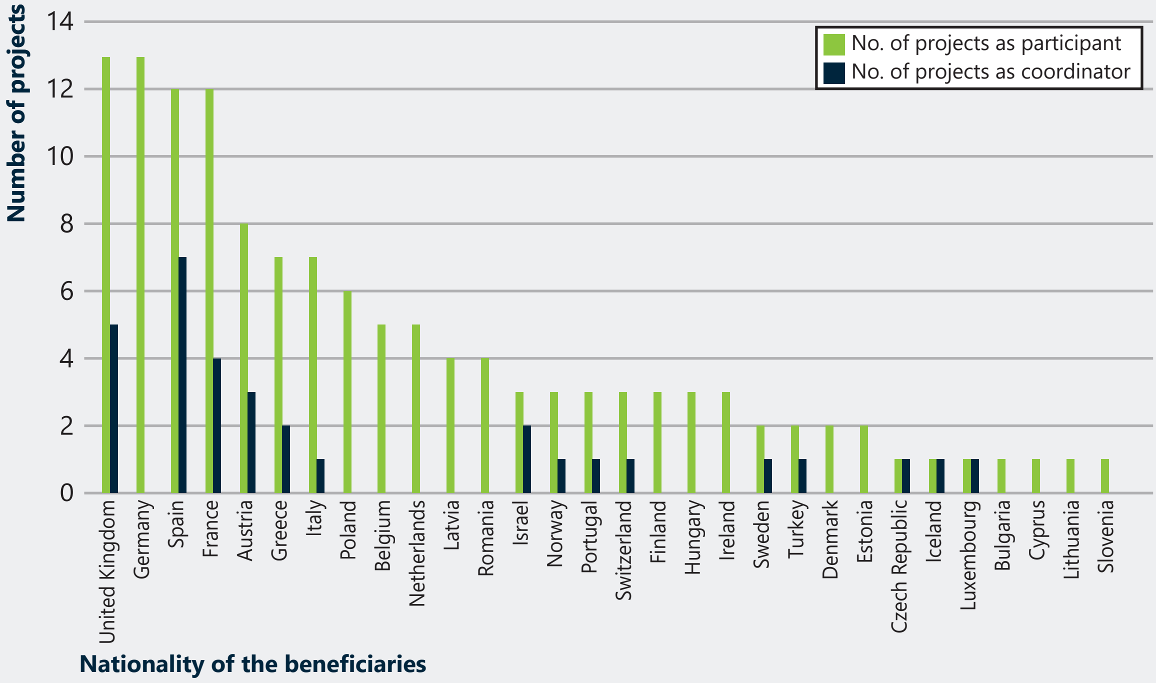


Figure 6: *Nationality of the beneficiaries of EU-funded R&D projects on topics relevant to the five main technological fields analysed (Face recognition, Friction ridge recognition, Vascular pattern recognition, Periocular recognition and Speaker recognition).*

Considering the general overview in Table 5, the following can be observed:[36]

- Among the technologies analysed, *Face recognition* presents the largest number of projects (16).
- In terms of both number of projects and financial support, EU-funded R&D mainly focused on three technological fields: *Face recognition* (16 projects, 38.3 M€), *Friction ridge recognition* (10 projects, 23.5 M€) and *Speaker recognition* (6 projects, 30.2 M€). These three technological clusters, with a total of 25[37] relevant research projects, together cover over 78% of the total number of funded projects.
- *Hand geometry recognition* and *DNA biometrics* are the only fields that received full coverage of the budget by the EU. Generally, the percentage of the EU contribution settles around 84%.

Only five technological fields (i.e. *Face recognition, Friction ridge recognition, Vascular pattern recognition, Periocular recognition, Speaker recognition*) were addressed in five or more projects. These seem to be the fields of particular interest to the EU. In contrast, no projects related to *Heart signal recognition* or *Handwriting recognition* were retrieved from CORDIS, suggesting that such technologies were not deemed relevant enough to pursue publicly funded academic or industrial R&D. Another five technologies appeared of moderate/minor interest under EU framework programmes for R&I,

36 Given the relatively small number of funded projects of relevance in each of the 20 technological clusters (in some cases, no projects were identified), it was decided to further group the clusters into their respective taxonomical second-level technological fields (with regard to the Taxonomy of biometric technologies), whenever possible.

37 Not 32, as a single research project may, in fact, be relevant for multiple technological clusters.

having been touched upon by fewer than five projects each: *Iris recognition* (4 projects), *DNA biometrics* (2 projects), *Hand geometry recognition* (1), *Keystroke recognition* (1) and *Gait recognition* (1).

Face recognition, Friction ridge recognition, Vascular pattern recognition and *Hand geometry recognition* are the only fields included in EU-funded projects for which at least one project with a starting date in 2019[38] was retrieved, meaning that R&D activities on these clusters were recently funded by the EU.

The Research Team decided to consider a minimum number of five projects as a pre-requisite for conducting in-depth analyses, which left the five fields mentioned above (*Face recognition, Friction ridge recognition, Vascular pattern recognition, Periocular recognition* and *Speaker recognition*). As shown in Figure 6, the analysis of EU-funded projects in these fields revealed that British, German, Spanish and French organisations participated in the largest number of projects related to technological clusters. Thus, the analysis suggests that these countries are likely to possess the highest levels of knowledge and capability required for the implementation of the technologies.

Furthermore, Table 6 contains the list of entities most involved, as participants or coordinators, in the projects. *ITTI Sp. z o.o. – Poland* contributed the largest number of projects (8), followed by *Veridos GmbH – Germany*, with 6 projects, while *Komenda Główna Straży Granicznej* and *Fraunhofer* contributed to five projects each. The focus of particular entities varied:

- *ITTI Sp. z o.o.* and *Veridos GmbH* were active in the fields of *Face recognition, Vascular pattern recognition* and *Periocular recognition*;
- *Komenda Główna Straży Granicznej* was active in *Face recognition* and *Vascular pattern recognition*;
- *Fraunhofer* was active in *Face recognition* and *Friction ridge recognition*.

38 Latest year among the retrieved projects, in terms of starting dates.

Table 6: *Main actors in EU-funded projects within the five main fields (i.e. Face recognition, Friction ridge recognition, Vascular pattern recognition, Periocular recognition, Speaker recognition) and number of projects in which they took part as participant or coordinator.*

Beneficiary entities	Number of projects
ITTI SP. Z O.O.	8
VERIDOS GMBH	6
KOMENDA GŁÓWNA STRAŻY GRANICZNEJ	5
FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	5
EURECOM	4
THE UNIVERSITY OF READING	4
IDEMIA IDENTITY & SECURITY FRANCE	4
UNIVERSIDAD CARLOS III DE MADRID	3
AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	2
FACEPHI BIOMETRIA SA	2
KENTRO MELETON ASFALEIAS	2
PARIS-LODRON-UNIVERSITÄT SALZBURG	2
WOJSKOWA AKADEMIA TECHNICZNA IM. JAROSŁAWA DĄBROWSKIEGO	2
COMMISSARIAT À L'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES (CEA)	2
INSPECTORATUL GENERAL AL POLIȚIEI DE FRONTIERĂ	2
SYNTHEMA S.R.L.	2
MINISTÉRIO DA JUSTIÇA	2
INTREPID MINDS LTD	2

In conclusion, the results discussed above may be employed by Frontex to prioritise future studies on biometric technologies.

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

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 analysis – a plan, a technological sector or a strategy. The primary purpose of *Scenario Analysis* is to stress-test strategies, insights and solutions to verify whether they are "future-proof".

The role of the *Scenario Analysis* method in the *Technology Foresight on Biometrics for the Future of Travel* was primarily to stress-test roadmaps that illustrated the projected paths of development with regard to the five biometric technological clusters identified as crucial in the *Delphi Survey*. Plausible yet challenging scenarios, which described 2040 realities, provided an opportunity to deepen and broaden the knowledge about the possible future of each technological cluster by pinpointing key turning points, challenges and opportunities in technological developments under future scenarios.

Scenario Analysis was also used to assess the potential weaknesses of technological clusters under the stress conditions posed by specific future scenarios, as described in Chapter 6.

Finally, *Scenario Analysis* was also used during the capability readiness analysis (see Section 9.2), where the expected future capability readiness of the key technological clusters was assessed by evaluating the degree to which the cluster-specific needs would be met under future scenarios.

As scenario development is usually a lengthy process that might take several months, the Research Team searched for suitable, existing scenarios. Desk research revealed no ready-made scenarios for the future of travel, border checks and biometric technologies in the EU. Therefore, we had to create subject-specific scenarios. This process was conducted in two stages:

1. **Search for the most suitable generic EU scenarios in the timeframe up to 2040:** Existing EU development scenarios for the year 2040 were analysed to select a set of generic scenarios suitable for further customisation. The choice was primarily based on the need to have a set of scenarios with similar levels of probability and desirability.
2. **Adaptation of selected scenarios to the study's subject:** The selected realities became a starting point for the creation of detailed scenarios devoted to the future of travel, border checks and biometric technologies. The backcasting technique was used for determining the steps that could lead to a particular vision of the future. The adaptation was conducted by the Research Team with the support of the Group of Experts during the *First Technology Foresight Workshop on Scenario Building*.[39]

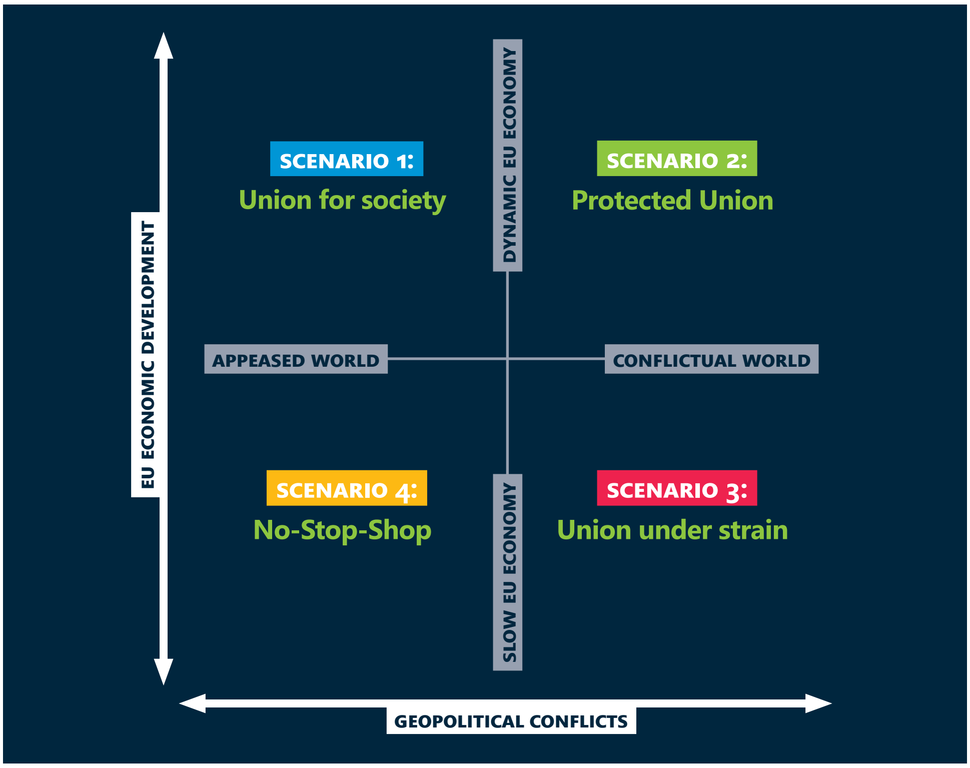
39 For more details, see Annex I – Technology Foresight Manual – Section 2.4 and Chapters 11, 12, 13, 14 and 16.

5.1. Stage 1 – Search for the most suitable generic EU scenarios in the timeframe up to 2040

The set of scenarios selected for further analysis originated from *The Future of Customs in the EU 2040: A foresight project for EU policy*,[40] a study published in 2020 by the European Commission's Joint Research Centre (JRC) in collaboration with the Directorate-General for Taxation and Customs Union (DG TAXUD). The project aimed to support strategic reflections on the future of the EU's Customs Union. Thus, the similarity of subject matter was merely one of the reasons behind the choice. The relevance of the time horizon, the general scope of scenarios and the method of scenario development were taken into account, as were multiple further factors.[41] The chosen scenarios provided detailed information concerning customs, but these were discarded as unessential for the project. The key aspect of the selected scenarios was the socio-techno-economic background, which provided a suitable context for developing alternative futures of biometrics for border checks. An overview of the four scenarios can be found in Figure 7.

The scenarios were constructed using a 2x2 Matrix technique, in which 2 important factors are 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). The resulting four scenarios are described in more detail below.

Figure 7: *Scenarios for EU in the year 2040 – 2x2 scenario matrix.*



40 A. Ghiran, A. Hakami, L. Bontoux and F. Scapolo, "The Future of Customs in the EU 2040: A foresight project for EU policy", EUR 30463 EN, Publications Office of the European Union, Luxembourg, 2020.

41 For more details, see Annex I – Technology Foresight Manual – Section 2.4.

SCENARIO 1 **Union for society** (see Table 7 for scenario details)
In 2040 the EU is prospering economically and has significant standing. International relations have stabilised as member states have adopted a cooperative attitude. However, global megatrends (climate change, increased migration, the rise of Asia and Africa and the global technological race) are exerting pressure on the EU.

Deep reforms have focused on sustainability and well-being across all sectors and EU institutions, which resulted in a high standard of living for all. Individual citizens have adopted sustainable lifestyles. Europe's population is ageing, and to counter the trend the EU has adopted policies designed to integrate migrants into society and the workforce. The economy has shifted towards a sustainable social market model, accompanied by major investments in new technologies and infrastructures. Digitalisation is now a key source of progress for society. The EU is also providing asylum to refugees displaced by issues related to climate change. Non-state actors have become more influential. However, significant market actors are controlled by governments and comply fully with international and European standards (which they co-shape).

SCENARIO 2 **Protected Union** (see Table 8 for scenario details)
In 2040 the EU is prospering economically and has a strong position in the global arena. However, the world is full of conflicts and is witnessing a power struggle. Countries compete for resources and influence, promoting their own worldviews, while intense geopolitical competition leads to proxy wars. A major direct conflict cannot be ruled out.

However, with increased strategic autonomy, high investments in R&D and a resource-efficient economy, the EU remains a significant global economic power with a high standard of living. EU migration policy has developed towards a combination of selectivity ('brain gain') and active integration, which counters the effects of ageing in the native population. Technological innovation in the EU is strongly supported and pursues three priority objectives: strategic autonomy, frugality and digital resilience, in which data protection is a key goal. Disruptions caused by extreme weather, rising sea levels and climate change, in general, are putting pressure on infrastructure, agriculture and logistics chains.

SCENARIO 3 **Union under strain** (see Table 9 for scenario details)
Intense competition for resources and influence between powerful nations has led to the spread of conflicts around the world. The EU economy has shrunk and its political situation is challenging.

Violent extremism has grown notably during the past couple of years. Conflicts and wars in other parts of the world are a significant concern for the EU and are, to some extent, transferred to European soil due to tensions between various political and migrant groups. EU Member States are leaning towards a more autonomous, closed and protective EU. On the other hand, privileged trade partnerships are developed for strategic reasons as well as to gain access to critical raw materials and energy. Economic opportunities in Europe are poor overall and are not distributed equally, leading to migration and the creation of ghettos. EU institutions are weakening, putting a strain on EU integration. A global technological race is raging, fuelled by climate change and security issues, with technology gaps between countries around the world increasing dramatically.

SCENARIO 4 **No-stop-shop**[42] (see Table 10 for scenario details)

Buffeted by climate change and confronted with the increasing power of the global East and South, the EU economy has slowed down and the EU's political strength is in decline. International relations are peaceful. There are few conflicts around the globe and new partnerships have emerged.

Policymaking is slow at the EU level and in many Member States due to strong constraints imposed at the international level and limited financial reserves. The impact of climate change has been significant, leading to resource scarcity and extreme weather. Thus the EU has largely shifted to a circular economy, with significantly lower energy and raw material consumption. Yet inequality is rising, fuelling populist movements and reducing social cohesion. Moreover, the EU's technological development has slowed down due to limited resources. There is a focus on frugal innovation: new technologies and products target maintaining quality of life while reducing energy and material consumption. High-tech developments originate primarily in other areas of the world.

42 The "no stop shop" is a model of e-government service delivery where the citizen does not have to perform any action or fill out any forms to receive government services. See: H. Scholta, W. Mertens, M. Kowalkiewicz and J. Becker, "From one-stop shop to no-stop shop: An e-government stage model", Government Information Quarterly, vol. 36, no. 1, pp. 11-26, 2019.

Table 7: *Scenario 1: Union for society – scenario details.*

SCENARIO 1					
Politics	**Economy**	**Society**	**Technology**	**Law**	**Environment**
Most countries have adopted more cooperative attitudes to address the common challenge of climate change.	The EU bases its economic model on the delivery of social welfare and the achievement of its own goals for sustainable development rather than GDP growth.	Society has largely adopted a sustainable model of life. There is less emphasis on reducing the price and duration of services (including transport, e-commerce) and more on making them sustainable. Society is focused on non-material goods.	Digitalisation is now a key source of progress for society. Investments in technology are primarily aimed at improving sustainability and maintaining high living standards.	The EU uses a revised set of sustainable development goals as a compass for all its policies. EU policies are well integrated; sustainability and social cohesion are at the core of the European project, with strong societal support.	In the two decades leading to 2040, Europeans experienced food shortages, wildfires, extreme weather conditions, mass extinction of plant and animal species and rising sea levels. Water resources were also impacted. The damage remains serious.
While Asia and Africa have gained a great deal of geopolitical weight, the relationship between China, Russia and the US has stabilised, and the re-energised European project inspires the rest of the world.	The world's trade system has evolved and now recognises the importance of sustainability in managing international trade. More multilateral agreements are created based on trusted economic exchanges, mutual benefits and peaceful relationships.	The EU's population is ageing; to counter this, the EU has adopted policies designed to integrate migrants into society and the workforce. The EU is also providing asylum to refugees displaced by issues related to climate change.	The EU invests heavily in new technologies and infrastructures.	Non-state actors have become more influential. Prominent market actors are controlled by Governments and comply fully with international and European standards (which they co-shape).	Environmental challenges created poverty in many regions of the world and intensified migration.
The EU's democracy and international standing have improved.	Trade flows freely, but there is no pursuit of ever-increasing volumes.	EU society is now inclusive and actively fights all types of inequality (including the digital divide and access to healthcare).	The EU supports re-skilling and education: IT and sustainability literacy are a part of the core curriculum.	The EU conducts deep and innovative internal reforms in sectors such as trade, environment and migration. The EU's decision-making processes have become very flexible.	The EU invests more funds into renewable energy sources and decarbonised means of transport. It stimulates new sustainable business models and invests in actions for the benefit of the environment and people.
The EU invests significantly in development aid and emergency response to natural and social catastrophes around the world to prevent further migration.	The EU has managed to combat protectionism internally.	Reforms aimed at sustainability and increased well-being require a level of social discipline unfamiliar to older generations (e.g. lower energy use, limited travel, limited use of individual transport).	Although there are fewer conventional security threats, disinformation and cybersecurity threats still need to be addressed.	Ambitious legislation to protect biodiversity, restore ecosystems and reduce pollution, waste and the depletion of resources has been promulgated.	International agreements regulate access to resources to avoid conflicts.
The threats of terrorism, organised crime and cyberattacks are still present. The EU also combats intellectual property theft and fiscal fraud.	The euro is very stable and is now a global benchmark currency, which boosts the EU's economic and political standing in the international arena.			The EU's public authorities cooperate with the private sector to combine resources and creativity and thus offer adequate services and products to the growing elderly population.	

Table 8: *Scenario 2: Protected Union – scenario details.*

SCENARIO 2					
Politics	**Economy**	**Society**	**Technology**	**Law**	**Environment**
The EU, China, the USA, India, Russia, Brazil, Iran, Saudi Arabia and other countries compete for resources and influence, promoting their own world views.	The EU economy has shifted towards an energy/resource efficient model and has become more resilient.	Migratory pressure is very high (due to the inflow from countries that suffer from poverty, natural disasters and geopolitical conflicts).	Geopolitical competitiveness and climate change fuel the technological race.	The perception of substantial common external threats has become an integrating factor for the EU across all Member States: EU nationalism is starting to emerge.	An increasing world population, increasing pressure from climate change and global trade troubled by political disagreements have led to increased urbanisation, competition for land and higher demand for local resources.
Intense geopolitical competition leads to proxy wars. A major direct conflict cannot be excluded.	Disruptions caused by extreme weather, rising sea levels and climate change, in general, are putting pressure on infrastructure, agriculture and logistics chains.	EU migration policy has developed towards a combination of selectivity ('brain gain') and active integration, which counters the effects of ageing in the native populations and boosts the economy.	Technological innovation in the EU is strongly supported and pursues three priority objectives: strategic autonomy, frugality and digital resilience, in which data protection is a key goal.	The need to counter numerous external threats has pushed the development of security measures and surveillance on many levels: at the borders, inside the Union (data collection, personal monitoring, cybersecurity, etc.) and outside (space technology investments).	The above factors have led to higher pollution and biodiversity loss around the world.
International organisations still exist, but strong disagreements and competition between the various geopolitical blocks mean that their authority is contested.	Trade agreements are made selectively with strategic allies.	EU citizens feel a strong need for protection. Furthermore, governments strive to gather intelligence on virtually every aspect of life.	Industrial espionage is rife and enforcing intellectual property rights internationally has become very difficult.	EU treaties have been updated and strengthened.	Resource scarcity (especially water) has resulted in unrest, forced displacement and increased migration.
There are strong economic disparities between various countries and regions of the world. Black market operations and organised crime exploit price differences between countries.	Energy and raw material consumption have slowed down, and the EU is largely self-sustaining.	The EU's cohesion policy has become more robust and encompasses economic disparities and the socio-political dimension (democracy, human rights, healthcare).		The EU and Member States' governments build strength by reinforcing their coordination and engaging in bold policy initiatives.	The traditional strengths of the EU in environmental technologies and environmental protection allow it to remain a significant international player in this area.
State-sponsored criminality and destabilisation efforts against the EU are common.	Due to geopolitical power shifts, the international standing of the euro has remained limited.				The EU's environmental policies are developing, and development aid is used to promote and implement the sustainability agenda elsewhere.

Table 9: *Scenario 3: Union under strain – scenario details.*

SCENARIO 3

Politics	Economy	Society	Technology	Law	Environment
The EU, China, the USA, India, Russia, Brazil, Iran, Saudi Arabia and other countries compete for resources and influence, promoting their own worldviews.	The EU's economy has slowed down and has adopted a circular model aimed at eliminating waste and reusing resources. Energy and raw material consumption are significantly lower.	The rapid forced transition to a sustainable economy in the context of increased international competition has created tensions within the EU. Polarisation has grown due to differing economic situations, principles, visions and worldviews across Europe.	A global technological race is raging, fuelled by climate change and security issues. Technology gaps between countries around the world are increasing dramatically. The same phenomenon can be observed, to some extent, within the EU.	While many people in the EU push for greener taxes, those hit the hardest by the slowing economy remain reluctant. Nonetheless, everybody agrees that there is a need for increased security.	The EU's agriculture is well-developed, but it must rely on other states for the supply of minerals and other resources.
International competition results in proxy wars, so a major direct conflict cannot be ruled out.	Some Member States believe protectionism is the best way forward, while others develop trade cooperation to increase sustainability both within the EU and globally.	Economic opportunities in Europe are poor overall and are not distributed equally, which leads to economic migration within the EU. Some of the most qualified move to other, wealthier countries.	The high priority of data security leads to increased efforts to harmonise data management inside the EU, although some Member States are hesitant or reluctant to cooperate.	Overall, EU institutions are becoming weaker, and the lack of respect for EU legislation is growing. This is putting a strain on EU integration.	Water scarcity is a severe issue. Large parts of Southern Europe have become deserts, and other regions struggle due to erratic rainfall and regular floods.
Violent extremism has grown notably during the past couple of years. Conflicts and wars in other parts of the world are a significant concern for the EU and are, to some extent, transferred to Europe due to tensions between various political and migrant groups.	Overall, EU Member States lean towards a more autonomous, closed and protective EU. Nonetheless, privileged trade partnerships are developed for strategic reasons and to gain access to critical raw materials and energy.	Cities become segregated and inequalities rise. Ghettos emerge along socio-economic, cultural and ethnic lines.	The shared concern about external threats creates consensus on the need for a strong border and for public R&D for the EU to hold its own in the international technological race.	The demanding international geopolitical situation requires much effort in areas far from citizens' daily concerns. As a result, citizen engagement is no longer a priority, and only minimal measures are taken to include citizens in policymaking.	Environmental protection efforts across the EU are unequal, with only some Members relying on renewable energy and attempting to reduce waste.
Large demonstrations often rock European capitals. Trust in government is low and the influence of non-state actors (e.g. digital communities, religious groups, transnational civil society orgs.) is growing.	The black economy is growing, exploiting tax differences and the weakness of companies and entrepreneurs in the context of shrinking margins. Government agencies have few resources to audit/track fraud.	The EU's population is ageing. In the context of slow economic development, this has put a strain on pension systems and led to an increasing retirement age. Also, unemployment is high.	Prioritised technology developments include IT, robotisation, AI, cybersecurity and resource independence (e.g. biotech for biofuels).	There is a tendency to make decisions locally whenever possible. Decisions made at the EU level tend to be limited to geopolitical and high-level issues.	
The influence of multilateral institutions has declined. The WTO is particularly weak.	The euro's international standing has weakened, putting the currency under threat.	Although the number of refugees in need of protection around the world has never been higher due to conflicts and climate change, the EU is unwilling to accept many migrants, arguing that those who wish to relocate to Europe are unqualified.		EU citizens want changes, but fundamental disagreements between various groups of Europeans often lead to political gridlock.	

Table 10: *Scenario 4: No-stop-shop – scenario details.*

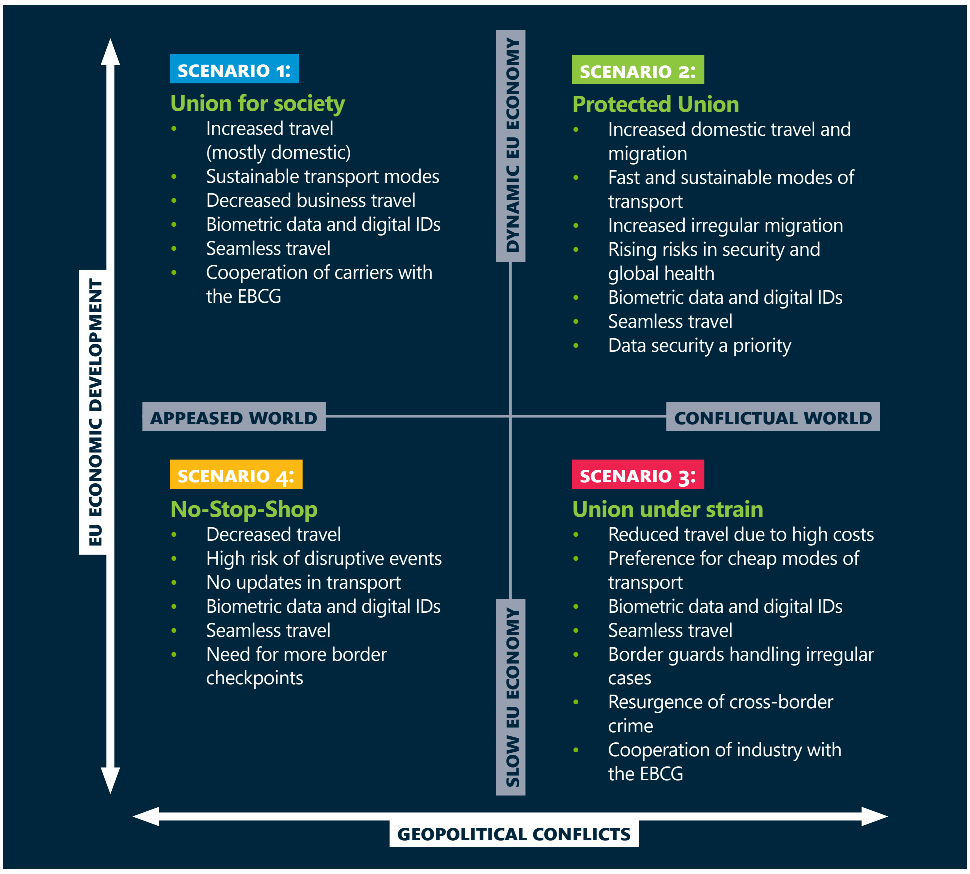
SCENARIO 4

Politics	Economy	Society	Technology	Law	Environment
International relations are peaceful and there are few conflicts around the globe.	EU economy has slowed down and the EU's political influence has decreased.	Inequality rises, fuelling populist movements and affecting social cohesion.	The EU's technology development has slowed down due to limited resources.	Policymaking is slow at the EU level and in many of the Member States due to strong constraints imposed at the international level and limited financial means.	The impact of climate change has been significant, including resource scarcity and extreme weather.
Most countries have adopted more cooperative attitudes to address the common challenge of climate change. The influence of multilateral organisations has increased.	The EU has largely shifted to a circular economy with significantly lower energy and raw material consumption.	An increasing share of highly educated Europeans is migrating to other parts of the world, looking for better job opportunities.	There is a focus on frugal innovation: new technologies and products target maintaining quality of life while reducing energy and material consumption.	Migration policy has clearly shifted towards facilitating integration. It is easier for newcomers to obtain citizenship.	Climate issues resulted in competition for land, deforestation and loss of biodiversity.
Asia and Africa have gained a lot of geopolitical weight. The relationship between China, Russia and the USA has stabilised. New international partnerships have emerged.	The volume of international trade remains moderate due to high energy costs and short material loops.	The EU's population is ageing. The demographic issues (ageing population and emigration) primarily affect Eastern Europe.	High-tech developments originate mostly in other areas of the world (except for critical data, AI and security technologies).	Taxes on raw materials, energy and fossil fuels are very high, creating an incentive for fraud and barter.	There are large variations in the water supply. Parts of Southern Europe have become deserts, while other regions struggle due to erratic rainfall and regular floods. This affects river transport, hydroelectricity production and nuclear power.
There is an international competition for natural resources. Resources are controlled by a privileged few, which leads to rising inequality.	Due to climate change issues, raw material consumption has decreased and changed (emphasis on recycling, fewer single-use items).	There is an inflow of migrants (due to climate change issues in other parts of the world) who are rejuvenating the EU's workforce.		Tax harmonisation within the EU has increased.	International actors understand that climate change issues can only be tackled through cooperation.
International trade is relatively easy due to cooperative relations. There are fewer economic (trade) sanctions.	The economic weakness of the EU means that many foreign actors are buying EU assets. Market pressure tempts European actors to compromise on EU values.				

5.2. Stage 2 – Adaptation of selected scenarios to the study's subject

The second stage of *Scenario Analysis* was conducted during the *First Technology Foresight Workshop on Scenario Building*. The Group of Experts and the Research Team discussed the possible consequences of the 2040 scenarios for the travel and border check experience. Additionally, workshop participants were asked to envision a biometrics-related set of events, measures and conditions which would impact the future of travel in 2021-2040. The visions were instrumental to a better understanding of the cause-and-effect chains of events that might result in a particular set of potential 2040 outcomes. Various methods were used to facilitate the adaptation of the selected scenarios, including *Rip van Winkle*, *Futures Wheel* and *Backcasting*.[43] In general, the backcasting technique is used for determining the steps that could lead to a particular vision of the future, represented by a snapshot scenario, describing the world many years from now. It consists of the subsequent identification of events that would need to occur between that future and the present for that particular vision to occur. The workshop was conducted using the *Miro Board*[44] tool. An overview of the results is presented in Figure 8, which shows the anticipated high-level developments in travel and border checks for each of the scenarios.

Figure 8: *General overview of scenarios on the future of travel, border checks and biometric technologies shown in a 2x2 scenario matrix.*



43 See Annex I – Technology Foresight Manual – Chapters 11, 12, 13.

44 See Annex I – Technology Foresight Manual – Chapter 18.

Figure 8 uses the same 2x2 matrix structure as the one developed for *The Future of Customs in the EU 2040* but contains added information related to travel and border checks. A more detailed description of the adapted scenarios is provided below.

SCENARIO 1 Union for society

The most common reasons for travel include migration, education and leisure, and there is an increased share of senior travellers. Technological progress and digitalisation have reduced the need for business travel. Overall, the flow of travellers has increased compared to 2021. Domestic travel dominates, while intercontinental travellers typically plan longer stays at their destination. The leading modes of transport include land transport and shared solutions. Air travel is usually selected for long-distance (international) journeys. The number of electric cars and trains is increasing, but there are no disruptive changes in transport modalities.

Information about travellers, including IDs and tickets, is handled purely digitally, and biometric data is highly relevant. Member States have real-time access to a unified EU biometrics data repository. Border management is smart (easily adaptable and relies on systematic risk-based threat assessment) and external borders can now be crossed seamlessly, with border guards intervening only in exceptional cases. There is close collaboration between carriers and the EBCG authorities, but privacy protection and the private operators' limited access to personal data remain a challenge. There is high demand for an innovative legal framework that would guarantee data protection and compliance with fundamental rights.

Table 11: *Scenario 1 adapted to the realm of travel and border checks. Table includes enabling, neutral and inhibiting factors (in terms of scenario realisation), key information on travel and border checks in the scenario, as well as key turning points (potential events and developments that may lead to scenario realisation).*

	SCENARIO 1	Union for society				
	Politics	**Economy**	**Society**	**Technology**	**Law**	**Environment**
Enabling factors	Peaceful world Strong international cooperation	Euro currency is stable Strong global EU influence Sustainable social market model Growing number of multilateral trade agreements	Widespread sustainable lifestyle (focus on long-lasting rather than fast and cheap solutions) and consumer behaviours Strong social cohesion High standard of living	Digitalisation as a key factor of progress for society Heavy investments in new technologies and infrastructures	Intense and smooth data exchange across EU external borders EU policies well integrated into Member States' legal frameworks	
Neutral factors	Growing role of non-state actors Global consciousness Prominence of social media platforms Rise of Asia and Africa	Large market actors (controlled by governments and fully compliant with international and European standards)	Large scale of migration to and from the EU Ageing EU society	Investments focused on sustainability and maintaining living standards Global technological race	Sustainable development goals are a driving force for policies	
Inhibiting factors			Poverty in multiple regions worldwide driven by climate change	Cyber-threats and disinformation are continuously countered and debunked	Challenge of implementing global legal frameworks that guarantee data protection and compliance with fundamental rights	Consequences of climate change: food shortages, extreme weather, loss of biodiversity, rising sea levels

SCENARIO 1	Union for society
KEY INFORMATION	
TRAVEL	**BORDER CHECKS**
Increased traveller flow compared to 2021. Predominant reasons for travel include migration, education and leisure. Significantly higher share of senior and migrant travellers. Technological progress and digitalisation result in a reduced need for business travel. Intracontinental (domestic) travel dominates and business travel between Asia and the EU increases. Fewer intercontinental trips, but for longer durations. Prevalent modes of transport include land transport and shared solutions (electric cars, trains, buses), while air travel (primarily electric) is used mainly for long-distance travel. Usage of electric cars and trains has increased, but there are no disruptive changes in transport modalities. The widespread use of digital solutions requires education focused on digital skills and the avoidance of biased data.	Traveller information is handled purely digitally, Digital IDs and tickets included. Biometric data is highly relevant; EU MSs have real-time access to a unified EU biometrics data repository. Borders are smart (easily adaptable and relying on systematic risk-based threat assessment) and external borders can now be crossed seamlessly (no physical barriers, supported by large-scale IT systems), with border guards intervening only in exceptional cases. Biometric technologies facilitate identification whenever complications arise (e.g. in the case of refusals at border checks and the identification of irregular migrants). Cooperation with carriers has become an integral part of border management and there is close collaboration between carriers and the EBCG authorities, although privacy protection and the private operators' limited access to personal data remain a challenge. Strong national authorities are able to react quickly to changes in traveller flow and unforeseen events. Data storage and handling remain a sensitive topic. A robust legal framework for the regulation of technologies and easy exchange of passenger data with third countries is in place (standardisation is a key enabler). There is high demand for a legal framework that would guarantee data protection and compliance with fundamental rights.

KEY TURNING POINTS		
2022-2027	**2028-2033**	**2034-2040**
Standardisation of data processing and implementation of robust legal frameworks (regarding fundamental rights compliance, AI, data protection). Biometric technologies widely accepted by society.	Effective data exchange across EU external borders established. Seamless border check systems in place. Societal awareness and sensitivity to the issue of access to and control over personal data. Quantum computers available to large companies. Strong public financial support for mass transport.	International security data exchange is possible for LEAs in real-time. EU biometric repository established. Fully autonomous border check systems using robots (AI-embedded). Major technological breakthrough: ultra-high-speed data handling and storage enabled by hybrid computers (traditional / quantum-neuromorphic). Fully established common digital identity management system. New commercial route around the North Pole impacting Northern EU.

SCENARIO 2 Protected Union

Migration and business are the predominant motives for travel. Travel to destinations within the EU (mainly group travel) is more popular than travel to third countries (primarily business travel and long-term stays). Overall, business travel has become less popular due to new technologies which enable virtual interactions. The main modes of transport are air taxis, autonomous cars or coaches, trains and the hyperloop (which significantly decreases travel time). Irregular migration has increased, and numerous security challenges are present (e.g. terrorism, human trafficking and large numbers of refugees). Security risks for EU citizens travelling outside the EU have risen due to inequality and high crime rates. Pandemics are a persistent threat that forces health authorities to track travellers by accessing their data.

National and international law enforcement authorities have implemented numerous solutions that enable secure and standardised information exchange at borders. Biometric data is required when travelling, and digital identities are used. Therefore, physical passports are no longer necessary. Border checks have become seamless, with human assistance required only in exceptional cases. Additional border checks have been established (e.g. at train stations and on board autonomous cars), and collaboration with carriers is essential for effective border management. There is high demand for better policies on data protection and personal data handling.

Table 12: *Scenario 2 adapted to the realm of travel and border checks. Table includes enabling, neutral and inhibiting factors (in terms of scenario realisation), key information on travel and border checks in the scenario, as well as key turning points (potential events and developments that may lead to scenario realisation).*

	SCENARIO 2	Protected Union				
	Politics	**Economy**	**Society**	**Technology**	**Law**	**Environment**
Enabling factors	Strong EU	Increased strategic autonomy Resource-efficient economy The EU is a major global economic power	Willingness to accept surveillance and security measures Border control is a priority Strong social cohesion within the EU	Technological innovation in the EU is strongly supported Major investments in R&D	Reinforced coordination and bold policy initiatives (of the EU and the Member States) Pressure for the development of security measures and surveillance	
Neutral factors		Selective trade agreements with trusted partner states	High standard of living in the EU High degree of migration to EU Ageing EU society	Focus on strategic autonomy, frugality and digital resilience (data protection) Global technological race		Increased urbanisation
Inhibiting factors	Intense competition for global influence Proxy wars and major direct conflicts Weak international institutions High degree of organised crime, state-sponsored crime and espionage		Constant sense of threat			Intense competition for resources Increasing world population Climate change pressure: high demand for local resources, high degree of pollution and loss of biodiversity

SCENARIO 2	Protected Union

KEY INFORMATION

TRAVEL	BORDER CHECKS
The predominant motives for travel are migration (including family reunions) and business. Travel to destinations within the EU (mainly short stays and group travel by families and seniors) is significantly more popular than travel to third countries (mostly business travel and long-term stay). Business travel has become less popular due to new technologies that enable virtual interactions (e.g. Virtual Reality). Tourism is mostly limited to EU territory. The typical destinations are small-towns and villages (focus on nature, avoiding crowds). Some safe long-distance destinations also remain popular. VIP travel (often including door-to-door services mainly for security reasons) has gained popularity. The main modes of transport are air taxis, autonomous cars and coaches, trains and the hyperloop (which significantly decreases travel time). Irregular migration has significantly increased, and numerous security challenges are present (e.g. terrorism, human trafficking and large numbers of refugees).	Security risks for EU citizens travelling outside the EU have risen due to inequality and high crime rates. Pandemics (and similar global health crises) are a persistent threat that forces health authorities to track travellers by accessing their data. EU migration policies for third-country nationals are well established, and visas remain mandatory. Biometric data is required when travelling, and digital identities are used. Therefore, physical passports are no longer necessary, and border checks have become seamless, with human assistance required only in exceptional cases, which fuels identity theft. There is high demand for better policies on data protection and personal data handling, as control over personal data remains in the hands of travellers. National and International Law Enforcement Authorities have implemented global solutions to enable secure and standardised information exchange at borders. A significant portion of data required for border checks is collected before travel, although it may not be mandatory to specify the start and finish points for a traveller's journey in advance. Numerous additional border checks have been established (e.g. at train stations and on board autonomous cars), which facilitate the tracking of travellers. Collaboration of authorities with carriers has become essential for efficient border management. Carriers possess extended responsibilities for collecting passenger data and exchanging information with authorities. The procedures comply with fundamental rights and data protection regulations; travellers are always notified about data usage. Members of the EBCG community are required to improve their capabilities and resources (e.g. additional training, effective change management, increased automation, technical resources, emphasis on IT systems). An independent international body is established to monitor compliance with human rights and data policies.

KEY TURNING POINTS

2022-2027	2028-2033	2034-2040
Privacy and data protection embedded into IT products, networks and AI. Transparent laws and regulations concerning border checks lead to social acceptance and trust. Dual-citizenship possibilities have been expanded to include multiple non-EU countries.	Fully staffed and operational EU Border and Coast Guard standing corps. EU army established. Ultra-fast means of transport (e.g. hyperloop).	Leading role of the EU in defining new technical standards, e.g. regulation of machine-to-machine communications. Shared, self-sovereign identity (SSI) database available. Strong restrictions on migration into the EU have been imposed. The EU is independent of other countries regarding raw material resources.

SCENARIO 3 **Union under strain**

The flow of travellers through both internal and external borders has significantly decreased compared to 2021. Travel for leisure occurs mainly within the EU (for short trips) and is considered a luxury, while intercontinental travel has become significantly less popular. The dominant reasons for travel include migration, education, research and business. The cheapest travel modes are preferred due to an overall increase in travel costs (a consequence of environmental protection costs and the reduced number of travellers). Air travel is significantly less popular, while autonomous cars and high-speed trains prevail.

Border checks require the handling of large data flows, and there are significant discrepancies in technical standards and procedures for implementing biometrics-enabled technological systems at border crossing points. Digital credentials have replaced paper travel documents, but the increased complexity of pre-travel authorisation procedures complicates journeys. However, external borders can be crossed seamlessly, owing to efficient and fully automatic traveller pre-registration and check-in procedures (supported by carriers), as well as the use of AI and autonomous systems. Nevertheless, border guards are still indispensable in irregular cases. The EBCG is also confronted with a resurgence of cross-border crime and illicit trade. There is close collaboration between biometric technology providers and the EBCG.

Table 13: *Scenario 3 adapted to the realm of travel and border checks. Table includes enabling, neutral and inhibiting factors (in terms of scenario realisation), key information on travel and border checks in the scenario, as well as key turning points (potential events and developments that may lead to scenario realisation).*

	SCENARIO 3	Union under strain				
	Politics	**Economy**	**Society**	**Technology**	**Law**	**Environment**
Enabling factors		Circular economy (resource efficient)	Consensus on need for strong external borders and publicly-funded R&D	Prioritised technologies include IT, robotics, AI, cyber-security and solutions which improve resource independence	High importance of data security Overall harmonisation of personal data management within the EU	Well-developed EU agriculture
Neutral factors	External pressure increases the need for unity and autonomy	Selective protectionism	Ageing EU society	Global technological race	Fundamental disagreements between various groups of Europeans often lead to political gridlock	Unequal environmental protection efforts across the EU
Inhibiting factors	Poor international cooperation Strong nationalism Violent extremism, conflicts and wars outside the EU Tension within the EU The growing influence of non-state actors	Slow EU economy Low public budgets Increased disparities within the EU	Low trust in government Social unrest: inequality and class society; tension between immigrants Increased number of refugees (EU unwilling to accept many migrants) High unemployment and criminality	Large technological gaps between countries around the world	Weak EU institutions Disrespect for EU legislation	Strong competition for resources The EU is dependent on other states for minerals and raw resources

SCENARIO 3 **Union under strain**

KEY INFORMATION

TRAVEL	BORDER CHECKS
The flow of travellers has significantly decreased compared to 2021. Travel is considered a luxury, and business travel has become obsolete due to advances in communication technology. The dominant reasons for travel include migration, education, research and business. Travel for leisure occurs mainly within the EU (for short trips) and is considered a luxury, while intercontinental travel has become significantly less popular. The cheapest travel modes are preferred due to an overall increase in travel costs (a consequence of environmental protection costs and the reduced number of travellers). Air travel is significantly less popular, while autonomous cars and high-speed trains prevail. The complexity of pre-travel procedures has increased (e.g. due to social scoring systems), which complicates journeys.	Border checks require the handling of large data flows. Digital identity management solutions have replaced physical travel documents. Border checks at external EU borders are smoother, thanks to pre-travel procedures (supported by carriers). External borders can be crossed seamlessly, owing to efficient and fully automatic traveller pre-registration and check-in procedures. AI and autonomous systems are widely used in border checks. However, border guards (whose numbers have decreased) are still indispensable in irregular cases. Systems for passenger flow management and border checks can easily be reconfigured at border crossing points. Increased monitoring efforts are necessary at external EU borders. There are high discrepancies in technical standards and procedures for the implementation of biometrics-enabled technological systems at border crossing points. Cooperation with carriers has become an integral part of border management. Carriers provide the infrastructure for pre-enrolment and fast border crossing. The EBCG is confronted with a resurgence of cross-border crime and illicit trade. Well-rehearsed response plans are set up for health crises. Training and skills development are necessary to prepare Border Guards for high-risk and irregular cases. There is a secure and efficient supply chain for biometric devices and data exchange systems within the EU. There is close collaboration between biometric technology providers and the EBCG.

KEY TURNING POINTS

2022-2027	2028-2033	2034-2040
Radicalisation and a massive inflow of refugees exert pressure on the EU. Specific GDPR-like regulations in place for biometric data protection in the context of border checks. Setting up tech clusters for industrial research in biometric domains to ensure critical mass within the EU. CO_2 footprint quota to be considered.	Conflicts between states (competition for resources). Weak economy, limited resources. Severe climate crisis and social unrest. Rise of totalitarian governments, weakened democracies. No harmonised standards or regulations for biometric technologies in place.	Nationalism over cooperation, the EU breaks apart. Numerous cyberattacks. High degree of inequality worldwide. Close collaboration on biometrics between the EBCG, industries and research institutions. Resource autonomy within the EU.

SCENARIO 4 No-stop-shop

The frequency of travel within the EU has decreased compared to 2021. Travel (especially by air) is now considered a luxury. The share of business travel is lower than that of travel for leisure and migration. No technological breakthrough has emerged when it comes to the modes of transport, and there is a high risk of unprecedented (possibly disruptive) events which could affect travel, e.g. another global pandemic.

Owing to the use of biometrics, technological systems for seamless border checks have been widely implemented, allowing the vast majority of checks at external borders to be processed automatically. However, the EBCG authorities are challenged by exceptional and complex cases that require new competencies. The latter include irregular migration and unforeseen events (e.g. pandemics, which require the introduction of medical checks and flexible stand-alone technologies). Numerous additional BCPs have been introduced to increase security and facilitate the crossing of land and maritime borders. Carriers take an active role in facilitating border management processes. There is a strong need for worldwide standards for personal data handling and AI use.

Table 14: *Scenario 4 adapted to the realm of travel and border checks. Table includes enabling, neutral and inhibiting factors (in terms of scenario realisation), key information on travel and border checks in the scenario, as well as key turning points (potential events and developments that may lead to scenario realisation).*

SCENARIO 4	No-stop-shop					
	Politics	**Economy**	**Society**	**Technology**	**Law**	**Environment**
Enabling factors	Peaceful world Strong international cooperation	Circular economy (low raw material and energy consumption) Free international trade			Intense and efficient data exchange across the EU's external borders	
Neutral factors		Low international trade volume due to high energy costs and resource scarcity	High levels of migration to and from the EU Ageing EU society	Frugal innovation: maintaining the quality of life, reducing energy and material consumption High-tech developments mostly from outside the EU (exception: some critical data, AI and cybersecurity technologies)		
Inhibiting factors	Slow policy-making at the EU level Decrease in the EU's political influence Organised cybercrime and fraud	Slow EU economy	Social inequality reducing social cohesion, fuelling populist politics	Limited financial means	Very high taxes on raw materials and energy create an incentive for fraud and barter	Resource scarcity Climate change consequences: extreme weather, competition for land, deforestation and loss of biodiversity

SCENARIO 4 **No-stop-shop**

KEY INFORMATION

TRAVEL	BORDER CHECKS
Travel within the EU has declined compared to 2021. Travel in general, especially air travel, is considered a luxury (air travel has decreased significantly). The share of business travel is lower than travel for leisure and migration (e.g. family reunions and student exchanges). Significant changes in travelling patterns require the application of new business models (by carriers). No technological breakthrough has emerged concerning the modes of transport; the modes of transport are simply the upgrades of 2021 versions. High risk of unprecedented (possibly disruptive) events affecting travel, e.g. another global pandemic.	Owing to the use of biometrics, technological systems for seamless border checks have been widely implemented, allowing the vast majority of checks at external borders to be processed automatically. A high volume of data is handled during border checks. Solutions for digital identity management provide individual travellers with control over personal biometric data. Strong GDPR-like regulations are in place. There is a strong need for worldwide standards for personal data handling and AI use. EBCG authorities are challenged by exceptional and complex cases that require new competencies. Unforeseen events (e.g. pandemics) require swift and flexible adjustments to border check procedures (e.g. the introduction of medical checks, the use of flexible stand-alone technologies and the reintroduction of border control at internal borders). Diverse types of travellers (and various visa types) are an additional impediment at border checks. Numerous additional BCPs have been introduced to increase security and facilitate crossing land and maritime borders. Carriers take an active role in facilitating border management processes.

KEY TURNING POINTS

2022-2027	2028-2033	2034-2040
First pilot of a seamless travel system. High cost of raw materials (especially materials used in the production of batteries and microchips). 5G networks deployed and AI technologies widely adopted, but issues related to biased data have been encountered (e.g. related to travellers' ethnicity). The legal framework has caught up with technological developments. Overall societal trust and acceptance of biometric systems.	Extreme weather conditions are more frequent (including water scarcity). Asia takes the global lead (politically but also economically and technologically), diminishing the EU's influence. Paper ID/passport replaced by digital identity management solutions. Migration remains high, but citizenship procedures are facilitated.	Legally approved and fully operational seamless travel system. A new version of the Cold War.

6. Security aspects of biometric technologies

Even the most accurate biometric recognition technology may prove ineffective if it is not resilient to fraud or hostile attacks, thus rendering it useless for facilitating border crossing. Evaluating the security of technologies per se is challenging compared to the assessment of specific products or systems, i.e. technology implementations. Technologies can be implemented in numerous ways and can also be integrated with other technologies to form comprehensive systems. The specific parameters of such systems can be compared (in terms of overall performance, security, cost etc.). The present study, however, considered the technologies themselves and their potential future implementations. Therefore, the security analysis focused on the technologies' comparative vulnerability to adversary attacks.

The 20 biometric technological clusters identified within the taxonomy were compared in terms of their inherent vulnerability. A taxonomy of vulnerabilities and defences was used for reference[45] and a scale from 0 to 5 was employed, where 5 signifies the highest vulnerability and 0 is the lowest (i.e. the strongest resistance to adversary attacks) amongst all the assessed clusters. Naturally, if a given technology is used in a specific product or system, the inherent vulnerabilities may be overcome (e.g. by combining a technology with another one, which offsets its vulnerabilities). Nonetheless, the inherent vulnerabilities should be weighed when the possibility of utilising a particular technology is considered.

The security assessment considers vulnerability to adversary user-level attacks, which feed fake or compromised samples to biometric systems. These types of attacks include presentation attacks and face morphing attacks. Vulnerability to user-level attacks is directly connected to the properties of a specific biometric technology and related modalities. Other attacks, including attacks on components (of biometric systems) and biometric templates, were not considered,[46] as they are not relevant to the clusters being analysed but instead to cross-cutting technologies that were not considered in this study (i.e., privacy-enhancing technologies).

In addition to assessing the inherent vulnerability to adversary attacks on a numeric scale, Table 15 describes the principal risks and opportunities associated with the clusters we analysed. This additional qualitative information supplements the quantitative assessment.

45 Y. N. Singh and S. K. Singh, "A taxonomy of biometric system vulnerabilities and defences", Int. J. Biometrics, vol. 5, no. 2, pp. 137-159, 2013.

46 With the exception of face morphing that in some cases is classified as an attack on biometric templates.

Table 15: *Comparative inherent vulnerability to adversary attacks of biometric technological clusters.*

No.	Technological Cluster	Comparative inherent vulnerability to adversary attacks: 0-5[47]	Main associated risks and drawbacks	Main associated opportunities and benefits
1	DNA biometrics	0	Considered intrusive Possible attacks with DNA cloning	Extremely accurate
2	Infrared face recognition	1	New attack methods such as face masks made of metamaterials Acquisition at lower distances than 2D face recognition in the visible spectrum	Impressive presentation attack detection capabilities Relatively easy to capture
3	2D face recognition in the visible spectrum	5	Vulnerable to morphing attacks Vulnerable to presentation attacks (artefacts, make-up)	Modality based on a unique biometric characteristic High social acceptance Simple acquisition process
4	3D face recognition	3	New attack methods, such as more accurate 3D masks Acquisition at lower distances than 2D face recognition in the visible spectrum	More accurate than 2D face recognition (in both the infrared and the visible spectrum) More resistant to attacks than 2D face recognition in the visible spectrum
5	Infrared friction ridge recognition	2	New presentation attack methods using artefacts made of metamaterials or highly transmissive spoofing items Higher failure-to-enrol rate than for typical contact-based friction ridge scanners (capacitive scanners)	Can be integrated into other solutions, e.g. built into displays High degree of miniaturisation compared to other friction ridge scanners
6	3D friction ridge recognition	3	New presentation attack methods with various artefacts Accuracy limited by the size of the acquisition area Complex acquisition setup, risks high failure-to-acquire rate	The friction ridge pattern is not deformed by contact with a surface This modality captures the natural 3D shape of ridges
7	Contactless friction ridge recognition	4	Possible lower accuracy compared to contact-based methods Complex acquisition process Higher vulnerability to presentation attacks with various artefacts compared to contact-based friction ridge methods	Highly acceptable during pandemics due to contactless operation
8	Contact-based friction ridge recognition	2	Might be problematic in the event of pandemics due to physical contact Accuracy limited by the size of the acquisition area	High social acceptance Simple and reliable acquisition process

47 5 means the highest inherent vulnerability amongst all the assessed clusters, while 0 is the lowest (meaning the strongest inherent resistance to adversary attacks) amongst all the assessed clusters.

No.	Technological Cluster	Comparative inherent vulnerability to adversary attacks: 0-5[47]	Main associated risks and drawbacks	Main associated opportunities and benefits
9	Iris recognition in the NIR spectrum	2	New presentation attack methods using new artefacts including contact lenses with changing patterns Careful design of the illumination system is needed to ensure eye- safety Complex acquisition of biometric samples due to human factors and usability challenges	Impressive recognition capabilities in terms of accuracy – this modality is very distinctive Contactless acquisition
10	Iris recognition in the visible spectrum	2	Difficulties in biometric acquisition from people with dark irises New presentation attack methods using new artefacts including contact lenses with changing patterns	Easier acquisition process than in near infrared Little eye-safety risk
11	Iris recognition at a distance	2	New presentation attack methods using new artefacts including contact lenses with changing patterns	Technically still complex, but the ability to capture this very distinctive biometric characteristic from a distance would be a breakthrough that the community expects
12	Eye vein recognition	1	Intrusive Acquisition from a close distance	Unique biometric features Vein pattern stable over time
13	Hand vein recognition	2	New presentation attacks possible (e.g. performed with printed vein images)	Unique biometric features Very distinctive biometric characteristic
14	Heart signal recognition	2	Not very distinctive Complex acquisition Acquisition process may be impacted by various human-related factors (e.g. physical exertion) May reveal health issues not otherwise visible	May allow the detection of people in need of assistance (by revealing health issues)
15	Hand geometry recognition	4	Contact-based modalities that might be problematic in the event of pandemics Vulnerable to presentation attacks with artefacts	Relatively easy to capture Can easily be linked with friction ridge modalities
16	Periocular recognition	2	If associated with iris recognition – lower performance while acquired in the visible light spectrum due to the challenge of capturing dark irises	Can be acquired together with 2D face biometrics in the visible spectrum
17	Keystroke recognition	3	This modality is not very distinctive Not suitable as the main modality for recognition at border checks Acquisition should be done under specific conditions (seated subject) Vulnerable to presentation attacks, e.g. mimicking attacks consisting in imitating a target's timing with regard to keystrokes	Very easy acquisition process where a keyboard is present

No.	Technological Cluster	Comparative inherent vulnerability to adversary attacks: 0-5[47]	Main associated risks and drawbacks	Main associated opportunities and benefits
18	Gait recognition	4	This modality is not very distinctive Not suitable as the main modality for recognition at border checks Gait pattern may be impacted by various factors including temporary health issues Vulnerable to presentation attacks, e.g. spoofing attacks where a person tries to imitate the walking style of a target	Non-intrusive acquisition that does not require the subject to cooperate Easily captured from a distance Suitable for on-the-move acquisition
19	Handwriting recognition	3	Contact-based modality that might be problematic in the event of pandemics Vulnerable to presentation attacks, e.g. handwriting forgeries	High social acceptance Very easy acquisition process
20	Speaker recognition	3	Vulnerable to new presentation attack methods including voice generation Acquisition may be affected by background noise	Very easy acquisition process

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, it is highly secure. This is common for security-related measures in general: less invasive solutions are usually not the most secure ones, so the challenge lies in combining seamlessness and security. *DNA biometrics* is closely followed by *Infrared face recognition* and *Eye vein recognition*. Both display relatively low vulnerability to adversary attacks. At the other end of the scale, there 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. Solutions such as *Gait recognition*, *Hand geometry recognition* and *Contactless friction ridge recognition* received only a slightly better assessment than *2D face recognition in the visible spectrum*. The technological clusters deemed most vulnerable have one risk in common: vulnerability to presentation attacks.

The analysis presented in Table 15 shows a comparative assessment of vulnerabilities, risks and opportunities related to specific technological clusters. The accompanying assumption is that the future will resemble our current reality. Therefore, the analysis is based on a "business as usual" (BAU) scenario. This does not necessarily mean that nothing will change. The BAU scenario assumes an expected, extrapolative continuation of currently observed trends, with no significant disruptions. Such a scenario should certainly not be discarded, but it would also be a mistake to take it for granted. Therefore, a cross-comparison was also performed to obtain a more comprehensive picture of the potential weaknesses of technological clusters in specific future scenarios. It aimed to identify the shortcomings of the analysed technologies under the stress conditions of scenarios for 2040 described in the previous chapter. The compatibility of technological clusters with particular scenarios has been assessed on a scale of 1 to 5, with 1 signifying major incompatibility and 5 signifying high synergy (i.e. a technology especially well-suited to a particular scenario). The assessment considered vulnerabilities to adversary attacks, but was not limited to them. Low compatibility with a given scenario could result, for example, from social, political or economic factors that would hinder the widespread employment of a given technology in a particular scenario. The results of the assessment are presented in Table 16.

Most technological clusters perform very differently under the stress conditions of specific scenarios. For example, *DNA biometrics* received a low rating in three of the four scenarios and only a mediocre rating in the fourth. This does not necessarily mean the technology should not be pursued, but rather signifies potential difficulties in making the cluster future-proof enough to be a safe direction of development. Even poorer compatibility with the scenarios can be observed in the case of 4 other technological clusters: *Heart signal recognition, Eye vein recognition, Keystroke recognition* and *Handwriting recognition,* primarily because of the challenges associated with the seamless acquisition of biometric data using these technologies. If the clusters are to be pursued further, careful analysis is necessary. At the other end of the spectrum is a set of relatively future-proof technologies, at least within the four scenarios. They include *Contactless friction ridge recognition*, *Hand vein recognition* and *Iris recognition at a distance*.

Table 16: *Compatibility of technological clusters with the selected scenarios.*

#	Cluster name	Technological clusters' compatibility with scenarios (1 – major incompatibility, 5 – high synergy)			
		SCENARIO 1 Union for society	SCENARIO 2 Protected Union	SCENARIO 3 Union under strain	SCENARIO 4 No-stop-shop
1	DNA biometrics	1	3	1	1
2	Infrared face recognition	3	4	3	3
3	2D face recognition in the visible spectrum	4	3	3	3
4	3D face recognition	3	4	3	3
5	Infrared friction ridge recognition	2	4	3	3
6	3D friction ridge recognition	3	4	3	3
7	Contactless friction ridge recognition	5	5	4	4
8	Contact-based friction ridge recognition	2	3	3	3
9	Iris recognition in the NIR spectrum	2	3	4	4
10	Iris recognition in the visible spectrum	2	3	4	4
11	Iris recognition at a distance	5	5	4	4
12	Eye vein recognition	1	1	1	1
13	Hand vein recognition	3	4	4	4
14	Heart signal recognition	1	1	1	1
15	Hand geometry recognition	2	2	2	2
16	Periocular recognition	2	2	3	3
17	Keystroke recognition	1	1	1	1
18	Gait recognition	5	5	2	3
19	Handwriting recognition	1	1	1	1
20	Speaker recognition	1	1	3	3

7. Prioritisation of biometric technologies. Findings of the Delphi Survey

To proceed with an in-depth analysis of technological developments, the initial list of 20 technological clusters needed to be narrowed down to a shortlist of the most promising ones.

7.1. 4CF Matrix

The tool selected for this task was the *4CF Matrix*. This relatively simple method has proven its worth when it comes to the identification, verification and systematisation of potential solutions developed through strategic analyses and planning. It has been applied successfully both during short workshops, to assess the possible directions of development for a given area or market, and in complex, weeks-long processes of developing long-term strategies.

To prepare a 4CF Matrix, each of the solutions (in this case, the 20 clusters of biometric technologies) needs to be evaluated with regard to two criteria:

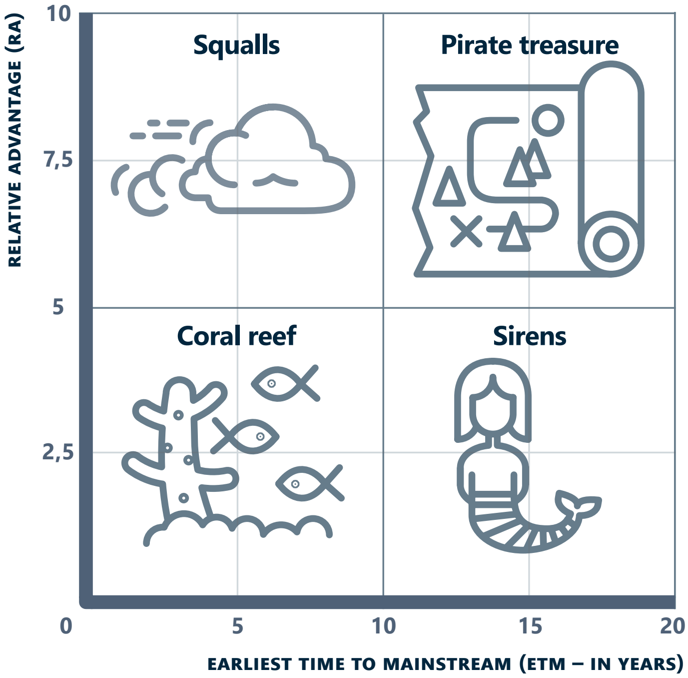
- **Relative Advantage (RA):** the degree to which a proposed solution might contribute to the fulfilment of a particular need;
- **Earliest Time to Mainstream (ETM):** the shortest time needed for the dissemination of a solution, taking into consideration aspects such as delays caused by technological, financial, social and legal barriers.

The scale used for the assessment is described in more detail in Section 7.2. A matrix structured according to the above criteria shows areas of importance to strategic planning: from areas of solutions that offer little promise with regard to relative advantage but could be implemented quickly, to those that are far from implementation but contain ground-breaking solutions.

The 4 quadrants of the 4CF Matrix (Figure 9) were named after the type of solutions characteristic of a given area.

- ***Coral reef:*** solutions with a short ETM but a low relative advantage. Choosing a solution from this area is risky, as it may entail the loss of an opportunity to develop a long-term strategic advantage in the name of short-term benefits. Exploring the reefs is, therefore, usually a poor choice in the long run, but the solutions might be worth veering slightly "off course" if their entry barriers are not high. The choice should, however, be a conscious one, and the decision to invest time and resources in a solution from this area requires caution so as not to lose sight of the search for more future-oriented solutions. An efficient navigator can use the reef to his advantage, shortening the way to long-range targets.
- ***Squalls:*** solutions with a short ETM and a high relative advantage. These are solutions that may change the way a need is met dramatically within a short period of time. Thus, their implementation is likely to constitute a significant advantage

Figure 9: *Schematic of the 4CF Matrix.*



and can place the implementing entity ahead of the competition. Solutions with a combination of a particularly high RA and short ETM (near the top-left corner of the matrix) may be called "White Squalls".

- ***Sirens:*** solutions with a long ETM and a low relative advantage. Following a siren's voice is very dangerous: they tempt sailors with beautiful songs but could prove a costly distraction. Solutions from this area involve the substantial risk of investing time and resources into a solution that might not prove successful in the long term and, consequently, the risk of losing strategic advantage by failing to seize other market opportunities.
- ***Pirate treasure:*** solutions with a long ETM but a high relative advantage. Solutions from this area require a bold decision: choosing them is like setting off on a long journey with no guarantee of success. Not everyone who possesses a treasure map (and these are often enigmatic and incomplete) can actually find the treasure. The reward for those who succeed, however, is often worth the risk. It should be stressed that an equal risk could result from ignoring hidden treasures and seeking safer solutions: if someone else seizes the opportunity, it may give them a huge strategic advantage and leave their competitors far behind.

It is important to look past the current trends and consider scenarios of future development that could change the evaluation independently of other factors. The scenarios provide the opportunity to cross-check solutions for unexpected threats and opportunities, which might have been omitted during the initial assessment, and thus ensure that more informed choices are made.

7.2. The Delphi Survey

To assess the 20 biometric technological clusters with the support of the collective intelligence of the Group of Experts, a *Delphi Survey* was set up with the employment of the *4CF HalnyX* online Delphi platform.[48] The iterative, real-time survey collected expert opinions, while at the same time stimulating consensus-oriented discussions. Thus, it incorporated the benefits of collective intelligence, as opposed to traditional quantitative surveys, which focus primarily on providing a statistical distribution of the experts' answers. For the entire duration of the *Delphi Survey*, the Group of Experts could revisit the platform to familiarise themselves with new assessments and comments, as well as to provide new (or revised) assessments and comments of their own.

As described in the *Futures Research Methodology Version 3.0 by The Millennium Project*,[49] the *Delphi* method was originally developed in the 1950s and 1960s in the United States by the RAND Corporation to assess the impact of contemporary technologies on the military domain and to support decision-making. An analysis of forecasting approaches available at that time[50] led RAND researchers to the conclusion that gathering experts in a conference room is likely to introduce undesirable factors, which hinder a fruitful and unbiased consultation process. For example, the discussion might be influenced by the loudest voice rather than the soundest argument; an expert might also be reluctant to change a previously stated opinion in the presence of their peers.

The Delphi method[51] (named after the famous Greek oracle) was designed by RAND to encourage genuine debate, as free as possible of cognitive bias, resulting from the recognition of authority (through anonymity) and unaffected by psychological, rhetorical or sociological factors. A typical *Delphi Survey* is round-based. After the first round of expert consultations, the researchers collect the most extreme opinions and synthesise the justifications provided by experts, giving them equal "weight". In the second round, the justifications are provided to the experts for further analysis and to help them reach a consensus. In summary, anonymity and feedback are the key elements of the Delphi method used in about 10% of all foresight initiatives since its introduction.[52]

The *4CF HalnyX* is a fourth-generation Delphi platform. The first generation, developed in the 1960s, was updated in the 1990s by introducing the first online *Delphi Surveys* (second-generation). The third-generation introduced real-time Delphis, which were no longer organised into consecutive rounds. The current fourth generation focuses on streamlining the survey and minimising information overload by using new capabilities of application design. The goals include facilitating the identification of new and relevant information provided by the Group of Experts, and improving the discussion structure.

48 The 4CF HalnyX Smart Delphi Platform is a proprietary tool developed by 4CF.

49 J. C. Glenn and T. J. Gordon, "Futures Research Methodology Version 3.0", The Millennium Project, 2009.

50 Typically, simulation gaming (involving individuals acting out the parts of nations or political factions) and genius forecasting (involving a single expert or an expert panel addressing the issues of concern).

51 O. Helmer-Hirschberg, "Analysis of the Future. The Delphi Method", RAND Corporation, 1967.

52 United Nations Industrial Development Organization, "Unido Technology Foresight Manual, Vol. 1: Organization and Methods", 2005.

The 20 biometric clusters were assessed in a *Delphi Survey* with the aid of questions constructed according to a similar pattern. The participants were asked to imagine a technological solution for border checks that would use biometric recognition technologies from a given cluster. The requirements for the proposed solutions included the seamless acquisition of biometric data during checks; high accuracy and security; compatibility with policies and measures typically introduced during pandemics; and full compliance with EU regulations and values. Subsequently, the participants were asked to assess the solution according to two metrics, Relative Advantage (RA) and Earliest Time to Mainstream (ETM), by simply moving a slider in the online survey. The following description of the metrics was provided to the participants of the *Delphi Survey*:

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;
- 10 indicates a so-called "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 envisaged technological solution to become available on the market and widely adopted in border checks at external EU borders. In other words, the 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. The 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 cases of technological solutions which can never be realised.

There were 33 participants in the *Delphi Survey*, belonging to the Group of Experts. The results of the survey are presented in Table 17.

Table 17: *Results of the Delphi Survey.*

Technological cluster		Earliest Time to Mainstream			Relative Advantage		
		Average (years)	Standard Deviation (years)	Number of assessments	Average dimensional)	Standard Deviation (adimensional)	Number of assessments
TC01	DNA biometrics	15.50	3.90	30	5.19	3.16	31
TC02	Infrared face recognition	4.80	2.30	31	5.86	1.96	29
TC03	2D face recognition in the visible spectrum	3.30	2.50	31	5.17	2.27	30
TC04	3D face recognition	6.70	3.50	32	6.81	1.51	32
TC05	Infrared friction ridge recognition	6.70	3.40	29	3.73	1.93	30
TC06	3D friction ridge recognition	8.70	5.00	27	1.63	1.47	27
TC07	Contactless friction ridge recognition	7.70	4.10	28	3.79	2.18	28
TC08	Contact-based friction ridge recognition	2.10	1.50	26	4.04	1.99	28
TC09	Iris recognition in the NIR spectrum	6.80	3.40	27	6.48	1.79	27
TC10	Iris recognition in the visible spectrum	7.40	3.30	27	5.18	2.12	28
TC11	Iris recognition at a distance	12.00	4.50	28	7.11	2.57	27
TC12	Eye vein recognition	13.20	3.80	28	4.25	2.20	28
TC13	Hand vein recognition	9.90	4.00	29	4.52	2.27	29
TC14	Heart signal recognition	15.00	3.40	28	1.11	0.77	28
TC15	Hand geometry recognition	9.20	4.20	28	2.74	1.84	27
TC16	Periocular recognition	9.30	2.60	27	5.11	2.15	27
TC17	Keystroke recognition	10.00	5.50	27	1.00	0.72	27
TC18	Gait recognition	10.10	3.90	27	4.52	1.89	27
TC19	Handwriting recognition	8.70	5.00	27	1.63	1.47	27
TC20	Speaker recognition	7.70	4.10	28	3.79	2.18	28

It is interesting to compare ETM assessments produced during the *Delphi Survey* with the stage of a given technology's lifecycle, as described in Chapter 4 (see Table 18). Naturally, ETM takes many factors into account, rather than being limited to technological maturity, so a strong correlation cannot be expected. Nonetheless, the clusters categorised as

Mature in the technology lifecycle analysis have the shortest average ETM (slightly over seven years), while those labelled *Maturity — minor relevance* (due to long time-intervals and low values of inventive activities, suggesting that no growth will occur in the future) have the longest average ETM (over 11.5 years). No significant difference in ETM assessment can be observed in clusters in the *Childhood* and *Growth* stages. Both these categories have an average ETM of close to 10 years. Clusters 12 and 13 (*Eye vein recognition* and *Hand vein recognition*) display long ETMs despite being categorised as technologically mature — this may signify major non-technological barriers to their mainstream adoption.

Table 18: *ETM vs stage in technology lifecycle of technological clusters.*

Technological cluster name		Average Earliest Time to Mainstream (years)	Stage of technology lifecycle
TC08	Contact-based friction ridge recognition	2.1	Maturity
TC03	2D face recognition in the visible spectrum	3.3	Maturity
TC02	Infrared face recognition	4.8	Maturity
TC04	3D face recognition	6.7	Maturity
TC05	Infrared friction ridge recognition	6.7	Growth
TC09	Iris recognition in the NIR spectrum	6.8	Maturity
TC10	Iris recognition in the visible spectrum	7.4	Growth
TC07	Contactless friction ridge recognition	7.7	Maturity
TC20	Speaker recognition	7.7	Maturity
TC06	3D friction ridge recognition	8.7	Growth
TC19	Handwriting recognition	8.7	Maturity
TC15	Hand geometry recognition	9.2	Maturity – minor relevance
TC16	Periocular recognition	9.3	Childhood
TC13	Hand vein recognition	9.9	Maturity
TC17	Keystroke recognition	10	Maturity – minor relevance
TC18	Gait recognition	10.1	Childhood
TC11	Iris recognition at a distance	12	Growth
TC12	Eye vein recognition	13.2	Maturity
TC14	Heart signal recognition	15	Growth
TC01	DNA biometrics	15.5	Maturity – minor relevance

The results of the *Delphi Survey* are easier to interpret when presented in the form of a 4CF Matrix, as shown in Figure 10. It shows a wide distribution of technological clusters on the matrix. This is a desirable outcome, meaning that a broad spectrum of clusters was identified for the analysis. Over two-thirds of the clusters were rated with an average ETM of 10 years or less and none of the remaining ones has an ETM over 16. Therefore, all the clusters we considered can potentially enter the mainstream within the analysed timeframe.

TC 1: DNA biometrics
TC 2: Infrared face recognition
TC 3: 2D face recognition in the visible spectrum
TC 4: 3D face recognition
TC 5: Infrared friction ridge recognition
TC 6: 3D friction ridge recognition
TC 7: Contactless friction ridge recognition
TC 8: Contact-based friction ridge recognition
TC 9: Iris recognition in the NIR spectrum
TC 10: Iris recognition in the visible spectrum
TC 11: Iris recognition at a distance
TC 12: Eye vein recognition
TC 13: Hand vein recognition
TC 14: Heart signal recognition
TC 15: Hand geometry recognition
TC 16: Periocular recognition
TC 17: Keystroke recognition
TC 18: Gait recognition
TC 19: Handwriting recognition
TC 20: Speaker recognition

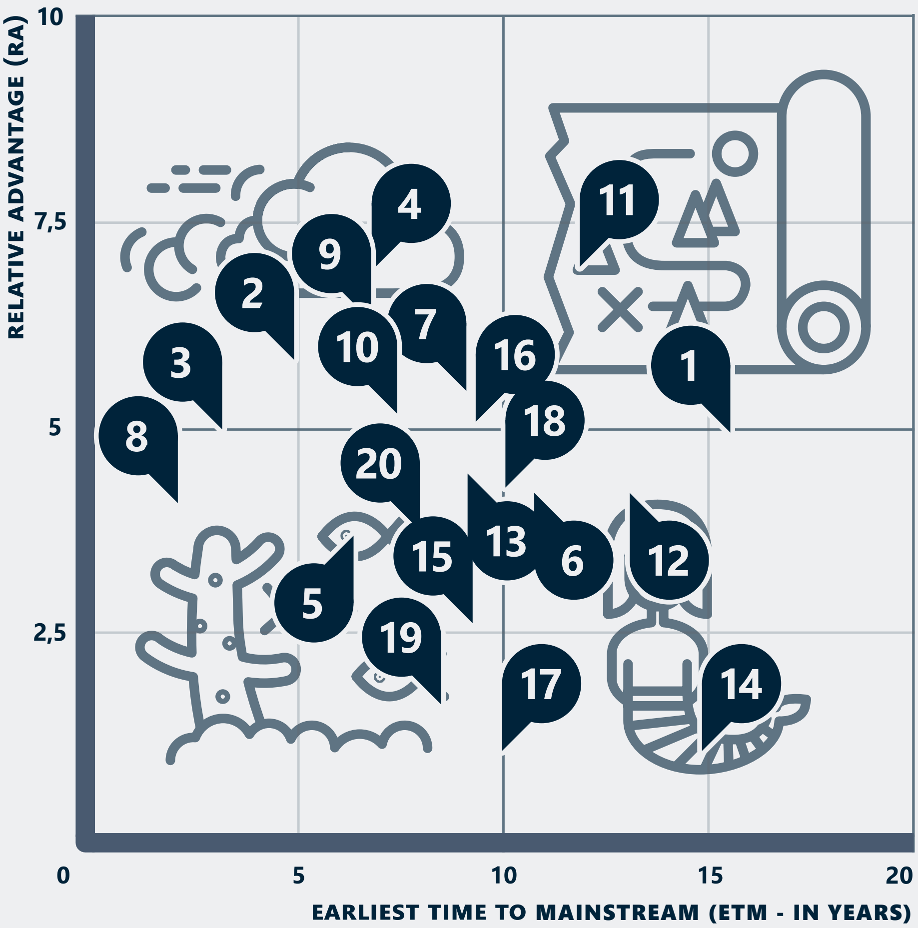


Figure 10: *4CF Matrix presenting the outcomes of the Delphi Survey. Assessment of the 20 biometric technological clusters in terms of their Relative Advantage and Earliest Time to Mainstream.*

There are quite a few clusters in the top-left **"Squalls"** quadrant of the matrix, i.e. technologies with an average ETM rating below 10 years and an average Relative Advantage above 5. Technological clusters with the highest average RA ratings within this quadrant include TC02: *Infrared face recognition*, TC09: *Iris recognition in the NIR spectrum,* and TC04: *3D face recognition*. When compared to current solutions, room for improvement was identified, especially in the area of seamless acquisition, but overall, all these clusters received high RA ratings. Four clusters are placed on the dividing lines between the "Squalls" quadrant and other areas: TC03: *2D face recognition in the visible spectrum*, TC10: *Iris recognition in the visible spectrum*, TC07: *Contactless friction ridge recognition,* and TC16: *Periocular recognition. 2D face recognition in the visible spectrum* is generally considered a relatively mature technology with an unquestionably strong impact on border checks. For this cluster, the main hurdles mentioned by *Delphi Survey* participants are related to policy, legal and ethical issues. *Iris recognition in the visible spectrum* and *Contactless friction ridge recognition* have longer ETMs, which places them relatively close to the middle of the matrix. Opinions as to these two clusters were mixed, with some of the participants questioning the convenience and seamlessness of the solutions compared to alternatives. *Periocular recognition* is roughly in the middle of the matrix and only formally within the "Squalls" quadrant. Many doubts were expressed about the accuracy of this technology, but it was also recognised that it could potentially prove easy to combine with other methods. All the solutions that appear in the "Squalls" quadrant should be considered very carefully because of the disruptive potential inherent to combining a high RA and a low ETM.

Only one technological cluster was rated higher in terms of Relative Advantage than the "Squalls" described above — TC11: *Iris recognition at a distance*. It received an average ETM rating of 12 years, which placed it in the **"Pirate treasure"** quadrant, albeit with a relatively high ETM standard deviation (4.5 years), meaning that neither a shorter nor much longer ETM could be ruled out without further analysis. The technical challenges of *Iris recognition at a distance* were the primary source of uncertainty. TC01: *DNA biometrics* was also placed in the "Pirate treasure" quadrant but received a more distant ETM rating (15.5 years, the longest of any cluster) and an RA rating that placed it on the verge of the "Sirens" quadrant. The main uncertainties related to this cluster concerned the potential for seamless acquisition in border checks as well as privacy issues.

The perilous **"Sirens"** quadrant contains five clusters, i.e. TC18: *Gait recognition*, TC06: *3D friction ridge recognition*, TC12: *Eye vein recognition*, TC14: *Heart signal recognition*, and TC17: *Keystroke recognition*. *Keystroke recognition* is on the dividing line between the "Sirens" quadrant and the "Coral reef", with an ETM of 10 years. However, as it has the lowest average RA rating of all the analysed clusters, it can safely be assumed that it belongs to the "Sirens" quadrant. *Keystroke recognition* was almost universally criticised for its impracticality and inaccuracy. Further doubts are related to the usefulness of this technology in an increasingly digital world. *Heart signal recognition* also received a low RA rating for similar reasons, and an additional issue was identified in this case: the technological challenges hindering seamless acquisition resulted in a distant ETM (15 years). *Gait recognition*, *3D friction ridge recognition* and *Eye vein recognition* are very close to the centre of the matrix and, although they are technically in the "Sirens" quadrant, it should be noted that the opinions of the Group of Experts were mixed. Their main concerns were related to practicality and technological challenges as well as the non-obvious advantages compared to alternatives. In the case of *Gait recognition*, the technology's accuracy was also questioned.

The **"Coral reef"** quadrant contains the remaining technological clusters assessed during the *Delphi Survey*. TC08: *Contact-based friction ridge recognition* displays an understandably low ETM, but the seamlessness of the technology is doubtful, which prevented this cluster from scoring higher in terms of RA. Such issues resulted in a similar RA assessment for TC05: *Infrared friction ridge recognition*, which received an ETM rating of almost seven years. An analogous placement on the matrix can be observed in the case of TC20: *Speaker recognition*, which, although relatively easy to implement, is considered questionable in terms of accuracy and can also be problematic in noisy environments. TC13: *Hand vein recognition* is placed close to the centre of the matrix and could potentially be used in combination with *Friction ridge* (fingerprint) *recognition*. Opinions are mixed, however, as to the added value of such a solution. TC19: *Handwriting recognition* is placed in the lower part of the matrix because of a poor RA assessment. TC15: *Hand geometry recognition* is also close to the "Sirens" quadrant, with only a slightly higher RA rating. The main reason for a low RA assessment, in this case, is the lack of advantages compared to fingerprint scanning.

7.3. Prioritisation by multi-metric assessment

Based on the results of the *Delphi Survey*, a **composite metric (p) combining Relative Advantage and Earliest Time to Mainstream** was calculated for each of the clusters, using the formula p=(RA-ETM/2), which produces higher values for technological clusters closer to the top-left corner of the 4CF Matrix (those with a high RA and low ETM). RA and ETM are considered to be of equal weight, so ETM is divided by 2 for normalisation (it is originally assessed on a scale of 0 to 20, while RA is evaluated on a scale of 0 to 10). ETM is subtracted in the formula because a lower ETM entails the potential for faster utilisation and is, therefore, more desirable.

A ranking list of the composite metric outcomes is presented in Table 19 below. For detailed results of the *Delphi Survey* (RA and ETM assessments for specific technological clusters), please refer to Table 17 in the previous section.

Table 19: *Ranking of technological clusters by RA and ETM composite metric. Clusters selected for an in-depth analysis are marked in green. Clusters discarded despite a high composite metric are marked in red (see explanation below).*

Cluster		Delphi assessment (composite metric p)
TC 3	2D face recognition in the visible spectrum	**3.52**
TC 4	3D face recognition	**3.45**
TC 2	Infrared face recognition	**3.44**
TC 9	Iris recognition in the NIR spectrum	**3.07**
TC 8	Contact-based friction ridge recognition	**3.00**
TC 10	Iris recognition in the visible spectrum	**1.49**
TC 11	Iris recognition at a distance	**1.09**
TC 7	Contactless friction ridge recognition	**0.84**
TC 16	Periocular recognition	**0.44**
TC 5	Infrared friction ridge recognition	**0.41**
TC 20	Speaker recognition	**-0.07**
TC 13	Hand vein recognition	**-0.41**
TC 18	Gait recognition	**-0.56**
TC 6	3D friction ridge recognition	**-0.98**
TC 15	Hand geometry recognition	**-1.87**
TC 12	Eye vein recognition	**-2.34**
TC 1	DNA biometrics	**-2.56**
TC 19	Handwriting recognition	**-2.70**
TC 17	Keystroke recognition	**-4.02**
TC 14	Heart signal recognition	**-6.38**

Not all the clusters with the highest composite metric scores were selected for further analysis, because an additional cross-check with a set of factors identified during the needs assessment and the security evaluation was performed. As described in Chapter 1, the four "must-haves" included:

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

The first of the above (low vulnerability to adversary attacks) was addressed in the preceding analysis of security aspects (Chapter 6). Table 20 below explains the cross-checking process, which determined whether a cluster fulfilled the requirements of the four "must-haves". Failure to meet any of those requirements eliminated a cluster from the shortlist for an in-depth analysis.

Table 20: *Cross-check logic used to select technological clusters to be shortlisted.*

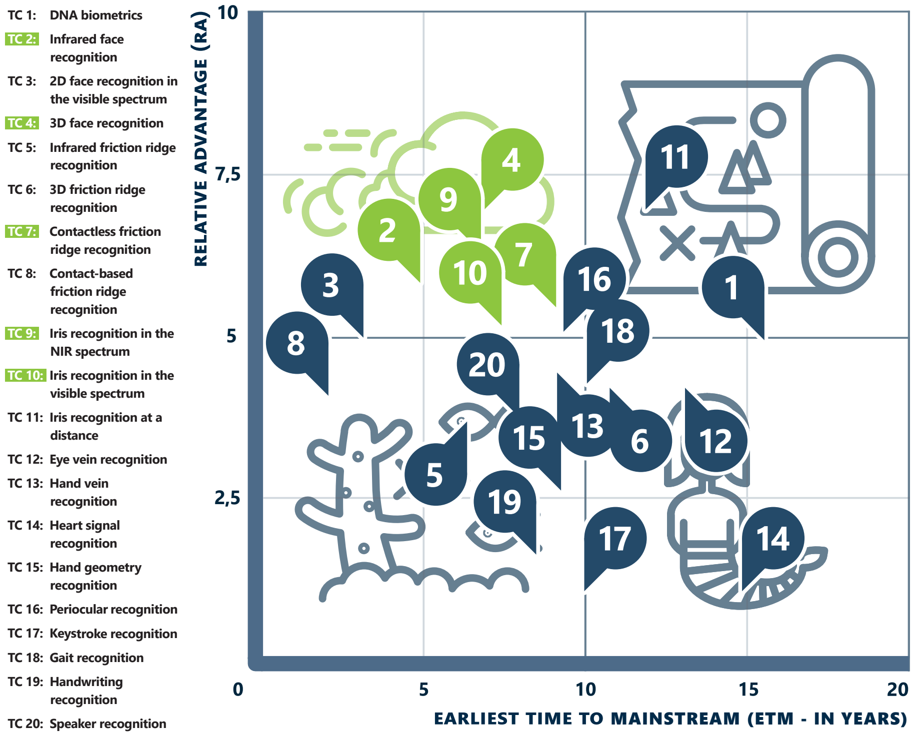
	CROSS-CHECK OF NEEDS			
	Vulnerability to adversary attacks	**Other factors**		
Category	Comparative inherent vulnerability to adversary attacks: 0-5 (5 – highest vulnerability compared to other assessed clusters, 0 – lowest)	Compatibility with policies and measures typically taken in the event of pandemics	Compliance with fundamental EU values and regulations	Potential to enable seamless biometrics acquisition in border checks
Failing condition	Vulnerability assessment = 5	Any major and obvious incompatibilities, with no solutions suggested during the course of the Delphi Survey	Any major and obvious non-compliance, with no solutions suggested during the Delphi Survey	Any major and obvious problems, with no solutions suggested during the Delphi Survey

Detailed results of the cross-check are presented in Table 21 below.

Table 21: *Results of the cross-check for selecting clusters to be shortlisted. Clusters with the top 6 composite metric assessments and without any failing conditions marked in green.*

Cluster		Delphi assessment (Composite Metric)	Vulnerability to adversary attacks	Compatibility with policies and measures typically taken in the event of pandemics	Compliance with fundamental EU values and regulations	Potential to enable seamless biometrics acquisition in border checks	IN / OUT recommendation (OUT if any failing conditions are present)
TC3	2D face recognition in the visible spectrum	3.52	FAIL	✓	✓	✓	OUT
TC4	3D face recognition	3.45	✓	✓	✓	✓	IN
TC2	Infrared face recognition	3.44	✓	Uncertain	✓	✓	IN
TC9	Iris recognition in the NIR spectrum	3.07	✓	✓	✓	✓	IN
TC8	Contact-based friction ridge recognition	3.00	✓	FAIL	✓	FAIL	OUT
TC10	Iris recognition in the visible spectrum	1.49	✓	✓	✓	✓	IN
TC11	Iris recognition at a distance	1.09	✓	✓	✓	✓	IN
TC7	Contactless friction ridge recognition	0.84	✓	✓	✓	✓	IN
TC16	Periocular recognition	0.44	✓	✓	✓	✓	IN
TC5	Infrared friction ridge recognition	0.41	✓	Uncertain	✓	Uncertain	IN
TC20	Speaker recognition	-0.07	✓	✓	✓	FAIL	OUT
TC13	Hand vein recognition	-0.41	✓	✓	✓	Uncertain	IN
TC18	Gait recognition	-0.56	✓	✓	✓	✓	IN
TC6	3D friction ridge recognition	-0.98	✓	✓	✓	Uncertain	IN
TC15	Hand geometry recognition	-1.87	✓	✓	✓	✓	IN
TC12	Eye vein recognition	-2.34	✓	FAIL	✓	FAIL	OUT
TC1	DNA biometrics	-2.56	✓	FAIL	✓	FAIL	OUT
TC19	Handwriting recognition	-2.70	✓	FAIL	✓	FAIL	OUT
TC17	Keystroke recognition	-4.02	✓	FAIL	✓	FAIL	OUT
TC14	Heart signal recognition	-6.38	✓	FAIL	✓	FAIL	OUT

Figure 11: *4CF Matrix presenting the outcomes of the Delphi Survey with the shortlisted technological clusters marked in green.*



As a result of this additional cross-check:

- *2D face recognition in the visible spectrum* was not placed on the shortlist due to high vulnerability (please refer to Chapter 6 for details);
- *Contact-based friction ridge recognition* was not placed on the shortlist due to incompatibility with policies and measures typically taken in the event of pandemics as well as issues related to seamless acquisition during border checks.

Furthermore, since iris recognition-based technologies were present in 3 of the 6 resulting technological clusters, TC11 (*Iris recognition at a distance*) was also omitted to avoid redundancy. Its inclusion would have required the analysis of three clusters devoted to iris recognition during the subsequent roadmapping workshop (see Chapter 8), while its omission provided an opportunity for an in-depth analysis of TC7 (*Contactless friction ridge recognition*).

The five **key technological clusters** (KTCs) selected for the roadmapping exercise were therefore as follows:

- TC 4: *3D face recognition,*
- TC 2: *Infrared face recognition,*
- TC 9: *Iris recognition in the NIR spectrum,*
- TC 10: *Iris recognition in the visible spectrum,*
- TC 7: *Contactless friction ridge recognition.*

The selected clusters are marked in green on the 4CF Matrix in Figure 11.

It is worth noting that as expected, all the shortlisted clusters are placed in the "Squalls" quadrant of the 4CF Matrix (see Sections 7.1 and 7.2) and are therefore a natural choice for an in-depth analysis.

8. Roadmaps for the key biometric technological clusters by 2040

Following the prioritisation, the roadmapping method was used to determine the turning points, threats and opportunities for the further development of the five chosen key technological clusters. The aspects considered included potential future developments in terms of application areas, the functionalities of technologies and products, in the short-, medium- and long-term. The chapter contains an introduction to the method and describes the results of the roadmapping analysis for each technological cluster.

8.1. Introduction to roadmapping

Technology roadmapping is a planning method generally applied to envision the short-, medium- and long-term issues faced by a specific sector in terms of 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:

- to identify the development paths of the key biometric technological clusters in the 2021-2040 timeframe;
- to identify key turning points in technological development (factors delaying or accelerating the envisioned developments);
- to confront technology roadmaps with alternative scenarios regarding border-check processes and the future of travel in the 2021-2040 timeframe, in order to compare how the conditions of the alternative scenarios might influence the developments envisaged in the roadmaps.

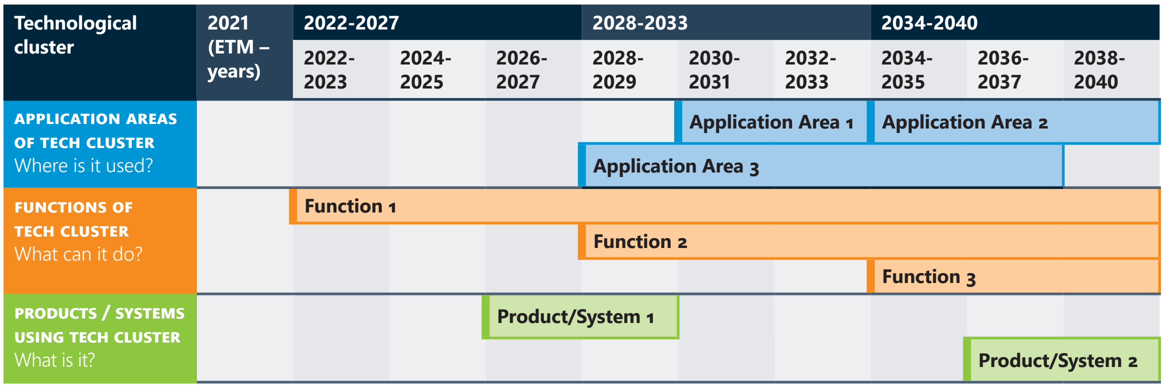
The most general and flexible approach to developing roadmaps consists in creating visual, time-based, multi-layered charts, as illustrated in Figure 12. These provide a structured framework to address three key questions: "Where are we now?" (in 2021), "Where do we want to go?" (in 2040) and "How can we get there?" (2022-2039).

The roadmap created for each of the five key clusters consists of three layers:

- **Application areas:** lists the potential applications of the key cluster;
- **Functions:** refers to the evolving technical capabilities of the cluster;
- **Products or systems:** provides examples of devices and solutions that use the specific technologies from the cluster.

Roadmapping was performed during the *Second Technology Foresight Workshop*, which took place on 10-11 June 2021 and involved about 30 members of the Group of Experts. The four scenarios (resulting from the *First Technology Foresight Workshop*) constituted the input for the analysis. The results were further processed by the Research Team to ensure the highest possible quality.

Figure 12: *Technology roadmap structure applied in the context of the Tech Foresight on Biometrics.*



8.2. Results of roadmapping

This section provides the results of an in-depth roadmapping analysis of the following key technological clusters selected based on the outcomes of the *Delphi Survey*:

1. Cluster A: Contactless friction ridge recognition (TC07),
2. Cluster B: 3D face recognition (TC04),
3. Cluster C: Infrared face recognition (TC02),
4. Cluster D: Iris recognition in the NIR spectrum (TC09),
5. Cluster E: Iris recognition in the visible spectrum (TC10).

For each of the TCs, the results consist of:

- a baseline visual technology roadmap chart;
- a list of expected key turning points in technological developments (i.e. opportunities and threats) in the 2021-2040 timeframe;
- a comparative analysis of the key developments envisaged in the baseline roadmap under the conditions of the four scenarios regarding the future of travel, border checks and biometric technologies in the EU in 2040.

When thinking about the future, it is often tempting to extrapolate current trends, assuming that they will remain unchanged in the coming years. This perspective is reflected in the technology roadmap charts that display a "business as usual" scenario. But the future may follow various paths. In the coming two decades, biometrics may be influenced by several hypothetical factors described in the four alternative future scenarios. Confronting "business as usual" developments envisaged for each technological cluster with a broader array of possible scenarios allows us to determine whether they are resistant to changes in the external environment and to identify conditions that might facilitate or impede the implementation of a technological cluster or a particular solution based on it. Therefore, the final part of the roadmapping process puts the projections visualised in the technology roadmap under the stress conditions of scenarios regarding the future of travel and border checks in 2040, stemming from a combination of two factors: EU economic development and geopolitical conflicts. *Scenario Analysis* provides insights that can be used in strategy-making processes by prioritising specific solutions and defining suitable measures for their development and implementation.

It must be underlined that each roadmap presented in the subsequent paragraphs is a visualisation of the opinions and insights collected during a two-day workshop and should be treated as a basis for further analysis rather than an authoritative source of information.

Some application areas and functions visualised in the roadmaps may fall outside the scope of this study, as they concern other potential uses, e.g. in financial services, the military, medicine or other law enforcement applications (e.g. forensics, surveillance, crowd monitoring and control, detection of aggressive behaviours and attacks). Although the Research Study focuses on the primary function of the five technological clusters (recognition of persons in border-check processes), the Group of Experts agreed that when envisioning the future, additional application areas, technological functions and products or systems should be considered since they may radically accelerate the development of the technology itself and increase social acceptance of biometrics for border checks. In addition, it is important to clarify that behaviour detection cited in the roadmap of the *3D face recognition* technological cluster is only considered within the scope of this Research Study if it involves solutions aimed at the detection of people in need of assistance or special care (e.g. not moving for an extended period of time, disoriented children or elderly people). More details regarding the specific scope of the study can be found in the Introduction.

8.2.1. Technological cluster A: Contactless friction ridge recognition

8.2.1.1. Technology roadmap

The general vision of the role of the *Contactless friction ridge recognition* technological cluster in border-check processes in 2040 is as follows: "*In 2040, this technology will be ready to use in the entire border-check process. It will be a complementary technology, used in combination with other solutions (e.g. facial recognition), which jointly allow seamless travel. However, social acceptance will be a key factor in determining whether the technology can be used on a large scale*."

The developments shown in the technology roadmap (Figure 13), which are modelled for the short- (2022-2027), medium- (2028-2033) and long-term (2034-2040) timeframes, represent possible pathways to this vision.

The key assumption behind the visualisation of data on each layer of the roadmap is that the applications, functions and products will be continuously improved in the years following their first occurrence, at least within the analysed timeframe. The experts who participated in the roadmapping workshop did not envision a high likelihood of discontinuation for any of the items before 2040.

Figure 13: *Technology roadmap for the Contactless friction ridge recognition technological cluster.*

Contactless friction ridge recognition	2021 (ETM: 7.7 years)	2022-2027			2028-2033			2034-2040		
		2022-2023	2024-2025	2026-2027	2028-2029	2030-2031	2032-2033	2034-2035	2036-2037	2038-2040
APPLICATION AREAS OF TECH CLUSTER Where is it used?	It is not used in border checks. Pilot tests took place within the "Biometrics on the move" Frontex project at Lisbon Airport in 2019	**Growing number of pilot applications in seamless border check processes**				**Mainstream applications in the area of seamless border checks**				
	Self-driving cars				**Military and security applications**					
	Entertainment sector (e.g. digitising paintings and sculptures via 3D scanning)				**Public (i.e. e-government) and private sector services (i.e. physical access control and information security)**					
					Financial services (authentication process in banking and digital transactions)					
FUNCTIONS OF TECH CLUSTER What can it do?	Person recognition at a very short distance	**Recognition of persons from a very short distance**								
					Recognition of persons from a short distance					
								Stand-off person recognition (a few meters' distance)		
PRODUCTS / SYSTEMS USING TECH CLUSTER What is it?	Stationary scanners (and sub-systems)	**Stationary scanners**								
					Mobile scanners (e.g. portable/handheld devices; portable/handheld mobile phone-based scanners; portable/hand-held tablet-based scanners)					
					Self-service systems					
								Stand-off scanners (a few meters' distance)		

8.2.1.2. Key turning points in technological development

The fulfilment of the vision for this technological cluster ("*In 2040, this technology will be ready to use in the entire border-check process. It will be a complementary technology, used in combination with other solutions (e.g. facial recognition), which jointly allow seamless travel*") depends on key functional developments and specific product innovations. These include:

- Recognition of persons from a short distance,
- Stand-off person recognition (a few meters' distance),
- Mobile scanners,
- Self-service systems.

Some of the technological and non-technological drivers (*opportunities* or *enablers*) that might support the development of the *Contactless friction ridge recognition* cluster are listed in Table 22, along with potential challenges that might block or slow down the envisaged trajectory of developments.

Table 22: *Development challenges and opportunities (enablers) related to the Contactless friction ridge recognition technological cluster.*

Opportunities (enablers)	Contactless friction-ridge recognition	Challenges
Application Areas		
Combining biometric modalities for better accuracy: Contactless friction ridge recognition used in conjunction with facial recognition for improved security, accuracy, economic efficiency and overall operational performance optimisation. Research aimed at the development and analysis of the quality of contactless fingerprint samples. Development of measures against presentation attacks that combine other technologies (e.g. thermal infrared imaging technologies).	Mainstream applications in the area of seamless border checks	Accuracy and security might be a challenge in mainstream use for border checks. There is a need for new databases (e.g. a database of EU citizens' fingerprints) and the need for compatibility of existing databases with this new modality (contactless) of acquiring samples. Contactless fingerprint acquisition (especially from a distance) increases security risks and requires standards of use that should ensure social acceptance.
	Financial services (authentication process in banking and digital transactions)	Using the technology for purchases in traditional stores might not be secure enough and could require the availability of additional scanners.
Improving physical access control and information security by replacing ID cards and enabling password-less authentication when accessing buildings or when logging into online working environments.	Public (i.e. e-government) and private sector services (i.e. physical access control and information security)	
Functions		
Contactless biometrics is advantageous during pandemics. Contactless fingerprint acquisition avoids issues with face and demographic disparity (neutral in terms of race and eye colour).	Recognition of persons from a very short distance	The need to develop novel systems for feature extraction and matching techniques based on recent machine-learning capabilities, such as Deep Learning (DL) and Convolutional Neural Networks (CNNs). Contactless friction-ridge scanners require secure communication with the databases.
3D fingerprint data acquired with contactless scanners could be used to generate 2D fingerprint data and to match with current passports.	Recognition of persons from a short distance	Need for research to extend the distance and increase the accuracy of the technology.
Contactless image acquisition during border checks takes place in a secure, supervised environment.	Stand-off person recognition (a few meters' distance)	Security becomes an issue if contactless friction ridge scanners can be owned by private individuals and used for frauds, similarly to contactless smartcard readers, which can read a payment card in the owner's pocket.
Products/ Systems		
Contactless fingerprint systems might not require high-resolution cameras for sample acquisition during the biometric capture process in border checks (e.g. cameras in smartphones might be used). However, the situation is different in the case of enrolment, where more expensive high-resolution scanners are required.	Stationary scanners	If the NFIQ1.0 fingerprint quality estimation method is used for contactless readers, rather than the more accurate NFIQ2.0, this can result in inaccurate or unpredictable results in quality estimation. The key feature of software for all types of contactless scanners is to ensure interoperability of the novel contactless biometric systems with legacy systems and with existing quality algorithms for contact-based scanners.
A marker can be placed on the ground to determine the subject's placement and limit drift in the location of hand/fingers.	Mobile scanners (e.g. portable/handheld devices; portable/handheld mobile phone-based scanners; portable/hand-held tablet-based scanners)	Motion stability: moving/unstable capture device coupled with a moving subject makes it difficult to perform the acquisition.
For seamless operation, combination with novel systems using face recognition for subject tracking as well as separate sensors and laser tracking systems for iris detection.	Stand-off scanners	There is a need to regulate and set standards for contactless fingerprint acquisition and data exchange.

A more in-depth analysis of the technology roadmap devoted to the *Contactless friction ridge recognition* technological cluster reveals several challenges associated with developments projected onto each layer of the roadmap.

Crucial technology-related challenges are associated with the key function of this cluster: contactless recognition from a distance. Specifically, a need to achieve high accuracy in biometric data acquired from a distance was identified. Another challenge is the need for new databases and the compatibility between biometric samples obtained by this new modality (contactless) and existing databases (e.g. in the case of fingerprints, databases of samples acquired by the traditional contact-based modality). In addition to these, security becomes a serious issue, prompting the need to introduce regulations for the use of contactless friction ridge scanners outside of the EBCG community (e.g. in business).

Another set of technological challenges is related to products and systems. Ensuring the motion stability required to perform capture via contactless friction-ridge scanners, especially in mobile scanners, is a potential impediment of technological progress in this area. Another issue is the need for the interoperability of contactless devices with legacy systems and with existing quality algorithms for contact-based scanners.

A significant non-technological challenge is the need to set standards for contactless fingerprint acquisition and data exchange to ensure that security and privacy are maintained. In this case, the Group of Experts agree that technological progress in the area is faster than the pace at which shared standards and guidelines are being developed.

While the list of challenges is relatively long, key opportunities are associated with the potential for seamlessness, not only in border checks but also in other applications, e.g. physical access control and information security, where *Contactless friction ridge recognition* would avoid the use of ID cards and enable password-less authentication when accessing buildings or when logging into online working environments.

Technology uptake could be sped up significantly with the use of existing scanners (e.g. using cameras in mobile phones) because the contactless acquisition of samples might not require high-end cameras. Finally, the Group of Experts agreed that seamless operation could be ensured in the coming decade by combining this technology with novel systems which use face recognition for subject tracking, as well as separate sensors and laser tracking for iris detection.

8.2.1.3. Comparative analysis under the conditions of the scenarios

The results of a comparative analysis of the key developments in the *Contactless friction ridge recognition* technological cluster under the conditions of the four alternative scenarios are presented in Table 23.

Table 23: *Comparative analysis of key developments in the Contactless friction ridge recognition technological cluster under the conditions of the four alternative scenarios.*

Contactless friction-ridge recognition	SCENARIO 1 Union for society	SCENARIO 2 Protected Union	SCENARIO 3 Union under strain	SCENARIO 4 No-stop-shop
General scenario impact on the developments of the cluster	Cyberattacks on border systems are frequent. There are also physical attacks on border control infrastructure. Physical failure of digital systems (e.g. due to power shortages) results in the need for contingency and business planning (offline databases). There are significant and irregular migration flows. There is public acceptance of the technology. The ageing society and the physical changes caused by ageing may affect the performance of contactless fingerprint recognition systems. Combining them with AI technologies may be beneficial and may result in better accuracy (despite obstacles posed by ageing processes) than contact-based technologies offer.	Possible threats are similar to those in the *Union for society* scenario, but are more serious. There is an increased danger of new presentation attack techniques. Due to the need for better data quality, the acquisition of samples from two hands could be mandatory. Multi-modality (a combination of several complementary biometric techniques) could play a significant role due to an increased need for security. Additionally, the impact of climate change (e.g. causing the need to wear face masks with various air filters) could decrease the effectiveness of other biometric technologies (e.g. face recognition), but may provide opportunities for contactless friction ridge technologies as an adequate alternative.	A slow economy and limited budgets result in preference being given to the most promising biometric technologies. It can be a threat or an opportunity, depending on whether *Contactless friction ridge recognition* is among the most promising biometric solutions. No harmonised EU standards or regulations for biometric technologies are in place, despite: • an increased number of external threats, • border security being a priority issue and • prioritised development of AI and automation technologies.	A system of seamless travel across the EU is in place and there are more BCPs and border-checks in general. The scenario is favourable for the development of this technological cluster. However, its implementation leads to the need for the increased number of personnel as the number of BCPs grows. If the demand for personnel cannot match the supply, this could potentially lead to significant advancements in automation. There is societal trust and acceptance of biometric systems, including contactless modalities. Digital IDs substitute paper documents.
APPLICATION AREAS OF TECH CLUSTER	The application areas of this technological cluster do not change in terms of their scope and timeframe compared to the roadmap. However, in this scenario, it becomes crucial that regulations and measures for the secure application of contactless technologies in the private sector as well as in the public sector (other than the EBCG community) are implemented before 2028.	The applications of *Contactless friction ridge recognition* are introduced in a timeframe and scope similar to those illustrated in the technology roadmap. However, legal regulations connected with the testing of contactless devices by individuals and with pilot studies in real-life conditions are simplified and introduced in the 2022-2027 timeframe. The launching of research and innovation sandboxes for testing new solutions at the EU level is easier in this scenario. The pilot-testing environment is virtual and enables flexible, less bureaucratic experimentation with pilot applications of the technology in border checks.	The applications areas of Contactless friction ridge recognition technologies remain largely unchanged. This scenario envisages a reduced flow of travellers. Nevertheless, irregular migration grows. Therefore, the analysed technological cluster is used on a larger scale in border checks, as it successfully facilitates the management of irregular migration. Successful applications in this area lead to a transition from touch to touchless technological solutions. In those EU Member States where more restrictive national security measures are taken, facial recognition tends to prevail (or iris recognition, provided that it has advanced technologically).	There are important advancements in the availability of entirely seamless travel systems compared to roadmap projections. Such solutions are already widespread in 2028. There are no further changes regarding other applications (neither in scope nor implementation dates).
FUNCTIONS OF TECH CLUSTER	The impact of external conditions does not affect the gradual evolution of the key functions visualised in the roadmap of this technological cluster.	The timeframe for the development of the key functions of this technological cluster adheres to the technology roadmap. Additionally, more emphasis is placed on the standardisation of biometric data (i.e. organisational bodies are established and good practices are developed).	The impact of external conditions does not result in major changes to the evolution of the cluster's key functions visualised in the roadmap. Only if *Contactless friction ridge recognition* becomes a prioritised biometric technology are faster research and functional advancements likely. Otherwise, the developments would occur as envisaged in the technology roadmap.	The timeframe for the main functionalities of this technological cluster adheres to the technological roadmap.

Contactless friction-ridge recognition	SCENARIO 1 Union for society	SCENARIO 2 Protected Union	SCENARIO 3 Union under strain	SCENARIO 4 No-stop-shop
PRODUCTS / SYSTEMS USING TECH CLUSTER	Devices that use *Contactless friction ridge recognition* develop gradually, in accordance with the technological roadmap.	Products and systems that use this technological cluster are introduced at the same points as those envisaged in the technology roadmap. In addition, multiple geopolitical issues impact developments in *Contactless friction ridge recognition*. Within a "Buy European" campaign, priority is given to EU-manufactured technological devices and systems. In the 2022-2027 timeframe, more funds than originally projected are allocated for biometrics research to advance work on accurate contactless sensors. Concurrently to the increased funding for research, a common protocol regarding access to research data from public funding is clearly defined.	Given the emerging nature of the technology and the potential challenges that it poses (accuracy, interoperability with the existing fingerprint eco-system), the adverse financial and geopolitical situation of this scenario might result in preference being given to less cost-intensive biometric systems.	The timeframe regarding product availability and the range of contactless devices adheres to the technology roadmap. No downward trend of gradual technological developments in the area is foreseen.

The Group of Experts underlined that biometrics is a highly regulated area, where overall progress results from gradual advances. Therefore, they agreed that the external conditions in the ***Union for society*** and ***Protected Union*** scenarios would not cause significant changes in the technological evolution of *Contactless friction ridge recognition* products and systems. The key factors driving developments of the cluster in the two scenarios are: an economically thriving EU and a peaceful (***Union for society***) or a conflicted (***Protected Union***) global geopolitical situation.

The Group of Experts also concluded that the ***No-stop-shop*** scenario, which assumes slow economic development in Europe and a peaceful geopolitical situation, would provide the most favourable conditions for the development of this technological cluster, resulting in the earlier introduction of an entirely seamless travel system. The more challenging external environment of the ***Union under strain*** scenario (poor economic situation and global conflicts) was assessed as a potential game-changer for the development of contactless biometric technologies. The role of *Contactless friction ridge recognition* in counteracting threats posed by geopolitical conflicts would increase, provided that decision-makers decide on preferential financing and prioritising this cluster in border checks.

8.2.2. Technological cluster B: 3D face recognition

8.2.2.1. Technology roadmap

The general vision of the role of the *3D face recognition* technological cluster in 2040 border-check processes can be summarised as: "*On-the-fly facial feature extraction and automated recognition for border checks.*"

The developments, modelled in the three timeframes: short- (2022-2027), medium- (2028-2033) and long-term (2034-2040), create a possible roadmap to the vision, as shown in Figure 14.

Similarly to Cluster A (*Contactless friction ridge recognition*), the key assumption behind the visualisation of data on each layer of the roadmap is that the identified applications, functions and products will continuously be improved in the years following their first occurrence, at least within the analysed timeframe. The Group of Experts who participated in the roadmapping workshop did not envision a high likelihood of discontinuation for any of the items before 2040.

Figure 14: *Technology roadmap for 3D face recognition technological cluster.*

3D face recognition	2021 (ETM: 6.7 years)	2022-2027			2028-2033			2034-2040		
		2022-2023	2024-2025	2026-2027	2028-2029	2030-2031	2032-2033	2034-2035	2036-2037	2038-2040
APPLICATION AREAS OF TECH CLUSTER Where is it used?	Physical access control	**Pre-enrolment for seamless travel (e.g. mobile-based solutions for starting passenger check-in remotely)**								
	Use in smartphones for unlocking the device, making payments and accessing sensitive data		**Physical access control to critical areas (e.g. military zones)**							
	3D facial recognition in healthcare (e.g. COVID-19 quarantine apps)			**Identity verification for payments and bank account access**						
					Seamless border checks using 2D and 3D face recognition (after check-in, biometric data is acquired and stored; it is removed after the passenger leaves the airport/BCP)					
						Surveillance and forensics (biometric data collected on specific people e.g. criminals and suspects)				
							Use in public security for fast detection of aggressive behaviours and attacks			
									3D face acquisition used in the mainstream consumer market (e.g. entertainment)	
FUNCTIONS OF TECH CLUSTER What can it do?	Verification of identity		**3D face identification (technology capable of searching against a biometric enrolment database of 3D face images)**							
				Recognising face images acquired from different camera angles						
				Short-distance 3D face recognition on the move for seamless border crossing						
						Detection of abnormal behaviours (i.e. detection of people in need of assistance or special care within the limited space of BCPs)				
							Long-distance 3D face recognition on the move for seamless border crossing			
									Distinguishing between deep fake and real face images	
										Detecting health issues

3D face recognition	2021 (ETM: 6.7 years)	2022-2027			2028-2033			2034-2040		
		2022-2023	2024-2025	2026-2027	2028-2029	2030-2031	2032-2033	2034-2035	2036-2037	2038-2040
PRODUCTS / SYSTEMS USING TECH CLUSTER What is it?	Smart-phones (esp. for unlocking the phone) 3D-assisted 2D (reconstructing 3D faces from 2D images)	**Improved sensors for 3D image acquisition**								
					Cameras recording 3D videos					
					3D cameras able to acquire images from afar, with a larger field of view, and to assess distance					
						3D facial image stored in the chip of e-passports				
								Placing sensors for 3D face acquisition on drones		
									3D image of face integrated in digital identity management solutions and digital travel documents (e.g. tickets and boarding passes) where biometric templates are protected by cancellable biometric schemes	

8.2.2.2. Key turning points in technological development

The fulfilment of the vision for this technological cluster ("*On-the–fly facial feature extraction and automated recognition for border checks*") depends on key functional developments and specific product innovations, which include:

- 3D face recognition on the move,
- 3D face recognition from long distances,
- Distinguishing between deep fake and real face images,
- Sensors capable of 3D face recognition with high accuracy, from long distances and on the move,
- 3D face images integrated into digital identity management solutions and digital travel documents.

The following table lists other essential enablers of the vision, including technological and non-technological drivers (opportunities), as well as potential challenges that might block or slow down the envisaged trajectory of technological developments. In particular, Table 24 provides extended commentary on the projections envisioned in the roadmap for *3D face recognition* by listing some of the key opportunities and challenges that should be taken into account by various stakeholders representing the EBCG community in the process of defining future capability developments and mainstreaming specific solutions within the cluster.

Table 24: *Development challenges and opportunities (enablers) related to the 3D face recognition technological cluster.*

Opportunities (enablers)	3D face recognition	Challenges
Application Areas		
The new proposal for an EU regulation on harmonised rules on AI allows the use of AI systems for border management.	Surveillance and forensics (biometric data collected on specific people e.g. criminals and suspects)	Biometrics is a highly regulated area, and future EU legal frameworks might impose further restrictions on its use for surveillance.
The popularity of the technology (linked to consumer market uptake) drives further development and reduces costs.	3D face acquisition used in the mainstream consumer market (e.g. for entertainment)	
	Seamless border checks using 2D and 3D face recognition (after check-in, biometric data is acquired and stored; it is removed after the passenger leaves the airport/BCP)	Border checks rely on access to biometric enrolment databases and passports for identification. The enrolment process involving the acquisition of a 3D face biometric sample for feeding the database might represent a barrier to the use of this cluster in border checks.
Functions		
	Long-distance 3D face recognition on the move for seamless border crossing	Need for research to extend the distance from a few meters to tens of meters. Need for IR illuminators and detectors is expected. A strong enough illuminator needs to be used. Switching to over 1550 nm (SWIR band) would result in greater range while ensuring sufficient eye safety.
	3D face identification (technology capable of searching against a biometric enrolment database of 3D face images)	For performing identification (at least on a large scale), a large number of biometric sample acquisitions would be needed, and appropriate regulations would need to be in place. Large databases imply the use of high-volume data storage and high-speed access to cloud or local IT infrastructures. Cost of disaster recovery infrastructures is an additional problem.
Can be combined with iris recognition. Gait recognition would also provide an extra security feature when combined with 3D face recognition.	Short-distance 3D face recognition on the move for seamless border crossing	Sensors with a fairly high frame-rate have to be achieved; the development of compressed versions of the 3D image would help in achieving low data volumes.
Novel processors, sensors and software solutions capable of producing greatly improved solutions.	Detecting health issues	
	Detection of abnormal behaviours (e.g. detection of people in need of assistance or special care within the limited space of BCPs)	There are highly sensitive and significant ethical and fundamental rights concerns. Face recognition might not be sufficient; full-body imaging might be needed. Legal frameworks might represent a challenge.

Opportunities (enablers)	3D face recognition	Challenges
Products/ Systems		
A digital biometric ID managed by smartphones would be easier to develop than a traditional passport with 3D face data.	3D facial image stored in the chip of e-passports	This would require reading the passport and processing a large volume of data, which would exclude seamlessness. A lack of technical standards might be a barrier. There is uncertainty on whether standardisation efforts regarding 3D face recognition will be undertaken by the ISO, the ICAO NTWG or if the EU will develop its own standards.
Availability of novel algorithms for processing non-ideal images through quality enhancement, improved segmentation, feature extraction and classification.	Cameras recording 3D videos	Not only are cameras important, but also data handling, databases, algorithms for comparison.
Need to create development roadmaps strictly correlated with other key enabling technologies (AI, nanoelectronics, microprocessors).	Improved sensors for 3D image acquisition	The availability of complete systems, composed of sensors, illuminators, optics and data handling is crucial
	Placing 3D sensors for face acquisition on drones	Difficult acquisition of 3D face images if people are not facing up or if very long distances are considered.

A more in-depth analysis of the technology roadmap reveals many challenges associated with developments projected onto its layers. Many of these issues concern the functions of technological cluster, as the challenges outweigh the opportunities and can be divided into two categories:

- challenges which condition the attainment of technical requirements,
- challenges associated with the legal framework.

Concerning the application areas, there seem to be few technological challenges. The main challenge applies to seamless border checks using 2D and 3D face recognition, where after check-in biometric data is acquired, stored and later removed after the passenger leaves the airport or BCP. Here, an obstacle could arise during the enrolment process, as the acquisition of a 3D face biometric sample for feeding the database could be difficult.

Crucial technology-related challenges are associated with the main function of this technological cluster (*3D face recognition*) and involve in particular:

- an agreement on what might comprise the biometric data and the acquisition methods for obtaining interoperable data formats for 3D face images,
- the availability of standardised and interchangeable 3D facial biometric datasets,
- systems with fully integrated sensors connected to large-scale IT systems for seamless border checks.

Another challenge is the high cost associated with these technological advances, which is primarily caused by the need to conduct further research to extend the operating distance from a few meters to tens of meters and to enable the storage of the significant volumes of data produced when acquiring 3D facial images in motion. Furthermore, future accuracy standards might require full-body imaging (for *detection of abnormal behaviours*) or the use of a strong illuminator, which would extend the range of image acquisition while maintaining eye safety for achieving *3D face recognition* from a long distance.

Further technological challenges and opportunities are related to products and systems. Product innovations should not be considered as standalone transformations (cameras recording 3D videos, improved sensors for 3D image acquisition) but treated as innovations related to systems composed of sensors, illuminators, optics, databases, data handling and comparison algorithms. They should, therefore, be correlated with advances in other key enabling technologies (e.g. AI, nanoelectronics and microprocessors), which is considered an opportunity in this case. One particular technological challenge is associated with the idea of storing 3D facial images in e-passports. If scanning the passport is required at border checks, travel cannot be entirely seamless because of the need to stop and the time needed to process large volumes of data.

The second group of challenges comprises those related to the legal aspects that affect the potential of new technical possibilities for becoming innovative biometric solutions. In the case of the application of *3D face recognition* in surveillance and forensics or for use in behaviour detection, technical feasibility needs to go hand in hand with legal feasibility as well as security of data, privacy and adhesion to ethical standards. Fundamental rights impact assessments need to be carefully considered to reduce the negative impacts that using these technologies might have on fundamental rights, especially the right to data protection.

While the challenges generally outweigh the opportunities, the latter are associated with adopting multi-modal biometric solutions which combine *3D face recognition* with other biometric modalities to achieve better accuracy. In particular, combining *3D face recognition* with *Iris recognition* and *Fingerprint recognition* to improve performance should be considered in the following application areas: seamless border checks using 2D and 3D face images, as well as surveillance and forensics. *Gait recognition* can be used as a separate biometric modality, which improves security (combined with *3D face recognition on the move*).

A game-changer in terms of accelerating the uptake of *3D face recognition* in law enforcement applications (especially border checks, documents and forensics) could be the mass usage of 3D face imaging in the mainstream consumer market (e.g. for entertainment), which would lower the costs of this technology due to its popularity and likely accelerate new developments.

8.2.2.3. Comparative analysis under the conditions of the scenarios

The results of a comparative analysis of the key developments in the *3D face recognition* technological cluster under the conditions of four alternative scenarios are presented in Table 25.

Table 25: *Comparative analysis of key developments in the 3D face recognition technological cluster under the conditions of the four alternative scenarios.*

3D face recognition	SCENARIO 1 Union for society	SCENARIO 2 Protected Union	SCENARIO 3 Union under strain	SCENARIO 4 No-stop-shop
General scenario impact on the developments of the cluster	Good collaboration between countries along with plentiful resources accelerates research and implementation. International collaboration enables EU Member States to import products and their components. The EU is also an active partner in international research. It can also afford to finance its own research and manufacturing. Thanks to these conditions, all the developments concerning *3D face recognition* can be applied as originally planned or earlier.	Security threats exert more pressure on developing biometric technologies and other security solutions. The EU is strong and experiences dynamic development, which enables policymaking to regulate the sector. Financial resources are available for R&D. Thanks to the available resources and because of the security threats, all technological developments happen sooner within the EU. Turning point: if an EU Army were created, it would foster the development of biometric technologies, although their applications would be in a different sector.	Limited financial resources slow down research, but the EU MSs cannot import products or acquire research from third countries because of conflicts and tensions. "Low-hanging fruit" technologies (easier to develop) are implemented faster to address the security needs, but the implementation of more advanced systems is delayed. Poor cooperation between the EU MSs increases the risk of disagreement between them. Therefore, the implementation of the technologies might vary within the EU (some MSs could reject biometric technologies or be unable to implement them).	Due to limited financial resources, the EU is importing rather than developing its own products (especially high-tech solutions) and thus becomes dependent on other countries. The market availability of new biometric solutions is not significantly delayed. Economic disparities between the EU MSs result in some MSs acquiring new technologies faster than others.
APPLICATION AREAS OF TECH CLUSTER	With one notable exception, the application areas of *3D face recognition* — in terms of their scope and timeline — do not change under the conditions of this scenario (compared to the technology roadmap projections). The exception is the use of 3D face image acquisition in the mainstream consumer market (in particular in entertainment), which will enter the mainstream as early as 2022, 14 years earlier than indicated by the technology roadmap projections.	The majority of applications of *3D face recognition* proposed in the technology roadmap are introduced at least one year ahead of projections. In two cases, the progress is even faster: • *3D face recognition* is applied in surveillance and forensics 3 years ahead of the roadmap projections (in 2027). • Use in public security for fast detection of aggressive behaviours and attacks is introduced 3 years faster (in 2029).	Applications of 3D face recognition remain largely consistent with the roadmap projections. However, pre-enrolment for seamless travel is delayed by about 2 years (to 2024).	Pre-enrolment for seamless travel is expensive, so it is introduced 2 years later (in 2024) than in the technology roadmap projections. No changes occur in the case of other applications (neither in regard to the scope, nor the implementation dates).
FUNCTIONS OF TECH CLUSTER	Compared to the technology roadmap projections, two functionalities of *3D face recognition* become available faster. First, the developments in technologies capable of distinguishing between deep fake and real faces advance up to 12 years faster (starting in 2024), than in the technology roadmap projections. Moreover, research on the use of *3D face recognition* for health issue detection becomes a priority 12 years earlier (by 2026) than in the original projections.	Several functions could become viable 2 years earlier, including: • Long-distance 3D face recognition on-the-move for seamless border crossing (by 2030). • Distinguishing between deep fake and real face images (by 2034). • Detecting health issues (by 2036).	Limited financial resources result in delays in the development of three technological functions of 3D face recognition: • 3D face identification is delayed by 3 years (to 2027). • Short-distance *3D face recognition* on the move for seamless border crossing is delayed by 2 years (to 2028). • Recognising face images acquired from different camera angles is delayed by 4 years (to 2030).	The EU economy's slow-down results in the delayed readiness of the three technological functions of *3D face recognition* that require high research investments: • 3D face identification is delayed by 2 years (to 2026). In two other cases, it is difficult to envision the exact scale of delays – recognising face images acquired from different camera angles, as well as short-distance *3D face recognition* on-the-move for seamless border crossing, are both delayed beyond 2027.

Continued on pg.98

Continued from pg.97

3D face recognition	SCENARIO 1 **Union for society**	SCENARIO 2 **Protected Union**	SCENARIO 3 **Union under strain**	SCENARIO 4 **No-stop-shop**
PRODUCTS / SYSTEMS USING TECH CLUSTER	A handful of the *3D face recognition* products and systems are introduced well ahead of the roadmap projections (6 to 8 years earlier): • Advances in the development of 3D cameras able to acquire images from afar, with a larger field of view, and to assess distance, will occur 6 years faster (beginning in 2022). • The inclusion of high-quality 3D facial images in the chip of EU e-passports is available in 2024, 6 years prior to the technology roadmap projections. • Placing sensors for 3D face acquisition on drones becomes prevalent 8 years earlier than in the technology roadmap projections (by 2026).	The majority of products and systems that use this technological cluster are introduced no earlier than one year ahead of the technology roadmap assumptions, yet placing 3D sensors for face acquisition on drones could become viable 5 years earlier (by 2029).	In the case of products and systems, some advances concern the development of systems that are less cost-intensive, such as: • 3D facial images stored in the chip of e-passports, which are introduced 3 years earlier, in 2027. Yet the delays in products and systems concern the development of more expensive and advanced systems, such as: • Cameras recording 3D videos, which are delayed by 2 years (to 2030). • 3D cameras able to acquire images from afar, with a larger field of view and to assess distance, which are delayed by 3 years (to 2031).	Product development in the EU is slower, but since it is possible to import (cheaper) systems from outside the EU, the timeframe regarding product availability does not change in this scenario.

The ***Union for society*** scenario creates the most favourable conditions for ground-breaking innovations in *3D face recognition* and represents a significant step towards fulfilling the vision for this technological cluster. In this scenario, a handful of products and systems that use *3D face recognition* are introduced well ahead of the roadmap projections (6 to 8 years earlier). This accelerates the advancement of the technology itself and enables the successful uptake of the technology in other (especially sovereign) application areas.

The *3D face recognition* technological cluster also performs well under the ***Protected Union*** scenario, which assumes significant pressure on the introduction of novel security technologies (due to security threats). It also assumes that the EU possesses adequate resources to finance such developments. Most applications proposed in the technology roadmap are introduced at least one year ahead of the roadmap projections. Some of the functions and the majority of products and systems that use this technological cluster are introduced one year earlier than in the technology roadmap.

In the ***Union under strain*** scenario, there is also pressure to develop new technologies that could enhance border security. However, the EU lacks appropriate financial resources, and international cooperation is complicated due to worldwide conflicts. These conditions delay the development of crucial functions of the cluster and cause several delays in the implementation of expensive, technologically advanced solutions. Nonetheless, the cheaper applications of *3D face recognition* systems retain a similar timeline to the projected one.

The ***No-stop-shop*** scenario also causes challenges in the area of technology development due to limited EU resources and low pressure on novel technological solutions for border checks (due to the peaceful environment). However, the timeframe for product availability and market uptake does not change compared to the projections in the technology roadmap, as it is still possible to import solutions (cheaply) from outside the EU. It is only the EU's own R&D speed and efficiency that decrease under this scenario.

8.2.3. Technological cluster C: Infrared face recognition

8.2.3.1. Technology roadmap

The general vision of the role of the *Infrared face recognition* technological cluster in 2040 border-check processes can be summarised as: "Improved *Infrared face recognition* with a highly developed PAD system, *applied in multi-modal biometrics for EU border checks, with additional usage in law enforcement and crowd control during large events*".

Similarly to the clusters A (*Contactless friction ridge recognition*) and B (*3D face recognition*), the Group of Experts who participated in the roadmapping workshop did not envision a high likelihood of discontinuation for most of the roadmap items before 2040. However, the key assumption behind the visualisation of data on each layer of the roadmap is that the identified applications, functions and products will develop most dynamically in the indicated time frames.

The developments, modelled in the three timeframes: short- (2022-2027), medium- (2028-2033) and long-term (2034-2040), create a possible roadmap to the vision, as shown in Figure 15.

Figure 15: *Technology roadmap for the Infrared face recognition technological cluster.*

Infrared face recognition	2021 (ETM: 4.8 years)	2022-2027			2028-2033			2034-2040		
		2022-2023	2024-2025	2026-2027	2028-2029	2030-2031	2032-2033	2034-2035	2036-2037	2038-2040
APPLICATION AREAS OF TECH CLUSTER Where is it used?	Proof of concept demos: thermal infrared cameras being used at airports, widely deployed NIR cameras, SWIR cameras being developed and improved	**Improvement of PAD for Infrared face recognition in border checks**						**Large-scale pilot projects to test the ever-developing functions of Infrared face recognition**		**Infrared face recognition included in multi-modal biometrics for EU border check systems**
				Infrared face recognition used for crowd monitoring at small events						**Infrared face recognition used for crowd control at mass events**
										Law enforcement applications: recognition of criminals, fugitives, persons of interest or missing persons
FUNCTIONS OF TECH CLUSTER What can it do?	Small number of biometric identity cards			**Combined NIR/SWIR Infrared face recognition**						
				Seamless face recognition on-the-move in reflective IR						
										Person tracking for crowd control
PRODUCTS / SYSTEMS USING TECH CLUSTER What is it?	IR camera connected, through a workstation, with a database			**Managed Databases of biometric data compatible with Infrared face recognition**		**Databases compliant with digital identity management schemes**				
							Large-scale IR systems			

8.2.3.2. Key turning points in technological development

The fulfilment of the vision for this technological cluster *("Improved Infrared face recognition with a highly developed PAD system, applied in multi-modal biometrics for EU border control, with additional usage in law enforcement and crowd control during large events")* depends on key functional developments and specific product innovations, which include:

- Improvement of PAD for *Infrared face recognition* in border checks,
- Large-scale pilot projects to test the functions of *Infrared face recognition*,
- Seamless face recognition on the move in reflective IR,
- Managed Databases of biometric data compatible with *Infrared face recognition*,
- Databases compliant with digital identity management schemes.

Additional important enablers of the vision, including non-technological drivers, are listed in Table 26. Potential challenges, which could block or slow down the envisaged trajectory of technological developments, are also included.

Table 26: *Development challenges and opportunities (enablers) related to the Infrared face recognition technological cluster.*

Opportunities (enablers)	Infrared face recognition	Challenges
Application Areas		
Lighting can be used for multiple purposes (e.g. in vehicle driver attention recognition, occupancy estimation, iris recognition in the IR spectrum, etc).	Infrared face recognition included in multi-modal biometrics for EU border check systems	Development of EU regulations A reference image has to be stored in the (digital) passport. Diverse datasets are needed to mitigate bias.
Pilot programmes to compare wavelengths and implement sensor fusion. Novel applications in behaviour detection.	Improvement of PAD for Infrared face recognition in border checks Law enforcement applications: recognition of criminals, fugitives, persons of interest or missing persons	Infrared systems might be biased in assessing certain issues. For example, when the IR illumination (or the thermal distribution) of a face changes, its appearance undergoes a nonlinear transformation and, due to the linear projection, the classification can fail. Thus IR systems might require additional witness-based methods of recognition, which lower seamlessness.
Functions		
Using thermal infrared cameras as "privacy-friendly" imaging to seamlessly count travellers and/or measure their temperature, which can be an important feature in the case of pandemics.	Combined NIR/SWIR Infrared face recognition	Development of EU regulations for IR image stored in the ePassport. Development of IR sources. Availability of foundries of affordable accessible NIR-SWIR-LWIR image sensors in the EU.
NIR-SWIR for face recognition can be combined with MWIR-LWIR for temperature measurement (at a lower resolution). The combination of iris, fingerprint and *Infrared face recognition* allows an extraordinary level of accuracy.	Seamless face recognition on the move in reflective IR	Development of components, e.g. illuminators and sensors. Development of EU regulations for IR image stored in digital identity management solutions. Availability of video analytics and AI.
Products/ Systems		
Testing infrared cameras for face recognition during pilots, e.g. at airports. The goal: to enable the acquisition (and processing) of images at different wavelength bands and effectively work at the sensor fusion level.	Large scale IR systems	Development of EU regulations and standards for IR image acquisition.

In the case of *Infrared face recognition*, the opportunities for further development slightly outweigh the challenges, because many of these challenges repeatedly refer to the need for common regulations and standards. The opportunities are primarily related to technological developments that could enhance precision and expand the applications of *Infrared face recognition*. Moreover, potential opportunities could result from combining various technologies. Firstly, NIR and SWIR face recognition systems could be combined with MWIR-LWIR systems that measure temperature (and can operate at low resolutions). Thermal infrared cameras could measure the temperature of passengers seamlessly, easing the flow of travellers without undermining their privacy, which is an advantage in case of safety measures undertaken during unusual circumstances such as pandemics. To achieve an extraordinary level of precision in recognition, a combination of *Infrared face recognition* with *Iris* and *Fingerprint recognition* could be applied. Finally, pilot programmes could be introduced to compare various wavelengths and undertake sensor fusion.

A challenge that could hinder the application of *Infrared face recognition* is the need for the timely development of appropriate EU regulations. Moreover, infrared technologies could introduce some degree of bias, thus, diversified databases and additional human assessment might be needed to avoid bias. Finally, enhanced IR face recognition (i.e. seamless, on the move) would require the simultaneous development of supporting technologies (e.g. NIR-SWIR-LWIR image sensors) and components (e.g. illuminators). This could introduce delays in the development of *IR face recognition* and increase the costs.

8.2.3.3. Comparative analysis under the conditions of the scenarios

The results of a comparative analysis of the key developments in the Infrared face recognition technological cluster under the conditions of the four alternative scenarios are presented in Table 27.

Table 27: *Comparative analysis of key developments in the Infrared face recognition technological cluster under the conditions of the four alternative scenarios.*

Infrared face recognition	SCENARIO 1 Union for society	SCENARIO 2 Protected Union	SCENARIO 3 Union under strain	SCENARIO 4 No-stop-shop
General scenario impact on the developments of the cluster	In this scenario, the timeframe and scope of the developments in *Infrared face recognition* technology remain unchanged compared to the roadmap projections. There is an assumption that a peaceful world and stable economic conditions allow for timely progress.	Geopolitical conditions of conflict combined with the dynamic development of the European Union accelerate the development of *Infrared face recognition*, which becomes a priority. At the same time, the strong economic position of the EU allows for better funding of the technology.	A conflict-ridden world and scarce economic resources create the need for strict prioritisation of the technologies that would successfully enhance security while being relatively inexpensive and easy to implement. Thus, *Infrared face recognition* is prioritised over e.g. *3D face recognition* (2D technology is already more advanced).	Limited economic resources in the EU and a peaceful global environment prioritise solutions focused on processing large volumes of travellers' data, digital crime detection and prevention.

Continued on pg.102

Continued from pg.101

Infrared face recognition	SCENARIO 1 **Union for society**	SCENARIO 2 **Protected Union**	SCENARIO 3 **Union under strain**	SCENARIO 4 **No-stop-shop**
APPLICATION AREAS OF TECH CLUSTER	Applications of *Infrared face recognition* technology, as well as the timeframe of their development, conform to original projections.	The improvement of PAD for *Infrared face recognition* in border checks accelerates. Pilot projects are introduced as early as 2022 and enhanced PAD is in widespread use by 2030. The final goal of the cluster's vision (*Infrared face recognition* included in multi-modal biometrics for EU border check systems) is accomplished about 5-10 years earlier than originally assumed (in 2030-2035).	The Improvement of PAD for *Infrared face recognition* in border checks is prioritised and accelerated: pilot programmes are introduced as early as 2022, and enhanced PAD is used on a large scale by 2030. Large-scale pilot projects to test the functions of *Infrared face recognition* are accelerated by about 10 years (2027-2028). The final goal of the cluster's vision (*Infrared face recognition* included in multi-modal biometrics for EU border check systems) is accomplished about 5-10 years earlier than originally assumed (in 2030-2035).	The Improvement of PAD for *Infrared face recognition* in border checks follows the initial projections. Enhancing capability in monitoring smaller-scale events (due to issues of local crime) is prioritised. *Infrared face recognition* is also useful for monitoring the flow of passengers and crowds, e.g. at airports. Applications of this technology would be introduced as originally projected (2040).
FUNCTIONS OF TECH CLUSTER	Functions of *Infrared face recognition technology*, as well as the timeframe of their development, conform to original projections.	Combined NIR/SWIR *Infrared face recognition* and seamless face recognition on the move in reflective IR are accelerated by about 2 years (2024).	Combined NIR/SWIR *Infrared face recognition* as well as seamless face recognition on the move in reflective IR are prioritised and potentially accelerated to ensure the faster application of *Infrared face recognition*. Although the implementation of large-scale systems is prioritised as well, economic constraints hinder accelerated development and the conflict-ridden world impedes the interoperability required for these systems.	Functions of *Infrared face recognition* technology, as well as the timeframe of their development, conform to original projections.
PRODUCTS / SYSTEMS USING TECH CLUSTER	Products and systems in the *Infrared face recognition* technology, as well as the timeframe of their development, conform to original projections.	The EU possesses the skills and the elevated scalability potential to implement Managed Databases of biometric data compatible with *Infrared face recognition* as originally projected by 2026. The development of Large-scale IR systems is prioritised and significantly accelerated — by about 4-5 years (2027/2028).	Databases compliant with digital identity management schemes' standards would be of a lower priority. This could delay their introduction by as much as 10 years (2040).	Managed Databases of biometric data compatible with *Infrared face recognition* and databases compliant with Digital Identity management schemes are developed within the originally projected timeframe (2026-2031). An emphasis is placed on keeping them secure, in light of prevalent cybercrime.

The ***Union for society*** scenario describes a peaceful world and dynamic EU development, thus creating favourable conditions for the timely implementation of functions, products and systems associated with *Infrared face recognition*. In this scenario, the timeframe and scope of developments conform to the original roadmap projections.

In the ***Protected Union*** scenario, a conflict-ridden world, combined with the dynamic development of the European Union, accelerates the development of *Infrared face recognition*. *Infrared face recognition* became a priority as it helps counter global security threats and risks on the borders. At the same time, the EU's strong economic position provides sufficient funding for developing this technology. Under these conditions, applications of *Infrared face recognition* in law enforcement, multi-modal biometrics for EU border checks, crowd control and person tracking are accelerated by 5-10 years. An important contributing factor is the accelerated improvement of PAD. Functions of the 2D technology, including basic facial recognition, seamless face acquisition and scalability to large systems, are also prioritised and accelerated by about 2-5 years.

Managed subject databases and databases conforming to digital identity management schemes are established as originally projected.

The ***Union under strain*** scenario pictures difficult conditions, with a conflict-ridden world and scarce economic resources in the European Union. However, such conditions require the prioritisation of biometric technologies. This constitutes an opportunity for *Infrared face recognition*, as it would be cheaper and easier to develop and implement than e.g. *3D face recognition* (bearing in mind that *2D face recognition* technology is already relatively advanced). In this scenario, prioritisation accelerates the application of *Infrared face recognition*, but scarce resources hinder some of the developments of functions and products. The improvement of PAD for *Infrared face recognition* in border checks, combined NIR/SWIR recognition systems and seamless face recognition on the move in reflective IR accelerate, and the final goals of the cluster's vision (*Infrared face recognition* included in multi-modal biometrics for EU border check systems, *Infrared face recognition* used for crowd control at mass events, law enforcement applications and person tracking for crowd control) are accomplished 5-10 years earlier than originally projected (in 2030-2035). However, the global environment of conflict complicates interoperability, which is required for scalability to large systems. Therefore, the development of scalability does not accelerate, but interoperability is achieved as initially projected. Databases conforming to standards for digital identity management schemes are not prioritised. Thus, their introduction is delayed by about 10 years (2040).

The ***No-stop-shop*** scenario is the least favourable for developments in *Infrared face recognition* technology, as it combines lower prioritisation of the technology (due to a peaceful environment) with scarce resources. *Infrared face recognition,* however, is not significantly set back, but rather developed within the context of border checks subject to large flows of passengers (especially due to increased migration). In this scenario, the functions and applications of the technology are generally developed in accordance with the roadmap timeframe. Capabilities related to monitoring smaller-scale events are prioritised (due to the prevalence of local crime). The databases are developed in accordance with the roadmap projections, and particular emphasis is placed on keeping them secure from prevalent cybercrime.

8.2.4. Technological Cluster D: Iris recognition in the NIR spectrum

8.2.4.1. Technology roadmap

The vision for the role of the *Iris recognition in the NIR spectrum* technological cluster in border check processes by 2040 includes: "*the widespread use and acceptance of this technology, enhanced technical performance that enables fast processing (to obtain comparison scores), iris image acquisition at a distance and from a moving subject (allowing seamless or near-seamless border checks) and iris presentation attack detection techniques*".

The vision assumes that the precision of *Iris recognition in the NIR spectrum* will increase due to algorithms for segmenting the iris region, as a non-circular shape, extrapolated from noisy ocular images affected by occlusions and/or low-level illumination. To ensure even higher accuracy, iris recognition would be combined with other technologies (multi-modal biometrics), thus addressing the limitations of the method in the case of blind persons and people whose irises are affected by a disease. By 2040, it should be possible to enrol in programmes of NIR iris recognition on a mobile device (smartphones, tablets or other similar devices existing in 2040).

The developments, modelled in the short- (2022-2027), medium- (2028-2033) and long-term (2034-2040), create a possible roadmap to the vision, as shown in Figure 16.

Figure 16: *Technology roadmap for the Iris recognition in the NIR spectrum technological cluster.*

Iris recognition in the NIR spectrum	2021 (ETM: 6.8 years)	2022-2027			2028-2033			2034-2040		
		2022-2023	2024-2025	2026-2027	2028-2029	2030-2031	2032-2033	2034-2035	2036-2037	2038-2040
APPLICATION AREAS OF TECH CLUSTER Where is it used?	Access control and border checks	**Used for near-seamless border checks (use cases include applications for people crossing external borders in vehicles and stopping for a short time)**				**Used for seamless border checks (use cases include applications for people crossing external borders in vehicles)**				
				Application in specific behaviour detection (e.g. detecting when a driver falls asleep)						
				Applied in digital identity management schemes						
FUNCTIONS OF TECH CLUSTER What can it do?	Person recognition, border checks (faster recognition), particularly useful for travellers wearing face masks or religious headgear		**Iris recognition in the NIR spectrum combined with Face recognition and Periocular recognition. These biometric modalities are included in e-Passport for easier border checks**		**Iris recognition in the NIR spectrum routinely combined with face recognition (improving the Iris image acquisition process and the quality of biometric samples)**					
			Development of suitable (eye-safe) NIR light sources for seamless recognition							
				Implementation in virtual traveller identification schemes			**Databases fully established for operational implementation of iris recognition in border checks**			
						Functionality and reliability highly improved by novel high-speed processors, use of AI, new broadband optics, fusion of VIS and NIR, long-distance devices, presentation attack detection algorithms				
PRODUCTS / SYSTEMS USING TECH CLUSTER What is it?	Airport and train check-in applications (example use case is the frequent-flyer initiative at Schiphol Airport – Netherlands)	**Enrolment through standard procedures**			**Small and flexible devices for making enrolment possible at home**					
			Pilot projects for including NIR Iris features in electronic travel documents (on mobile phones)	**Mobile check-point systems**	**Standardised digital travel documents containing enrolled NIR iris template at issuance**					
				Sensors available on a larger scale	**Iris recognition systems for border checks proven in operational environment**	**E-gates, corridors and kiosks that fully integrate Iris recognition in the NIR**		**NIR Iris sensors fully integrated in wearable systems (e.g. virtual reality goggles)**		

8.2.4.2. Key turning points in technological development

The fulfilment of the projections for the *Iris recognition in the NIR spectrum* technological cluster (widespread use, higher precision and effectiveness) depends on key functional developments and specific product innovations, which include:

- Development of suitable NIR light sources (eye-safe) to enable seamless *Iris recognition in the NIR spectrum*,
- *Iris recognition in the NIR spectrum* combined with face recognition and periocular recognition,
- Implementation of e-Passports on mobile phones with NIR iris features for easier border checks,
- Development of biometric databases suitable for operational implementation of NIR Iris recognition in border checks,
- Functionality and reliability highly improved by novel high-speed processors, use of AI, new broadband optics, fusion of VIS and NIR, long-distance devices, presentation attack detection algorithms,
- Enrolment at home made possible using small portable devices,
- Integration of *Iris recognition in the NIR spectrum* modality into e-gates, corridors and kiosks for border checks.

An application area deemed outside the scope of the present study is the use of iris recognition for the detection of specific behaviours (such as a driver falling asleep).

Additional important enablers of the vision, including non-technological drivers, are listed in Table 28. Potential challenges, which could block or slow down the envisaged trajectory of technological developments, are also included.

Table 28: *Development challenges and opportunities (enablers) related to the Iris recognition in the NIR spectrum technological cluster.*

Opportunities (enablers)	Iris recognition in the NIR spectrum	Challenges
Application Areas		
With the use of NIR iris recognition, presentation attacks (coloured contact lenses) can be detected more easily than in the visible light spectrum. Overall, the vulnerability of this technology to presentation attacks is very low (because of the high sensitivity of the eye to any physical alterations).	Applied in digital identity management schemes Used for seamless border checks (use cases include applications for people crossing external borders in vehicles)	Capturing biometric samples of such a small body part in motion will remain technically challenging in the future.
Functions		
NIR light sources (850, 905, 940 nm) are readily available.	Development of suitable NIR light sources (eye-safe) for seamless recognition	The far less developed SWIR light sources (1450, 1550 nm) are required for eye-safe active illumination.
Iris recognition is particularly useful if travellers are wearing masks or religious headcovers.	Iris recognition in the NIR spectrum combined with face recognition and Periocular recognition. These biometric modalities are included in e-Passport for easier border checks	

Continued on pg.106

Continued from pg.105

Opportunities (enablers)	**Iris recognition in the NIR spectrum**	**Challenges**
	Databases fully established for operational implementation of Iris recognition in the NIR spectrum in border checks	Research on large-scale databases compatible with the EES infrastructure would be needed, since currently, identification based on the iris is only available in the EU on databases of a scale far smaller than the EES.
	Functionality and reliability highly improved by new high-speed processors, the use of AI, new broadband optics, the fusion of VIS and NIR, long-distance devices, presentation attack detection algorithms	Certain diseases (e.g. cataracts) could interfere with iris recognition. AI could help to recognise an illness or adverse capturing conditions and notify the system.
Products/ Systems		
Iris recognition in motion avoids problems with checking at close distances and improving societal acceptance.	E-gates, corridors and kiosks that fully integrate Iris recognition in the NIR	Iris recognition on the move and at a distance is complex and thus difficult to integrate into biometric corridors for seamless biometric recognition.
	Small and flexible devices for making enrolment possible at home	Dependent on the adoption of suitable solutions by the mobile phone industry.

In the case of *Iris recognition in the NIR spectrum* cluster, the challenges outweigh the opportunities. The opportunities include, in particular, low vulnerability to presentation attacks due to the high sensitivity of the eye to any physical alterations and the ease of presentation attack detection. Moreover, there are already significant developments in terms of the eye safety of the NIR illumination technology – Light-Emitting Diode (LED) NIR light sources at 700-940 nm are readily available. Finally, *Iris recognition in the NIR spectrum* does not require the removal of face masks or cultural/religious face- or head-covers.

However, the development of systems for seamless border checks based on *Iris recognition in the NIR spectrum* poses significant challenges. There are technical difficulties with the capture of the physically small biometric features of the iris when the subject is in motion. Furthermore, while more research is needed regarding large biometric databases for iris recognition, there is already good real-world evidence for the use of iris recognition on a very large scale.[53] Eye-safety issues (photobiological hazard) in the case of illumination at 200-3000 nm wavelengths (thus including NIR and SWIR) are known.[54] Theoretically, SWIR light sources at 1450-1550 nm could be safer for the eye than NIR, but the performance of iris recognition at these wavelengths remains in the early stages of research and development. Finally, enrolment in iris recognition databases via mobile devices would be dependent on the mobile phone industry and its willingness to adopt the required technologies.

53 An example is India's Aadhaar biometrics-based national identification system (see https://uidai.gov.in/my-aadhaar/about-your-aadhaar.html).

54 As reported by the International Commission on Illumination (www.cie.co.at) and included in the IEC 62471:2006 standard on "Photobiological safety of lamps and lamp systems".

8.2.4.3. Comparative analysis under the conditions of the scenarios

The results of a comparative analysis of the key developments in the *Iris recognition in the NIR spectrum* technological cluster under the conditions of four alternative scenarios are presented in Table 29.

Table 29: *Comparative analysis of key developments in the Iris recognition in the NIR spectrum technological cluster under the conditions of the four alternative scenarios.*

Iris recognition in the NIR spectrum	SCENARIO 1 Union for society	SCENARIO 2 Protected Union	SCENARIO 3 Union under strain	SCENARIO 4 No-stop-shop
General scenario impact on the developments of the cluster	A robust legal framework is in place, requiring a stronger emphasis on privacy by design. It can be an opportunity or a threat: more technical effort would be needed to meet these requirements (causing delays in implementation), but they would ensure safety, security, reliability and social acceptance.	There is a significant risk of pandemics and security threats, which creates a need for the development of effective and reliable biometric methods and compatibility with personal protection devices. As a consequence, the Iris recognition in NIR spectrum for border checks is in place earlier to protect the population from external threats. The population is eager to accept the new technologies.	The security of borders and personal data protection are of critical importance, therefore the development of *Iris recognition in the NIR spectrum* accelerates.	Paper travel documents (e.g. e-Passports with visas) are replaced by digital documents (e.g. on mobile phones). This accelerates the development of solutions for iris enrolment and storage in digital documents. However, a lack of funds impedes these developments. There are attempts to adhere to the projected timeframe, but delays cannot be ruled out.
APPLICATION AREAS OF TECH CLUSTER	The application of *Iris recognition in the NIR spectrum* for near-seamless border checks is delayed by at least 1 year, as more research is required. The development of seamless border checks with subjects in motion is delayed by 2 years (2032).	Applications of *Iris recognition in the NIR spectrum* technology are all developed slightly earlier (by 1-2 years).	Land travel is predominant, which causes pressure to develop seamless border checks with *Iris recognition in the NIR spectrum* for people travelling in vehicles. Near-seamless border checks using *Iris recognition in the NIR spectrum* for travellers in vehicles are developed about 1 year earlier than originally planned.	Applications of *Iris recognition in the NIR spectrum* are developed within the original timeframe.
FUNCTIONS OF TECH CLUSTER	*Iris recognition in the NIR spectrum* combined with face recognition and periocular recognition is developed slightly more slowly (2025) due to the need for further research and privacy protection issues. Digital literacy and ethical design cause higher throughput of travellers and social acceptance. Digital identity management solutions are implemented faster, thus implementation in virtual traveller identification schemes happens slightly earlier (from 2025).	Particular attention is paid to the development of combined biometric methods (*Iris recognition in the NIR spectrum, Face recognition* and *Periocular recognition*). The functions of this cluster are all developed 1-2 years earlier than initially assumed.	Functions of the *Iris recognition in the NIR spectrum* cluster are developed earlier (by 1-2 years) due to the high importance of border security.	Functions of *Iris recognition in the NIR spectrum* are developed within the original timeframe.
PRODUCTS / SYSTEMS USING TECH CLUSTER	By design, traveller credentials are embedded in digital identity management systems by 2025. *Iris recognition in the NIR spectrum* systems for border checks are proven in an operational environment about 2 years earlier (2026). The establishment of databases is accelerated by about 4 years (2028).	The products and systems of this cluster are developed 1-2 years earlier than originally projected. As strategic autonomy is crucial, the availability of sensors from European manufacturers is more important in this scenario. High flexibility of the systems developed is also required, which includes the need to scale them up quickly and thus be able to react rapidly to changing circumstances at external borders. As a consequence, the development of mobile systems for border checks is prioritised.	There is a pressing need for thorough and effective border checks, thus, the development of novel products and systems accelerates (by 1-2 years). Particular emphasis is placed on the development of secured multimodal biometrics databases (due to the critical importance of data protection) and the use of AI and autonomous systems in solutions for border checks.	Products and systems related to *Iris recognition in the NIR spectrum are developed within the original timeframe*. There is a need for the creation of additional BCPs and for increased capacity of industry to produce novel systems for border checks, with a particular focus on mobile systems.

In the ***Union for society*** scenario, the dynamic development of the European Union and a peaceful world create conditions in which personal data protection and excellent accuracy are highly valued. This may delay some developments (due to the need for additional research and privacy protection frameworks) but eventually results in the creation of accurate, efficient and fundamental rights-compliant systems, which incorporate privacy-by-design. Moreover, high levels of data literacy result in an understanding of the new technologies, wide societal acceptance and high throughput of travellers. Under these conditions, the application of *Iris recognition in the NIR spectrum* for near-seamless border checks and, eventually, for seamless border checks on the move, is delayed by about 1-2 years due to the need for additional research. Iris recognition, combined with face and periocular recognition technologies, also develops slightly more slowly (by 1 year) due to the required research and the implementation of privacy protection requirements. Digital travel documents containing enrolled NIR iris template at issuance are developed 1 year earlier. The development of the *Iris recognition in the NIR spectrum* systems is accelerated by about 2 years, and the creation of databases by about 4 years.

The ***Protected Union*** scenario assumes a significant risk of pandemics and security threats. Therefore, accurate and reliable biometric recognition systems need to be developed, and compatibility with personal protection devices is required. *Iris recognition in the NIR spectrum* for border checks is implemented earlier to protect the population from external threats; society is eager to accept the new technologies; and the dynamic development of the EU provides funds for research and the development of biometric technologies. Applications, functions, products and systems related to the *Iris recognition in the NIR spectrum* technology are developed slightly earlier (by 1-2 years) than initially projected. Particular attention is paid to the development of combined biometric recognition modalities (*Iris recognition in the NIR spectrum*, *Face recognition* and *Periocular recognition*). EU strategic autonomy is crucial in this scenario, so the availability of sensors from European manufacturers is of greater importance. High flexibility of the biometric systems is also required, which includes the need to scale them up quickly to be able to react to changing circumstances at external borders. As a consequence, the development of mobile systems for border checks is prioritised.

The ***Union under strain*** scenario describes a slowly developing European economy. However, the security of borders and data is of critical importance, which accelerates developments related to *Iris recognition in the NIR spectrum* by 1-2 years. Land travel is predominant in this scenario, which creates a more pressing need for seamless border checks performed by systems based on *Iris recognition in the NIR spectrum* capable of recognising people travelling in vehicles – these developments are accelerated by at least 1 year. Furthermore, particular emphasis is placed on the development of secured multimodal biometrics databases (due to the critical importance of data protection) and the use of AI and autonomous systems in border checks.

In the ***No-stop-shop*** scenario, paper travel documents are replaced with digital ones (e.g. mobile phones), thus the development of iris enrolment and storage in digital documents accelerates. However, the lack of funds impedes progress in this regard. External pressure to introduce new biometric technologies is limited because the world is peaceful. Applications, functions, products and systems related to the *Iris recognition in the NIR spectrum* technology are developed within the projected timeframes, although delays cannot be ruled out. There is a need for the creation of additional BCPs and for an increased capacity of the industry to produce novel systems for border checks, with particular emphasis on mobile systems.

8.2.5. Technological Cluster E: Iris recognition in the visible spectrum

8.2.5.1. Technology roadmap

The vision concerning the role of the *Iris recognition in the visible spectrum* technological cluster in border checks by 2040 includes: "*using new wavelengths within visible light and overcoming current limitations, such as reflections, shadows, differences in iris pigmentation*".

The projections assume that the role of iris imaging in the visible spectrum will not be limited to biometric recognition but will also include uses such as automated medical check-ups (e.g. precise diagnostic health tests). *Iris recognition in the visible spectrum* will be integrated into multi-modal stationary biometric solutions based on the most effective combination of the other key technological clusters. By 2040, regulations and standards for iris imaging and its use for biometric recognition will be in place.

The developments, modelled in the three timeframes: short- (2022-2027), medium- (2028-2033) and long-term (2034-2040), create a possible roadmap to the vision, as shown in Figure 17.

Figure 17: *Technology roadmap for the Iris recognition in the visible spectrum technological cluster.*

Iris recognition in the visible spectrum	**2021 (ETM: 7.4 years)**	**2022-2027**			**2028-2033**			**2034-2040**		
		2022-2023	**2024-2025**	**2026-2027**	**2028-2029**	**2030-2031**	**2032-2033**	**2034-2035**	**2036-2037**	**2038-2040**
APPLICATION AREAS OF TECH CLUSTER Where is it used?	Physical access control Medical field (optometry, personalised medicine)	**Iris recognition in the visible spectrum adopted by the smartphone industry**								
				Near-seamless border checks	**Seamless border checks**					
					Adoption in the medical field (health diagnostics and other applications)					
FUNCTIONS OF TECH CLUSTER What can it do?	**Short-distance non-seamless biometric recognition**			**Near-seamless recognition**	**Seamless recognition**					
	Unlocking devices and granting physical access	**Remote recognition for online services, e.g. for access to online platforms such as for webinars or live video meetings**	**Recognition functionality implemented for people wearing glasses or contact lenses**	**Anti-spoofing mechanisms implemented (e.g. detection of standard colour-changing contact lenses)**	**Combination with complementary biometric technologies (e.g. face recognition) for multimodal biometric recognition**					
					Liveness detection to counteract physical spoofing attacks	**Presentation Attack Detection to counteract novel sophisticated fake representations of the iris such as 3D printed soft contact lenses with nano patterns**		**Iris imaging for recognition simultaneously used for health diagnostics and monitoring (e.g. display of automated health updates)**	**Iris recognition on mobile devices becomes more popular than stand-off detection or on-the-move biometric acquisition**	

Continued on pg.110

Continued from pg.109

Iris recognition in the visible spectrum	**2021 (ETM: 7.4 years)**	**2022-2027**			**2028-2033**			**2034-2040**		
		2022-2023	**2024-2025**	**2026-2027**	**2028-2029**	**2030-2031**	**2032-2033**	**2034-2035**	**2036-2037**	**2038-2040**
PRODUCTS / SYSTEMS USING TECH CLUSTER What is it?	Iris cameras	**Iris imaging devices (in the visible spectrum) suitable for biometrics recognition in border check systems**								
		Stand-alone short-distance recognition systems with limited functionalities for travel facilitation (prototype demonstrators, small biometric databases, pre-enrolment functions, e.g. at airports to accelerate boarding)		**Stand-off long distance iris recognition systems**	**Multi-sensor detectors enable the combination of iris recognition with other biometric recognition technologies, allowing seamless border checks**					
					Miniaturised and cost-effective multi-spectral or hyperspectral iris imaging cameras with optimised bands for improved iris imaging quality					
					Digital identity wallets including iris biometric reference data					

8.2.5.2. Key turning points in technological development

Key functional developments and specific product innovations of the *Iris recognition in the visible spectrum* cluster which are projected on the roadmap include:

- Detailed scientific research into the effectiveness of *Iris recognition in the visible spectrum*;
- The development of miniaturised and cost-effective multi-spectral or hyperspectral iris imaging cameras with optimised bands for improved iris imaging quality;
- The development of multi-sensor detectors (combining iris recognition with other biometric recognition technologies) to enable seamless border checks;
- The inclusion of iris biometric reference data in digital identity management schemes, including digital identity wallets;
- The implementation of anti-spoofing mechanisms.

Potential healthcare uses of iris imaging technologies (e.g. health diagnostics and ophthalmology) are an application area deemed outside the scope of the present study. Although the corresponding additional functionalities are not directly related to the primary function of the cluster (recognition in border check processes), promising research in related fields could accelerate the development of iris recognition technology in the visible spectrum and have a positive impact on the level of social acceptance.

Additional enablers of the vision, including non-technological drivers, are listed in Table 30. Potential challenges, which could block or slow down the envisaged trajectory of technological developments, are also included.

A more in-depth analysis of the roadmap for the *Iris recognition in the visible spectrum* cluster reveals many challenges associated with the developments projected onto the roadmap's layers.

During the roadmapping exercise, the Group of Experts underlined challenges associated with the cost of high-quality cameras/lenses and the EU's supply-chain dependence regarding camera components, coupled with a low capability for manufacturing sensors and cameras. This might pose a challenge in the development of miniaturised and cost-effective multi-spectral or hyperspectral iris imaging cameras with optimised bands for improved iris imaging quality.

Table 30: *Development challenges and opportunities (enablers) related to the Iris recognition in the visible spectrum technological cluster.*

Opportunities (enablers)	Iris recognition in the visible spectrum	Challenges
Application Areas		
Multimodal biometrics: *Iris recognition in the visible spectrum* used in conjunction with facial and/or periocular recognition for improved accuracy and security.	Seamless border checks Medical field (health diagnostics and other applications)	Restrictions/limitations applicable, for example, to imaging of dark irises that impact accuracy, universal applicability and security, which might be a challenge for mainstream use in border checks. It is necessary to convince society that iris image acquisition is eye-safe.
Functions		
Research on the use of multi-spectral or hyperspectral iris imaging for the increased accuracy (spatial resolution).	Near-seamless recognition	Developing innovative illuminators in the visible light spectrum (e.g. for illuminating the eyes discreetly but without negatively affecting the quality of the iris image). AI-based software that could improve the quality of iris images (e.g. filtering out undesirable light reflections).
	Iris recognition on mobile devices is more popular than stand-off detection or on-the-move biometric acquisition	Acquisition of iris images via mobile devices is not always feasible, so the importance of acquisition of images at large distances and/or from moving subjects should not be neglected.
Products/ Systems		
	Miniaturised and cost-effective multi-spectral or hyperspectral iris imaging cameras with optimised bands for improved iris imaging quality	High-quality multi-spectral and hyperspectral cameras/lenses are expensive. EU's supply-chain dependence concerning camera components. Relatively low manufacturing capability for sensors and cameras in the EU.
It is technically feasible.	Digital identity wallets including Iris biometric reference data	Lack of harmonised guidelines and standards for the assessment of the operational performance of technological systems based on iris recognition.

The experts also highlighted the lack of harmonised guidelines and standards for the assessment of the operational performance of technological systems based on iris recognition, which might have a negative impact on social acceptance and overall trust in the safety of iris recognition technologies in the medium and long term.

The few opportunities noted by the Group of Experts mainly relate to prioritising research on multi-spectral iris image capture to increase accuracy (spatial resolution), as well as using *Iris recognition in the visible spectrum* in conjunction with facial and/or periocular recognition for improved accuracy and security.

8.2.5.3. Comparative analysis under the conditions of the scenarios

The results of a comparative analysis of the key developments in the Iris recognition in the visible spectrum technological cluster under the conditions of four alternative scenarios are presented in Table 31.

Table 31: *Comparative analysis of key developments in the Iris recognition in the visible spectrum technological cluster under the conditions of the four alternative scenarios.*

Iris recognition in the visible spectrum	SCENARIO 1 Union for society	SCENARIO 2 Protected Union	SCENARIO 3 Union under strain	SCENARIO 4 No-stop-shop
General scenario impact on the developments of the cluster	Biometric technologies are widely accepted in border checks. The increased use of biometrics – especially in mobile phones – leads to dissemination in other fields that require recognition. Fewer border checks are necessary because of the "perfect world" described in the scenario. Most of the relevant information is verified by carriers. However, the possible acquisition of medical data from iris images still threatens public acceptance of iris recognition technology.	Constant security threats result in a greater societal willingness to accept measures that improve internal security in the EU. Therefore, the use of *iris recognition in the visible spectrum* is widely accepted. In this scenario, multimodal biometric systems are not used to achieve seamless border checks but to improve border security and grant entry to specific EU countries more effectively. VIP travel gains popularity, and the functionalities of the digital identity wallets need to be extended.	EU institutions are weak and border check standards and tools are not harmonised. There is an increased threat of cyberattacks. AI is widely used in border checks.	Reduced travel and a peaceful world decrease the importance of a "strong EU external border management system". International collaboration is strong but technological improvements in the field of biometrics in the EU are hindered by the lack of commonly accepted standards.
APPLICATION AREAS OF TECH CLUSTER	Applications of *Iris recognition in the visible spectrum* are developed within the original timeframe. Healthcare applications of the iris imaging technologies are more common due to the ageing society. Senior and migrant travellers are not at ease with the new technologies in border checks.	The use of this technological cluster for seamless border checks is postponed from 2028 to 2034; it is not possible to implement it earlier due to increased irregular migration.	Applications of *Iris recognition in the visible spectrum* are developed within the original timeframe.	The application areas of this technology remain unchanged compared to roadmap projections. But the timing might be postponed, however it is difficult to assess the scale of delays.
FUNCTIONS OF TECH CLUSTER	The majority of the technology's applications are developed within the original timeframe. *Iris recognition in the visible spectrum* and complementary biometric technologies (e.g. face recognition) are combined 2 years ahead of roadmap projections (starting from 2026). This development enables effective multimodal biometric recognition from around 2026.	Functions of *Iris recognition in the visible spectrum*, as well as the timeframe of their development, remain as originally projected.	Functions of *Iris recognition in the visible spectrum*, as well as the timeframe of their development, remain as originally projected.	It is difficult to assess the scale of delays, but resource scarcity and the high cost of raw materials and components (including chips) have a negative impact on the development of new technological functions.
PRODUCTS / SYSTEMS USING TECH CLUSTER	The faster implementation of effective multimodal recognition solutions is the result of the introduction of multi-sensor-detectors. These enable the combination of iris recognition with other biometric recognition technologies, allowing seamless border checks already in 2026. Digital identity wallets, including iris biometric reference data, are introduced in 2026 (2 years earlier).	There is a significant risk of pandemics; thus, the demand for seamless IR systems increases. The introduction of multi-sensor detectors enables the combination of iris recognition with other biometric recognition technologies, making seamless border checks technically feasible 3 years earlier than envisaged in the roadmap.	More mature biometric recognition modalities take over (for example, fingerprint-based), and there are no incentives to develop a new modality such as iris recognition for border checks. Much more trustworthy biometric recognition systems are needed due to increased international crime. Fewer people can afford sufficient hardware for the digital identity wallet. None of this negatively impacts the gradual development and implementation of products and systems using *Iris recognition in the visible spectrum* technologies. They develop as projected in the roadmap.	Delays in the attainment or improvement of functions will result in delays in the development of all products and systems indicated in the roadmap of the cluster. It is difficult to assess the scale of delays, though.

In the ***Union for society*** scenario, dynamic EU development and a peaceful world create favourable conditions for the acceleration of technological developments. The efforts to create multimodal biometric recognition solutions bring faster results: *Iris recognition in the visible spectrum* is effectively combined with other biometric technologies (e.g. face recognition), enabling a seamless travel experience already in 2026. Similarly, digital identity wallets containing iris biometric reference data and stand-off long-distance iris recognition systems are available earlier than the original roadmap projections. Although the use of biometric technologies in border checks is widely accepted, some concerns remain about the potential of iris imaging technology for medical purposes. The issues of data protection and security require further consideration and regulations developed in open dialogue with stakeholders.

The ***Protected Union*** scenario describes a conflict-ridden world but a dynamically developing European Union. Due to the external threat to EU external borders, the EBCG community prioritises security over seamlessness. This seriously delays (to 2034) the introduction of seamless border check systems based on this technological cluster at the EU's external BCPs, primarily due to irregular migration. At the same time, the increased threat of pandemics results in the prioritisation of touchless, multimodal biometric recognition solutions.

The ***Union under strain*** scenario assumes difficult conditions: a world of conflict, and scarce economic resources in the European Union. As a result, more mature biometric recognition technologies take over (e.g. fingerprint-based) and there are no incentives to develop new modalities (such as iris recognition) for border checks. Although the timelines visualised in the technology roadmap remain essentially unchanged, the introduction of effective multimodal biometric solutions might be delayed due to the lack of harmonised guidelines and standards for assessing the operational performance of technological systems based on iris recognition across the EU.

The ***No-stop-shop*** scenario describes a slowly developing European economy in a peaceful geopolitical situation. Unfavourable economic conditions lead to delays in the attainment or improvement of functions, which results in the delayed development of products or systems using *Iris recognition in the visible spectrum*.

8.3. Roadmapping: conclusions and take-aways

The goal of the following macro-perspective summary is to prompt readers to reflect upon the detailed roadmapping reports for each key biometric cluster. The summary points to the importance of cause-and-effect relationships and their implications. It also aims to inspire new ideas and further investigations into the continuously developing area of biometrics for border checks. Nevertheless, the summary does not discuss the key turning points in the technological developments exhaustively, nor does it provide a detailed comparative report of particular scenarios, for which the reader is referred to the previous paragraphs.

The roadmapping process usually focuses on a given technology and aims to anticipate the possible developments from a technological point of view. The process of constructing bird's-eye-view technology roadmaps enables all involved stakeholders to consider important opportunities related to technological development, such as new needs, new use cases, new products or systems. The roadmapping analysis conducted within this TF project focused on the drivers and "bottlenecks" that could potentially affect the envisaged technological projections. Table 32 shows a cross-cluster comparison of the key turning points (opportunities and challenges) which seem to have a crucial influence on the pace of development and uptake of the key biometric technological clusters in border checks for a secure and more seamless travel experience within the 2040 timeframe. Key turning points are classified into the main categories of the technology roadmap: applications, functions and products or systems.

When it comes to **opportunities**, mainstream consumer-market and health diagnostics applications should increase societal acceptance of *3D face recognition* and *Iris recognition in the visible spectrum,* respectively, which in turn would facilitate the dissemination of the technologies in border-check processes.

Accelerating technological feasibility for *Contactless friction ridge recognition* and *Iris recognition in the NIR spectrum,* on the other hand, would rely on the use of smartphones as mobile biometric scanners and for enrolment. Smartphones would also play a vital role in the dissemination of *3D face recognition* through the introduction of digital identity schemes. Further research and innovation were identified as enablers of technological developments for all the clusters, while specific priorities for further research were indicated for the *Contactless friction ridge recognition*, *Infrared face recognition* and *Iris recognition in the visible spectrum*. The first of these clusters requires research into the development and analysis of the quality of contactless fingerprint samples. The second and third clusters would benefit from research comparing wavelength bands and on the use of multi-spectral or hyperspectral iris imaging for increased accuracy, respectively. Low vulnerability to Presentation Attack Detection was identified as an important intrinsic strength of *Iris recognition in the NIR spectrum*. This cluster displays the additional advantage of usability for travellers wearing masks or headcovers. Applicability in exceptional circumstances (e.g. during global pandemics) was also considered an enabler for *Infrared face recognition,* as thermal infrared cameras can be used to take body temperature measurements, as well as for *Contactless friction ridge recognition*. Low technical barriers to the introduction of digital identity management schemes could be an important enabling factor for the development of the *Iris recognition in the visible spectrum* cluster. Meanwhile, the diffusion of products and systems using *Contactless friction ridge recognition* would benefit from using existing sensors (e.g. smartphone cameras).

While the opportunities are very diverse, almost all **challenges** could be described as technological or legal bottlenecks. Capturing biometric samples at a distance and on the move, and the associated motion stability issues, were identified as crucial impediments to seamless travel systems using the respective technologies. The fundamental challenge for *Iris recognition in the visible spectrum*, on the other hand, is inclusivity: its dissemination requires successful imaging for people with dark irises, who constitute over half of the world's population. A lack of common regulations and standards of use are considered a challenge across all the clusters.

During the roadmapping analysis, the Group of Experts underlined that biometrics is a highly regulated environment. Therefore, advances are introduced gradually, and external conditions (such as unfavourable economic standing or geopolitical situation) do not have a crucial impact on technological evolution. Nevertheless, confronting

Table 32 *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 33: *The impact of external realities described in the four scenarios on the technological developments envisaged in the roadmaps – a cross-cluster comparison.*

Scenario impact analysis	Key biometric technological clusters				
	Contactless friction ridge recognition	3D face recognition	Infrared face recognition	Iris recognition in the NIR spectrun	Iris recognition in the visible spectrum
SCENARIO 1 Union for society	Same	Much faster	Same	Somewhat slower	Same
SCENARIO 2 Protected Union	Same	Faster	Much faster	Faster	Somewhat slower
SCENARIO 3 Union under strain	Faster	Much slower	Faster	Much faster	Same
SCENARIO 4 No-stop shop	Faster	Somewhat slower	Same	Somewhat slower	Much slower

Legend
Compared to the roadmap projections, developments are: Much faster · Faster · Same · Somewhat slower · Much Slower

specific technological developments of the key clusters with possible scenarios of EU development by 2040 revealed that the solutions analysed are not entirely resistant to changes in the external environment. Thus, stakeholders and decision-makers are able to anticipate some of the potential discontinuities and discuss their potential implications for the biometrics field and for the respective technological cluster. Insights from such analysis may be potential indicators of problems or opportunities, which could support decision-makers in reviewing strategy options. A comparison of technological clusters' performance in the four scenarios is shown in Table 33.

The ***Protected Union*** scenario, in general, creates favourable conditions for the acceleration of technological developments due to external security threats, growing societal acceptance of advanced biometric technologies, and sound economic standing, which results in increased investments in innovations for biometrics-enabled border check systems. Three clusters (*3D face recognition*, *Infrared face recognition* and *Iris recognition in the NIR spectrum*) evolve faster than in the extrapolated visions of the future illustrated by the roadmaps. *Contactless friction ridge recognition* advances according to the original projections, while the development of *Iris recognition in the visible spectrum* is somewhat slower.

The deterioration of economic conditions that characterises the ***Union under strain*** reality, is still conducive to the progress of biometric technologies due to the increased need for EU internal security. Geopolitical uncertainty contributes to the creation of an EU army, which in combination with limited budgets results in the prioritisation of more technologically mature (*Iris recognition in the NIR*) and emerging (*Contactless friction ridge recognition, Infrared face recognition*) biometric clusters, which are still relatively undeveloped. The progress of *3D face recognition* slows down.

The ***No-stop-shop*** scenario, which describes a slowly growing European economy and a peaceful geopolitical situation, significantly decelerates developments for three technological clusters. The main reasons include: lower pressure for heightened security measures at external borders; higher resource expenditures required by industry and society (targeted public support measures are implemented in order to support citizens and businesses during economically challenging times) and the increased attention of decision-makers to the correct management of financial resources.

The ***Union for society*** scenario, which seems to be the most optimistic vision (dynamic development of the European Union and no geopolitical conflicts), allows three clusters to register gradual developments as envisaged in the technology roadmaps, and accelerates the progress of *3D face recognition*. A handful of products and systems that use *3D face recognition* are introduced well ahead of the roadmap projections (6 to 12 years earlier). This accelerates the advancement of the technology itself and enables the successful uptake of the technology in other (especially sovereign) application areas. Developments of *Iris recognition in the NIR spectrum* would be delayed by the need for additional research and privacy protection frameworks.

Two of the five clusters, *Contactless friction ridge recognition* and *Infrared face recognition,* perform well in changing external conditions — they are not subject to significant slowdowns. *Iris recognition in the NIR spectrum* also develops comparatively well. *3D face recognition* seems to display the highest sensitivity to changing external conditions with a high probability of "ups and downs" in its development. At the opposite end, *Iris recognition in the visible spectrum* would need particular attention (and perhaps dedicated support schemes) because none of the external enablers in the four scenarios seems to have a positive impact on its development. One possible cause lies in the technical limitations of iris biometrics in the visible spectrum as regards the imaging of dark irises. The Group of Experts recommended that additional detailed research should be conducted to verify feasibility and applicability.

The roadmaps presented and described in this chapter were primarily the result of a two-day workshop, and as such they synthesised insights provided by the Group of Experts. It should be underlined that such insights are rooted in the existing knowledge of the biometrics domain. Although the experts provided very valuable input, this may be imprecise, subjective, have multiple levels of interpretation and be based on a relatively small sample. The Research Team supplemented the Group of Experts' insights by drawing connections and underlining important aspects. Several correct interpretations of the reported results are possible, as are further insights. Readers are therefore encouraged to pose further questions and produce additional insights based on the information displayed above.

9. Capability mapping for the key biometric technological clusters

The roadmapping described above was accompanied by and supplemented with a capability mapping[55] exercise, the fifth and final phase of the Research Study. The exercise aimed to identify the existing capabilities for the five key technological clusters in the EU, as well as the expected development of capability readiness up to 2040. The capability landscape outlined by this exercise highlights both present and future opportunities and gaps. Therefore, it provides a good foundation for strategic decision-making with regard to the key technological clusters. Two sets of information were produced:

1. **Information set 1: key players representing the existing EU capability landscape** were identified for each technological cluster and grouped into 3 categories: research, industry and institutions (see Section 9.1).
2. **Information set 2: Present and expected future capability readiness** were assessed by evaluating the degree to which the identified cluster-specific capability needs are (or will be) met. *Capability readiness* defines the degree to which cluster-specific capability-related needs have been met or are foreseen to be met within the context of the four hypothetical scenarios. Therefore, it constitutes a good indication of the possible shortcomings and opportunities associated with a given technological cluster (see Section 9.2). Timeframes and the context of the four customised scenarios were considered in the assessment of capability readiness.

9.1. Existing EU capability landscape

The existing capability landscape within the EU for each of the five key technological clusters was analysed to gain an overview of the present capabilities available in each cluster. The aim was to provide information that could enable Frontex to develop suitable capabilities. Therefore, the definition of capabilities differs from what would be expected in the case of conventional business capabilities, as the emphasis was placed on aspects of strategic importance to Frontex. The analysis focused mainly on the research, industrial and institutional stakeholders that contribute to developing the selected biometric technological clusters. As a consequence, the key players within each of the three domains were defined as "capabilities". A list of associated entities in all three domains is shown in Table 34. Current or past specific EU-funded projects, although relevant as a measure of knowledge about a given KTC, were not explicitly mentioned, as all of

55 At this point it should be emphasised that the capability mapping and its use in future strategic capability-based planning discussed in this chapter is not directly connected with, although potentially relevant to, the capability development planning processes referred to in Article 9 (Integrated planning) of Regulation (EU) 2019/1896 of the European Parliament and the Council on the European Border and Coast Guard.

them are represented by a single capability ("EU-funded R&I framework programmes"). Further details on EU-funded projects can be found in Chapter 4.

Table 34: *Capability domains and what they comprise as used for the identification of key players within each of the five technological clusters.*

Research	Industry	Institutions
Academic Institutions	Industrial producers of systems and components	EBCG Community (Frontex and Border and Coast Guard National Authorities)
Research and Technology Organisations		EU Institutions, Bodies or Agencies
EU-funded R&I framework programmes		International Organisations
		Civil Society and Trade Associations

For each of the five KTCs, the Research Team selected key players located in the EU from the previously identified list of stakeholders (Appendix 2), based on their relevance to the clusters.

Figure 18: *Existing capability landscape for the selected key technological clusters in the EU. The values in coloured circles represent the number of key players identified in a capability domain and for each of the five KTCs. If a key player is relevant for all clusters, the corresponding value is shown only once, being representative for all.*

The number and distribution of key players in the fields of research, industry and institutions are displayed in Figure 18 and show the existing capability landscape within the EU.[56] The list of key players within the domains and categories is attached as Appendix 7.

Institutional players (the EBCG Community, EU Institutions, Bodies or Agencies, International Organisations, Civil Society and Trade Associations) can be regarded as equally relevant within all five key technological clusters. The same applies to the single identified EU-funded R&I framework programmes (Horizon Europe). Regarding Academic Institutions, Research and Technology Organisations and Industrial Producers, differences between the clusters were discovered:

- Technological clusters A (*Contactless friction ridge recognition*), B (*3D face recognition*) and C (*Infrared face recognition*) show a significantly higher number of relevant research and industry representatives in the EU than clusters D (*Iris recognition in the NIR spectrum*) and E (*Iris recognition in the visible spectrum*).
- The number of research representatives and industrial producers is highest for technological cluster B (*3D face recognition*).

The identified users of the capabilities are obviously the members of the EBCG community.

9.2. Present and future capability readiness

As indicated earlier, *capability readiness* is the degree to which cluster-specific capability-related needs have been met or are foreseen to be met. It points towards opportunities and gaps in the domains of research, industry and institutions, which should be considered when drafting a capability-based development plan. Capability readiness was assessed through a process called *Objective-Driven Capability Mapping*, which pursued specific objectives (see Step 1 below). The approach was selected due to ease of implementation: Frontex will be able to apply the method autonomously in future TF studies, within an acceptable timeframe and with limited effort.

The analysis followed a 7-step approach (Figure 19), based on best-practice procedures suggested in literature.[57]

Figure 19: *Objective-driven capability mapping process followed to perform the assessment of present and future capability readiness.*

- **Step 1** Identification of objectives
- **Step 2** Identification of capabilities
- **Step 3** Identification of capability-related needs
- **Step 4** Assessment of capability readiness
- **Step 5** Identification of capability gaps and opportunities
- **Step 6** Prioritization of capability gaps and opportunies
- **Step 7** Mapping of high-priority capability gaps and opportunities

56 Only stakeholders within the EU plus non-EU stakeholders that are located in Europe were considered.

57 P. Dortmans, et al., "Designing a Capability Development Framework for Home Affairs", RAND Corporation, 2019. This publication shares insights on the design of a tailor-made evidence-based capability development framework in the public security sector.

Step 1 – Identification of objectives

The first step is the identification of a suitable set of objectives for each KTC. The objectives depend on the individual requirements of the organisation that will utilise the capability mapping outcomes. Therefore, the step required consultations with Frontex. The following baseline question was formulated: "*What is the target state for a given technological cluster and when will this state be reached?*"

The set of objectives defined by Frontex was the same for all five technological clusters and is shown in Table 35. In addition, Frontex defined the targeted time for the implementation of each cluster.[58]

The defined set of objectives served as a baseline for the definition of needs in Step 3.

Table 35: *Targeted set of objectives for the key technological clusters (Tech Clusters) as defined in cooperation with Frontex.*

	Tech Cluster A: Contactless friction ridge recognition	Tech Cluster B: 3D face recognition	Tech Cluster C: Infrared face recognition	Tech Cluster D: Iris recognition in the NIR spectrum	Tech Cluster E: Iris recognition in the visible spectrum
Targeted implementation time	**Expected to reach TRL 9 by 2033**	**Expected to reach TRL 9 by 2031**	**Expected to reach TRL 9 by 2028**	**Expected to reach TRL 9 by 2031**	**Expected to reach TRL 9 by 2032**
Set of objectives	TRL ≥ 7: System prototype demonstrated in the operational environment to be suitable (at least) for testing in a pilot project				
	Full integrability in technological solutions for contactless and seamless border checks connected to large-scale IT systems (e.g. the Entry/Exit System) and compatibility with European Smart Borders requirements				
	Highly accurate and secure				
	Demonstrated suitability for improving operational response capacity of EBCG at Border Crossing Points (suitable throughput, scalability, reliability, durability and smooth human-machine interaction)				
	Proper economy of scale (cost) when on the market				
	Fully compliant with EU regulations and values (especially privacy, data protection and fundamental rights)				
	Compatible with policies and measures typically taken in the event of pandemics.				
	High level of social acceptance				
	Technological components available in the EU				

58 The sum of ETM average and ETM standard deviation, obtained in the Delphi survey through consultations with experts, was used to estimate the worst-case scenario of implementation (estimated latest time to reach TRL 9) for the key technological clusters.

Step 2 – Identification of capabilities

Relevant future capabilities need to be defined *a priori*. For the purposes of this study, a set of minimum capabilities (within the EU) that should be monitored by the EBCG community when strategically planning the development of key technological clusters were selected. These capabilities were defined by the Research Team in close cooperation with Frontex to include their specific needs.

In general, it is advisable to follow the MECE (Mutually Exclusive and Collectively Exhaustive) principle[59] for this exercise. "Mutually Exclusive" means that each capability is distinct and there are no duplicates, while "Collectively Exhaustive" ensures that all possible capabilities for each of the final technological clusters are included.

Both principles were considered, but because a practical approach was adopted, the capabilities were predefined based on best practice categories (e.g. supplies and human resources)[60] and supplemented with input provided by Frontex and the Group of Experts during the *Second Technology Foresight Workshop*. Thus, focus on capabilities most relevant to technological clusters was favoured over an exhaustive list of capabilities, which would have required more extensive desk research and analysis.

The defined capabilities were grouped into the three basic domains (here also known as first-level capabilities – research, industrial and institutional) and further subdivided (second- and third-level capabilities), where necessary (see Figure 20). The defined capabilities served as the input for the next step: the identification of capability-related needs.

Figure 20: *Defined minimum capabilities within the EU, categorised into the three levels.*

1st Level Capabilities | 2nd Level Capabilities | 3rd Level Capabilities

Research
- Research agendas
- Research institutions / incubators / clusters
- Research funding schemes
- Intellectual property protection
- Educational initiatives
- ...

Industrial
- OEMs (Original Equipment Manufacturers)
- Industrial standards
- Infrastructures of carriers
- Funding schemes for SMEs and start-ups
- Supplies (e.g. IT infrastructures and raw materials)
- ...

Institutional
- Security R&I agendas
- Networks of R&I practicioners
- IT systems and cybersecurity
- **EBCG internal organisation** (e.g. skills, operational capabilities, financial capabilities and HR)
- **Framework conditions** (e.g. legal or regulatory entities, standards, laws, multilateral international agreements)
  - **Technical and operational standards and regulations**
  - **Protection of Fundamental Rights** (including, but not limited to, privacy, data protection, non-discrimination, acces to justice and the rights to the child) taking into account the principles dictated by the Charter of Fundamental Rights of the EU, the European Convention on Human Rights, the General Data Protection Regulation and the Law Enforcement Directive.
- ...

59 See, for example, "How to Create a Business Capability Map" in https://www.jibility.com/business-capability-mapping-guide/.

60 P. Dortmans, et al., "Designing a Capability Development Framework for Home Affairs", RAND Corporation, 2019.

Step 3 – Identification of capability-related needs

The identification of capability-related needs for each of the five selected technological clusters and each of the three capability domains required the input of the Group of Experts. During the *Second TF Workshop*, the experts were acquainted with the capabilities defined in Step 2 (Figure 20) and the set of objectives identified in Step 1 (Table 35). Based on this background information, they were asked to define needs relevant for the achievement of the objectives for each key technological cluster (regardless of the timeframes). The capabilities served as guidelines for this exercise. The resulting capability-related needs and the associated capability domains (first-level capabilities) are listed in Table 36.

Table 36: *Capability-related needs identified for each key technological cluster and the respective abbreviations and capability domain (first-level).*

Capability domain	Abbreviation	Cluster-specific capability-related need
Technological Cluster A: Contactless friction ridge recognition		
Research	Res 1	EU Horizon Europe framework programme for R&I – call devoted to the analysis of contactless fingerprint images and the enhancement of their quality
Industrial	Ind1	Technological solutions for fast acquisition of high-resolution images
	Ind2	Proper economy of scale when on the market
Institutional	Inst1	Full compliance with EU regulations
	Inst2	High level of social acceptance
	Inst3	Full interoperability between EU information systems for border management to enable seamless border checks through the use of novel biometrics-enabled technological systems
Technological Cluster B: 3D face recognition		
Research	Res1	Datasets of 3D face biometric data for the performance evaluation of biometric systems
	Res2	EU-funded research initiatives to study novel 3D face acquisition methods and their efficiency, efficient new algorithms, applications/functions
Industrial	Ind1	Development of encryption techniques for biometric data
	Ind2	Development of multimodal biometric systems with enhanced accuracy
	Ind3	Manufacturing (at least assembly) facilities for biometric systems within the EU
	Ind4	Availability of accurate and affordable 3D face cameras
Institutional	Inst1	Full interoperability between EU information systems for border management to enable seamless border checks through the use of novel biometrics-enabled technological systems
	Inst2	Standardisation of biometric data
	Inst3	3D facial biometric data stored in EU e-passports
Technological Cluster C: Infrared face recognition		
Research	Res1	Evaluation of the performance of AI-assisted recognition methods applied to facial images acquired under different illumination conditions and wavelengths
Industrial	Ind1	Availability of components within the EU
	Ind2	Knowledge of promising use cases and their advantages
	Ind3	Original equipment manufacturers for image sensors operating at various IR wavelengths
Institutional	Inst1	Implemented legal frameworks to regulate the delivery of digital identity services
	Inst2	Development of EU regulation for use of infrared facial images in passports
	Inst3	Equipment for IR face image acquisition and technical standards for related biometric sample quality

Continued on pg.124

Continued from pg.123

Capability domain	Abbreviation	Cluster-specific capability-related need
Technological Cluster D: Iris recognition in the NIR spectrum		
Research	Res1	EU-funded research focused on iris recognition in the NIR spectrum
Industrial	Ind1	Development of fast search engines suitable for performing identification in large-scale biometric databases
	Ind2	Optimum accuracy in place in NIR iris recognition
	Ind3	Standards (technical and operational) available, similar to e.g. ISO/IEC 29794-6 and 39794-6
	Ind4	Strong attack detection capabilities available
	Ind5	OEMs of mobile devices capable to acquire iris images in the NIR and process them to produce the respective biometric templates
Institutional	Inst1	Large biometric databases for identification integrated into large-scale IT systems
	Inst2	Social acceptance for NIR iris recognition technologies in EU
	Inst3	EU standardised digital travel documents containing iris biometric reference data
	Inst4	Regulatory framework and policy fully in place and widely accepted
Technological Cluster E: Iris recognition in the visible spectrum		
Research	Res1	Expert knowledge on AI software within the EU
	Res2	Research programmes focused on *Iris recognition in the visible spectrum* to overcome current limitations (e.g. improve the quality of dark eye iris samples and optimise the illumination wavelength)
Industrial	Ind1	Secure supply chain for camera components to be used in EU products
	Ind2	Development of specialised AI software (e.g. for post-processing of visible light iris images)
	Ind3	High-quality camera lenses at affordable prices
	Ind4	Sufficient supply of innovative light sources for visible spectrum (e.g. for illuminating the eyes discreetly, without negatively affecting image quality)
	Ind5	Guidelines and standards for assessing the operational performance of technological systems based on iris recognition
	Ind6	Increased accuracy in *Iris recognition in the visible spectrum* by using multimodal biometric solutions
Institutional	Inst1	Public awareness/education campaigns to increase social acceptance
	Inst2	Standardised digital ID solutions
	Inst3	Regulations for adequate and safe use of *Iris recognition in the visible spectrum* within systems
	Inst4	Eye-safe devices for iris imaging in the enrolment phase (e.g. a kind of standardised "head mounted" device)

Step 4 – Assessment of capability readiness

Capability readiness defines the degree to which cluster-specific needs are met, or are foreseen to be met. Thus, the analysis points to possible gaps and opportunities within the present and future capability landscape. The latter should be considered when performing the strategic planning for the implementation of border check systems based on the key technological clusters.

To assess capability readiness, during the *Second Technology Foresight Workshop* the Group of Experts was asked to evaluate the identified capability-related needs for each key technological cluster (Table 36) by specifying whether a need is “fully met”, “partially met" or "unmet". Each timeframe until the ETM within each KTC (present, 2022-2027 and 2028-2033[61]) was considered separately within each of the four scenarios. The results were shown on a 5-colour scale[62] to account for in-between values. To validate the outcomes of the *Second TF Workshop*, the Research Team re-assessed both the capability-related needs and the corresponding ratings of capability readiness. Where necessary, missing assessments were added.

Since multiple needs can be associated with each of the first-level capability domains (research, industrial, institutional), averaging the diverse degrees of fulfilment across all associated needs within a domain would not be very insightful. Instead, all needs (and associated capability domains) were listed individually and treated as equally important. However, a prioritisation of capability-related needs and capability domains is highly recommended to fine-tune the strategic development of key technological clusters according to Frontex's needs. Details of this prioritisation process are described in Step 6. To obtain a comprehensive overview of capability readiness for each KTC, heatmaps were produced (Table 37 to Table 41) to show capability readiness within the capability domains at a glance, without omitting information about individual needs.

The heatmaps indicate the present degree of need fulfilment and the projected level of fulfilment under the conditions of the four scenarios.[63] In all timeframes, red areas indicate the largest disparity between identified needs and existing or projected capabilities. Therefore, they are characterised by a low capability readiness and represent **capability gaps**. Green areas show **opportunities** (reflected by a high capability readiness), indicating needs that are already fully met or will be met in the future. It should be emphasised that the gaps and opportunities discussed in this chapter are related to capabilities and thus are not similar to the opportunities and challenges described in Chapter 8. The abbreviations used for the capability-related needs (e.g. Res1) are explained in Table 36.

61 Under the assumption that once a biometric TC has entered the mainstream (at the ETM) it will be available for implementation in border check systems and therefore will not require any further capability development, the long-term timeframe (2034-2040) was eliminated from the capability mapping exercise, as all five KTCs demonstrate an average ETM before 2033 (see Table 17).

62 The colour scale ranges from green, through yellow to red — representing "fully met", "partially met" and "unmet" respectively.

63 Scenarios were customized and described for 2040 only; however, during the customization process of the scenario, context conditions (e.g. social and economic) that were prospected in the short- medium- and long-term to lead up to the scenarios in 2040 (see Section 5.2) were described to the Group of Experts and used in the capability mapping accordingly.

Table 37: *Heatmap of capability readiness for KTC A: Contactless friction ridge recognition.*

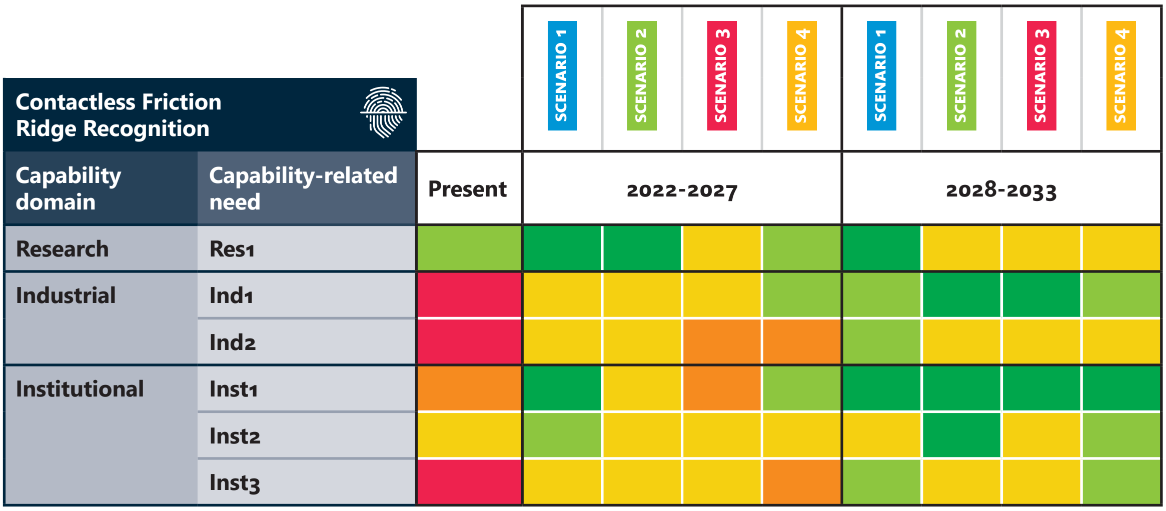
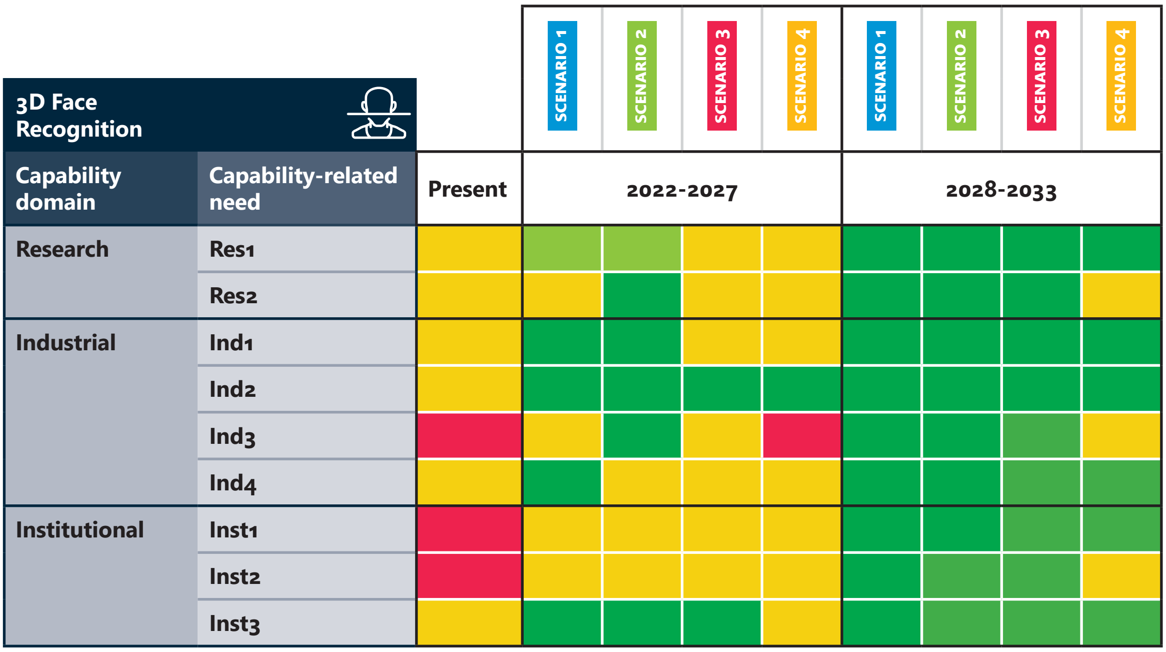


Table 38: *Heatmap of capability readiness for KTC B: 3D face recognition.*



Legend
Needs are/will be: Not met at all — Partially met — Completely met

Table 39: *Heatmap of capability readiness for KTC C: Infrared face recognition.*

Infrared Face Recognition											
			SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Capability domain	**Capability-related need**	**Present**	**2022-2027**				**2028-2033**			
Research	Res1									
Industrial	Ind1									
	Ind2									
	Ind3									
Institutional	Inst1									
	Inst2									
	Inst3									

Table 40: *Heatmap of capability readiness for KTC D: Iris recognition in the NIR spectrum.*

Iris recognition in the NIR spectrum										
			SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Capability domain	**Capability-related need**	**Present**	**2022-2027**				**2028-2033**			
Research	Res1									
Industrial	Ind1									
	Ind2									
	Ind3									
	Ind4									
	Ind5									
Institutional	Inst1									
	Inst2									
	Inst3									
	Inst4									

Legend
Needs are/will be: Not met at all — Partially met — Completely met

Table 41: *Heatmap of capability readiness for KTC E: Iris recognition in the visible spectrum.*

Iris recognition in the visible spectrum											
			SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Capability domain	**Capability-related need**	**Present**	**2022-2027**				**2028-2033**			
Research	**Res1**									
	Res2									
Industrial	**Ind1**									
	Ind2									
	Ind3									
	Ind4									
	Ind5									
	Ind6									
Institutional	**Inst1**									
	Inst2									
	Inst3									
	Inst4									

Legend
Needs are/will be: Not met at all — Partially met — Completely met

For the interpretation of results, certain limitations of the data should be taken into account:

- All data is based on input provided by participants in the *Second TF Workshop*. During the workshop participants had limited time for the activities, which naturally limited the amount of input.
- Not all participants provided assessments of all capability-related needs.

Hence, when interpreting the data, one needs to consider the workshop format, the specific composition of the Group of Experts who participated and the time available to them. The results reflect the participants' diverse expertise and inputs but do not purport to represent an exhaustive list of capability-related needs or capability readiness assessments within the key technological clusters, and may show some inconsistencies across the TCs. For example, the *AI software knowledge within the EU* mentioned in TC E is most likely also relevant for TC D but was not specifically mentioned there. Furthermore, it could be argued that strong presentation attack detection capabilities within the industry domain would require an equivalent academic capability that the workshop participants did not add.

The conclusions that can be drawn from the above results, with particular emphasis on capability gaps and opportunities, are described in Step 5 below.

Step 5 – Identification of capability gaps and opportunities

The heatmaps of capability readiness (see above) show gaps and opportunities for each technological cluster. The readiness cells marked in red (meaning capability-related need considered "unmet") correspond to *capability gaps*, while the dark green ones (capability-related need considered "fully met") correspond to *capability opportunities*.

The heatmap helps identify the capability-related needs that are expected to be met at a certain point in the future, as well as those that require active future development to fill the expected gaps. Only when the gaps are filled are the needs satisfied and can the associated capabilities be used for the realisation of the future target state.

The gaps and opportunities visible in the heatmaps vary across the four scenarios. The scenarios assume different conditions for the future of travel, e.g. varying degrees of international stability or a varying level of EU economic development. Thus, when planning capability development in an effort to close gaps and benefit from the opportunities, the assessments of all four scenarios should be considered. The resulting strategy will be future-proof and resilient if either of the underlying trends materialises in the coming years.

The outcomes (capability opportunities and gaps) of this step are summarised in the following paragraphs. Some of the five clusters show a very coherent picture in terms of capability readiness, while others present a rather mixed one. Where possible, joint conclusions were drawn for all clusters. The analysis focuses more on gaps than on opportunities, as the existence of gaps indicates that certain actions are required to ensure the sufficient development of a given technological cluster. Opportunities, on the other hand, can be regarded as additional information without an immediate need for action: a technological cluster showing many opportunities can be developed faster and with less effort since the capabilities either are already in place (with sufficient capability readiness) or are expected to be in place in the future.

Capability Opportunities

The (dark) green areas of the heatmaps display capability opportunities, which are apparent where KTCs show above a "partially met" capability readiness regardless of the scenarios. This happens for the majority of capability-related needs and can be summarised as follows:

- **Technological cluster A (*Contactless friction ridge recognition*)**
  For this TC only two specific capability-related needs show opportunities:
  - Ind1: Technological solutions for fast acquisition of high-resolution images;
  - Inst1: Full compliance with EU regulations.
- **Technological cluster B (*3D face recognition*) and D (*Iris recognition in the NIR spectrum*)**
  - Many opportunities (e.g. Res1 in KTC B: Datasets of 3D face biometric data for the performance evaluation of biometric systems, and Inst1 in KTC D: Large biometric databases for identification integrated into large-scale IT systems) are displayed for technological clusters B and D in all domains (research, industry and institutional), regardless of the scenario.
  - Cluster D appears to have good capability conditions slightly earlier (beginning in 2022) than Cluster B (starting in 2028).

- **Technological cluster C (*Infrared face recognition*)**
  The development of capabilities for technological cluster C looks promising in scenarios 1 and 2 in all domains, beginning in 2022 within scenario 1 and in 2028 within Scenario 2, i.e.:
  - research, e. g. Res1: Evaluation of the performance of AI-assisted recognition methods applied to facial images acquired under different illumination conditions and wavelengths;
  - industrial, e. g. Ind2: Knowledge of promising use cases and their advantages;
  - institutional, e. g. Inst2: Development of EU regulation for use of infrared facial images in passports.
- **Technological cluster E (*Iris recognition in the visible spectrum*)**
  - The development of capabilities for technological cluster E looks promising beyond 2028, since by that date all institutional-related needs are expected to be met, regardless of the scenario, as are research-related needs (except in scenario 3 – Res1: Expert knowledge on AI software within the EU).
  - Industrial capability readiness after 2028 also looks promising in scenarios 1-3.

Capability Gaps

Capability gaps arise whenever needs are unmet. They require more detailed analysis, as the associated capabilities cannot develop without additional actions that would ensure the sufficient fulfilment of needs. If no steps are taken to close the gaps, significant difficulties in the development of a technological cluster could ensue. Therefore, identifying and tackling capability gaps is crucial in capability-based planning and will thus need to be closely scrutinised by Frontex in any follow-on activities. Gaps identified for each of the key technological clusters are:

- **Technological clusters A (*Contactless friction ridge recognition*) and E (*Iris recognition in the visible spectrum*)**
  - At present, both clusters display many gaps in industry (e.g. Ind 1 – Technological solutions for fast acquisition of high-resolution images in TC A and Ind 1 – Secure supply chain for camera components to be used in EU products in TC E) and institutions.
  - In the case of Cluster E, gaps are present even in research (Res 1 – Expert knowledge on AI software within the EU).
  - However, given the assumption that research is being directed towards these gaps, it is expected that a significant number will be closed in the second timeframe (by 2027). As with all the underlying assumptions behind this assessment, any capability gap will have to be carefully monitored to define whether the respective TC is feasible or should not be pursued further.
  - Only one capability need in TC E (Ind1 – Secure supply chain for camera components to be used in EU products) seems to display a considerable gap across all scenarios in the first timeframe (the same is true for Ind2 under Scenarios 3 and 4 in Cluster A), which is however on a good path to closure in the second timeframe.
  - For TC E, in general terms, in the first timeframe industrial capability readiness seems more critical than research or institutional readiness.
  - In Cluster A, industrial and institutional capability readiness (in most scenarios) show a certain need for action, but a tendency towards resolving

the deficits can be seen across all needs in the second timeframe, and thus the gaps seem less critical in the longer term.

- **Technological clusters B (*3D face recognition*) and D (*Iris recognition in the NIR spectrum*)**
  - Both clusters display some gaps at present (one in industry and two in institutions for each cluster). These gaps are rapidly closing in the first timeframe (2022-2027), and practically all needs are fulfilled in the second timeframe (2028-2033).
  - This is the case for all four scenarios, leading to the conclusion that irrespective of the future scenario, no criticalities are foreseen from a capability point of view.
- **Technological cluster C (*Infrared face recognition*)**
  - This cluster shows only two gaps in the present state (Ind3 and Inst1), but they are sustained throughout both future timeframes in two of the four scenarios (scenario 1 and 2).
  - In addition, more gaps are displayed in the first timeframe, one of which is maintained in the second timeframe.
  - Thus, if for example the third scenario can be regarded as suitable for future development by Frontex, a thorough identification and analysis of the related capability gaps will be necessary and actions to close the gaps will be required.

Overall, once the prioritisation of capability gaps and opportunities (Step 6) is complete, it is recommended to revisit the heatmaps and identify and analyse the root causes of the highly prioritised gaps and opportunities in further detail. Thus, more precise conclusions can be drawn, which can serve as a foundation for the development of forward-looking strategies and respective actions.

Step 6 – Prioritisation of capability gaps and opportunities

Steps 6 and 7 are not part of the present Research Study and are included as a recommended approach. These two steps constitute the beginning of capability-based planning and are highly dependent on the needs of a particular organisation. Therefore, their exact implementation lies with Frontex.

The outcome of Step 5 provides a clear overview of gaps and opportunities, with a particular focus on the individual needs of each technological cluster.

The 7-step approach selected for capability mapping in the present study provides Frontex with information that constitutes the basis for prioritising capability-related needs (representing either gaps or opportunities) in strategic planning, taking into account Frontex-specific requirements, which is the key aspect of Step 6. The recommended method for the prioritisation of capability-related needs is the *Weighted Criteria Matrix* (an example is shown in Table 42). The criteria (e.g. *expected level of own influence*, *sufficient knowledge available*, etc.) to be applied are highly individual to each organisation. They should evaluate the impact of a capability-related need (which might appear as a capability gap or opportunity as seen in Step 5) on the organisation's capability development planning.[64]

The outcome of Step 6 would be a ranking of the listed capability-related needs, for each of the technological clusters, in terms of their priority level (the Weighted Sum in the respective Weighted Criteria Matrix).

Table 42: *Example of a Weighted Criteria Matrix.*

		Research				Industrial				Institutional			
Frontex requirements (criteria)	**Weight of criteria**	**Res1**	**Res2**	**Res3**	**...**	**Ind1**	**Ind2**	**Ind3**	**...**	**Inst1**	**Inst2**	**Inst3**	**...**
Criterion 1	1	5	3	4		3	3	4		5	2	5	
Criterion 2	4	3	5	3		1	2	2		2	4	3	
Criterion 3	5	4	5	4		4	5	1		5	4	5	
...	2	5	1	4		1	5	5		2	1	1	
Criterion n	4	1	4	1		1	4	4		5	3	3	
Sum		**18**	**18**	**16**		**10**	**19**	**16**		**19**	**14**	**17**	
Weighted Sum		**51**	**66**	**48**		**33**	**62**	**43**		**62**	**52**	**56**	

Step 7 – Mapping of prioritised gaps and opportunities
During Step 7, the prioritised gaps and opportunities are to be integrated into the capability development planning. The aim is to define prioritised capability goals (based on the prioritised capability-related needs) and timelines for Frontex to address them. This step is the beginning of capability-based planning. It visualises the strategic development paths for capabilities that are highly related to the individual needs of a given organisation. Therefore, like Step 6, this step is mentioned only for the sake of completeness, but will have to be performed by Frontex based on the outcomes of the previous steps.

9.3. Capability Mapping: conclusions and take-aways

The number of key players in the domains of research, industry and institutions identified through capability mapping suggests that overall, technological clusters A (*Contactless friction ridge recognition*), B (*3D face recognition*) and C (*Infrared face recognition*) are better equipped in terms of academic and industrial capability readiness within the EU than clusters D (*Iris recognition in the NIR spectrum*) and E (*Iris recognition in the visible spectrum*).

However, the second set of information, devoted to capability readiness, stresses the necessity to analyse cluster-specific needs and the estimated degree of their fulfilment

64 For further details on the Weighted Criteria Matrix tool, see the explanation in Annex I – Technology Foresight Manual – Chapter 15.

by current capabilities before conclusions can be drawn. At present, the majority of industrial and research capability readiness does not seem to be sufficient in any cluster (with the exception of research capability readiness in Cluster A). Fortunately, most of those needs are expected to be met by 2027 or 2033 at the latest. Scenarios 1 and 2 seem to be more conducive to the development of the key technological clusters than Scenarios 3 and 4.

From a needs perspective, the results seem to be most favourable for technological clusters B (*3D face recognition*) and D (*Iris recognition in the NIR spectrum*), closely followed by Cluster E (*Iris recognition in the visible spectrum*). The three clusters display good capability readiness by the year 2033.

The results provide a solid foundation for strategic decision-making, which should carefully consider the identified gaps. The related capability domains can be targeted selectively to close the gaps, and thus the objectives (as outlined in Table 35) for each technological cluster can be reached.

In summary, when performing capability-based planning, it is not sufficient to determine the number of key players and their capabilities within capability domains (research, industry and institutions). While this may give the first indication of baseline capabilities, it is necessary to analyse whether these capabilities meet the identified needs for the development of each technological cluster. In addition, any assumptions on future capability readiness levels should be closely monitored, on the one hand, to track which scenario best matches the materialising trends and on the other 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.

10. Conclusions

This Research Study describes the *Technology Foresight on Biometrics for the Future of Travel*. A custom Technology Foresight methodology was developed for the purposes of the study and was outlined in the accompanying Technology Foresight Manual. The Manual opens the door to the exploration of the vast field of biometric technologies, which was analysed from various perspectives in the context of border checks. Frontex can use the resulting extensive set of information to inform future strategic decision-making on the application of biometric technologies in border checks. The insights can support Frontex in prioritising research directions and investment decisions by transforming these insights into actionable implementation measures.

Overall, five key technological clusters (KTCs) were identified as most relevant:

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

More specifically, each of the phases of this complex Research Study produced its own set of insights with the intention of supporting Frontex and the entire EBCG community in decision-making processes that exploit opportunities, mitigate associated threats and result in the implementation of new biometric technologies and biometrics-enabled technological solutions. A summary of these insights is provided in this chapter.

The developed taxonomy of biometric technologies provides a systematic overview of this broad field of research. The scope of analysis was limited to the technologies that could potentially be applied in border checks, biometric recognition and access control. In the future, the taxonomy can serve as a tool for the classification of biometric technologies relevant to border checks. It can be employed to determine their placement within the hierarchy of associated research fields and facilitate the identification of relevant keywords and literature resources.

A taxonomy of biometrics-enabled technological systems was also constructed to accommodate the various uses of biometric technologies within systems. Particular focus was placed on the traveller experience and their interaction with the biometric solutions at various stages of a journey. Both taxonomies may be used and further developed by the EBCG community.

Patentometric and bibliometric analyses were performed for the 20 technological clusters deemed crucial for border checks. These analyses provided information, e.g. regarding the stage of a TC's lifecycle, the geographic distribution of inventive activities and the most active entities in producing inventions and scientific publications. Relevant EU-funded projects were also identified and analysed to assess EU interest in technological clusters and provide an overview of EU-funded R&I activity.

To identify the most promising biometric technological clusters, a *Delphi Survey* was conducted. A security analysis and a needs analysis served as additional filters for this prioritisation step. The *Delphi Survey*, during which the Relative Advantage and Earliest Time to Mainstream parameters were assessed, led to the construction of a 4CF Matrix, and thus to the selection of the five most promising technological clusters out of the 20 initially identified. Several conclusions can be drawn from the 4CF Matrix:

1. The five KTCs are all located in the "Squalls" quadrant of the 4CF Matrix, a clear indication that their importance should not be underestimated in strategic plans. However, the placement of the other 15 technological clusters on the 4CF Matrix is equally important.
2. Extreme caution should be applied when pursuing clusters that ended up in the "Sirens" quadrant: such a decision should be accompanied by further investigation to address the issues which resulted in such placement. The goal should be to introduce changes that would lower the ETM or increase the RA before committing further resources to development or implementation. These KTCs might display certain advantages in niche applications or enhance systems that use other technologies, but caution is advised.
3. Technological clusters in the "Coral reef" quadrant are a less risky direction, but careful verification is required to analyse whether the relatively low ETMs are in fact achievable. If the ETM increases, these technologies would shift to the hazardous "Sirens" quadrant, meaning that by the time they are ready for mainstream introduction, superior alternatives might exist.
4. Very few technological clusters were placed in the "Pirate treasure" quadrant. Despite the high RA values of these clusters, caution is also advised when considering them because the high ETMs carry risks related to the uncertainty of distant time horizons — the strategic environment may change, and more advanced technologies may be introduced. If lowering the ETM is not possible and the "Pirate treasure" technologies are pursued, it is advised to introduce a Strategic Early Warning System (SEWS), which detects changes in the strategic environment by continuous scanning for even minor signals of change.

Four scenarios reflecting alternative realities (in terms of politics, economy, society, technology, law and environment) were selected and customised. Opportunities and threats related to the future development of the key technological clusters were identified. The scenarios were used to stress-test the biometric technologies of interest. The analysis provided preliminary results showing whether the conditions of a particular scenario would hinder the developments within a given biometric cluster. In general, a cluster's lack of compatibility with certain scenarios can reveal technologies that might be impossible to future-proof because of fundamental incompatibilities with certain future developments. This does not mean that they cannot be pursued, but such cases require a more detailed risk assessment and, preferably, the introduction of a SEWS. 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. Clusters that would perform well regardless of the scenarios are *Contactless friction ridge recognition*, *Infrared face recognition* and *Iris recognition in the NIR spectrum*.

During the roadmapping phase, the future-proofing analysis of the five key clusters continued. The goal was to obtain a comprehensive overview of the factors that could influence specific developments and the extent of that influence. The roadmaps contain the possible functions, products and applications of each cluster in the short, medium and long term within the 2021-2040 timeframe. They can be used as input to further strategic planning.

Roadmapping revealed that the *3D face recognition technological* cluster is highly sensitive to future conditions. Such a result contrasts with the initial assumption of high immunity. Nonetheless, the preliminary assessment of the 20 biometric clusters under the conditions of the four scenarios appears to provide relatively accurate insights as to the impact of external conditions on technological developments – assessments for four of the five KTCs were comparable with the results of the roadmapping analysis. However, an in-depth future-proofing analysis (such as the one performed in roadmapping) is necessary to provide a deeper understanding of the impact of external factors on each technological cluster.

Capability mapping conducted parallel to the aforementioned roadmapping provided information on existing and expected research, industrial and institutional capability readiness within the EU for the five KTCs. It pointed towards opportunities and gaps in the capability landscape, focusing on cluster-specific capability-related needs. The results were presented as heatmaps that reflect capability readiness in the context of the four customised scenarios. The heatmaps indicated that the overall capability readiness for *Contactless friction ridge recognition* and *Infrared face recognition* is significantly lower than for the other three KTCs. *3D face recognition* and *Iris recognition in the NIR spectrum* have the highest overall capability readiness, closely followed by *Iris recognition in the visible spectrum*, so they seem favourable from a capability point of view. However, capability gaps that need to be addressed belong to the industrial and institutional domains in the case of two KTCs (*3D face recognition* and *Iris recognition in the NIR spectrum)* and to the research, industry and institutions domains in the case of *Iris recognition in the visible spectrum*. Combined with the information on research and industrial inventive activities within the EU (generated in the patentometric and bibliometric analyses), the results constitute a robust set of information that can serve as the basis for planning capability-building actions.

Apart from the direct outcomes, which are highlighted above and described in detail in respective chapters, the Research Study resulted in a number of deliverables that 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**, which accompanies this Research Study (Annex I), provides a thorough explanation of the Technology Foresight process, customised to the needs of the project with future implementations in mind, as well as the methods and tools adopted. It can be used to conduct a similar study on a different topic, to analyse newly identified technologies in a comparable manner or to conduct an in-depth analysis of the technological clusters identified as non-key within the present study.
- 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 on 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). It can also be used to track the impact of technological advances and other factors on the placement of technologies on the Matrix, and thus to monitor the evolving strategic recommendations regarding further investments in research or implementation.
- The **set of roadmaps** developed for the KTCs can be used as a starting point for further analysis of these clusters' development paths, monitoring associated opportunities and threats and questioning the assumptions of underlying strategic plans. The collected insights should undergo further analysis and can be reviewed cyclically to account for decisions made and for the occurrence of external events that might impact the course or nature of the original roadmap projections.
- The **capability readiness heatmaps** show a comprehensive overview of the extent to which cluster-specific needs are met at present or will be fulfilled in the future. They can be used by the EBCG community to identify the actions necessary for strategic capability development. The primary focus should be on those cluster-specific requirements that show the lowest capability readiness – the capability gaps. All identified gaps should be considered, regardless of the scenarios in which they appear. Such an approach ensures a robust capability development strategy, resistant to any future scenario.

In conclusion, the information obtained during this Research Study provides multiple opportunities for the further fruitful use of the findings, in this and other contexts. It is hoped that not only Frontex, but the entire European Border and Coast Guard community can take stock of the results. Due to the substantial amount of information provided and the adopted participatory foresight approach, the Research Study will directly contribute to an enhanced understanding of the relevance and applicability of foresight for strategic planning and forward-looking decision-making within the EBCG community.

The authors believe that a thorough analysis of the output will reveal that its benefits extend far beyond the immediate value of the presented 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 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. Furthermore, the Research Team believes that the findings of this Research Study 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.

Appendix 1 – List of main areas of research in biometrics

Table 43: *Main areas of research within biometrics.*

Research Area	Short description	Category	Estimated current TRL	Status TRL ≥5: Existing TRL < 5: Emerging	Potential applications in the context of border checks and other market segments *Scope of application/market segments*		
					Public security	Other public or business services	Consumer
Biometrics-based contactless technologies	Contactless techniques for biometric recognition	Biometric Technology	5-7	Existing	Border checks	Physical access control	Other services
Somatotype recognition	Recognition of individuals based on somatotype analysis	Biometric Technology	3-4	Emerging	Border checks Forensics	Health diagnosis	
DNA biometrics	Recognition of individuals based on DNA analysis	Biometric Technology	8-9	Existing	Forensics	Healthcare	
Face recognition	Recognition of individuals based on face images in 2D, 3D, infrared spectrum, visible spectrum	Biometric Technology	6-9	Existing	Border checks	Physical access control	M-Commerce
Fingerprint recognition	Recognition of individuals based on analysis of fingerprints	Biometric Technology	8-9	Existing	Border checks Forensics	Physical access control	M-Commerce
Gait recognition	recognition of individuals based on analysis of gait	Biometric Technology	5-7	Existing	Border checks Forensics		
Hand geometry recognition	Recognition of individuals based on image of hand (shape, palm and dorsal) geometry	Biometric Technology	8-9	Existing	Border checks	Physical access control Attendance tracking	
Iris recognition	Recognition of individuals based on analysis of iris pattern	Biometric Technology	8-9 (for NIR) 3-5 (for visible spectrum)	Existing (NIR) Emerging (Visible spectrum)	Border checks	Physical access control Healthcare	Retail banking
Keystroke recognition	Recognition of individuals based on analysis of keyboard typing pattern	Biometric Technology	5-7	Existing		E-learning	Retail banking
Vascular pattern recognition	Recognition of individuals based on palm vein, finger vein, wrist vein	Biometric Technology	8-9	Existing	Border checks Forensics	Physical access control	Retail banking
Speaker recognition	Recognition of individuals based on voice analysis	Biometric Technology	8-9	Existing	Border checks Forensics	E-commerce	Retail banking
Periocular recognition	recognition of individuals based on analysis of periocular image (area near eye)	Biometric Technology	8-9	Existing	Border checks	Physical access control	
Eye movement scanning	Recognition of individuals based on the movement patterns of the human eye	Biometric Technology	8-9	Existing	Border checks	E-commerce	M-Commerce
Biometrics based on physiological signals	Recognition of individuals based on physiological signals, e.g. heartbeat, blood flow, wavelength absorption	Biometric Technology	3-5	Emerging	Border checks	Healthcare	

Research Area	Short description	Category	Estimated current TRL	Status TRL ≥5: Existing TRL < 5: Emerging	Potential applications in the context of border checks and other market segments *Scope of application/market segments*		
					Public security	Other public or business services	Consumer
Handwriting recognition	Recognition of individuals based on multi-dimensional signature analysis	Biometric Technology	8-9	Existing	Authorisation of documents		Retail banking
AI in biometric systems	Application of AI algorithms and methods in biometrics	Biometrics-enabling technology	8-9	Existing	Border checks	IT security	Retail banking
Detection of biometric data manipulation by AI	Methods and techniques to detect fake biometric data created and manipulated by AI	Biometrics-enabling technology	5-7	Existing	Border checks Document security	Physical access control	Other services
Biometric database construction	Rules and methods to create biometric datasets and databases	Biometrics-enabling technology	8-9	Existing	Large-scale IT systems		
Document security	Additional layers of document security – physical and electronic layers	Biometrics-enabling technology	8-9	Existing	Border checks		
Document verification and fraud detection	Methods for verification of document authenticity and detection of falsified documents	Biometrics-enabling technology	5-7	Existing	Border checks Document security		
Manipulation attack detection	Methods to detect manipulation of biometric data	Biometrics-enabling technology	3-5	Emerging	Border checks Document security		
Morphing Attack Detection (MAD)	Techniques to detect morphing attacks in face recognition	Biometrics-enabling technology	5-7	Existing	Border checks Document security		
Presentation Attack Detection (PAD)	Techniques to detect presentation attacks for all biometric modalities	Biometrics-enabling technology	8-9	Existing	Border checks		
Privacy enhancing technologies	Algorithms and techniques to increase the privacy of users of biometric systems	Biometrics-enabling technology	5-7	Existing	Border checks Biometric databases	Biometric databases	Biometric databases
Machine learning	Computer algorithms that improve automatically through experience and by the use of data	Biometrics-enabling technology	8-9	Existing	Wide range of applications	Wide range of applications	Wide range of applications
Image and video analysis	Application of image and video automated algorithms to better understand content of images	Biometrics-enabling technology	8-9	Existing	Wide range of applications	Wide range of applications	Wide range of applications
Biometric template protection	Techniques to make the original information stored in biometric templates inaccessible to unauthorised users	Biometrics-enabling technology	5-7	Existing	Border checks Biometric databases Document security		
Biometric information security	Algorithms and methods to secure biometric information	Biometrics-enabling technology	8-9	Existing	Border checks Biometric databases Document security	Wide range of applications	Wide range of applications

Research Area	Short description	Category	Estimated current TRL	Status TRL ≥5: Existing TRL < 5: Emerging	Potential applications in the context of border checks and other market segments *Scope of application/market segments*		
					Public security	Other public or business services	Consumer
Pattern recognition	Algorithms and methods for automated extraction and recognition of regularities (patterns) in data	Biometrics-enabling technology	8-9	Existing	Wide range of applications	Wide range of applications	Wide range of applications
Novel biometric modalities, algorithms and systems	Novel biometric modalities, algorithms and systems	Biometrics-enabling technology	5-7	Existing	Border checks Forensics	Wide range of applications	Wide range of applications
Biometric system performance measurement	Methods to measure and assess performance of biometric systems	Biometrics-enabling technology	8-9	Existing	Border checks Forensics	Wide range of applications	Wide range of applications
Bias in biometric systems	Methods to evaluate and to reduce bias in biometric systems	Biometrics-enabling technology	5-7	Existing	Border checks Forensics	Wide range of applications	Wide range of applications
Computer vision	Algorithms and systems for acquisition, processing and analysis of images to produce numerical or symbolic information	Biometrics-enabling technology	8-9	Existing	Wide range of applications	Wide range of applications	Wide range of applications
Biometric sensors	Hardware to capture biometric samples	Biometrics-enabling technology	8-9	Existing	Border checks Forensics	Wide range of applications	Wide range of applications
(Semi-) autonomous robotics embedding biometrics	Autonomous and semi-autonomous robotic systems using biometric technologies	Application	5-7	Existing	Border checks	Wide range of applications	Wide range of applications
ABC gates	Gates/systems for automated border control	Application	8-9	Existing	Border checks		
Automated biometric identification systems (ABIS)	Systems for automated biometric identification	Application	8-9	Existing	Border checks		
Automatic next-generation rapid handheld and mobile small-scale solutions for biometric recognition	Mobile (smartphone) and handheld solutions for biometric recognition	Application	5-7	Existing	Border checks		
Document readers	Components and sub-systems to read ID documents	Application	8-9	Existing	Border checks Document security Forensics		Retail banking
Multimodal biometric and biometric fusion	Algorithms and methods to create fusion engines for the dynamic combination of biometric modalities	Application	5-7	Existing	Border checks		
Self-service border check kiosks	Kiosks for automated border checks	Application	8-9	Existing	Border checks		
Systems for biometric acquisition/recognition from seated drivers	Systems for biometric acquisition and recognition from drivers seated inside cars	Application	8-9	Existing	Border checks		
3D systems	Methods and devices that use three-dimensional spatial information	Application	8-9	Existing	Wide range of applications	Wide range of applications	Wide range of applications

Appendix 2 – List of Stakeholders

Table 44: *List of stakeholders identified within this Research Study.*

Stakeholder	Country	Stakeholder category
Frontex Research and Innovation Unit (RIU)	Poland	EBCG community – Frontex
Frontex RIU – Border Security Observatory	Poland	EBCG community – Frontex
Frontex RIU – Technology and Innovation	Poland	EBCG community – Frontex
Frontex RIU – Standards and Capacity Development	Poland	EBCG community – Frontex
Frontex Centre of Excellence for Combating Document Fraud	Poland	EBCG community – Frontex
Frontex Fundamental Rights Office	Poland	EBCG community – Frontex
Frontex ETIAS Task Force	Poland	EBCG community – Frontex
Frontex Liaison Officers (FLOs)	Poland	EBCG community – Frontex
Border and Coast Guard Authorities of Austria	Austria	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Belgium	Belgium	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Bulgaria	Bulgaria	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Croatia	Croatia	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Cyprus	Cyprus	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of the Czech Republic	Czech Republic	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Denmark	Denmark	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Estonia	Estonia	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Finland	Finland	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of France	France	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Germany	Germany	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Greece	Greece	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Hungary	Hungary	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Ireland	Ireland	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Italy	Italy	EBCG community – Border and Coast Guard National Authority

Stakeholder	Country	Stakeholder category
Border and Coast Guard Authorities of Latvia	Latvia	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Lithuania	Lithuania	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Luxembourg	Luxembourg	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Malta	Malta	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of the Netherlands	Netherlands	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Poland	Poland	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Portugal	Portugal	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Romania	Romania	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Slovakia	Slovakia	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Slovenia	Slovenia	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Spain	Spain	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Sweden	Sweden	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Iceland	Iceland	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Liechtenstein	Liechtenstein	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Norway	Norway	EBCG community – Border and Coast Guard National Authority
Border and Coast Guard Authorities of Switzerland	Switzerland	EBCG community – Border and Coast Guard National Authority
Directorate-General Joint Research Centre (JRC), Directorate Space, Security and Migration	Belgium	EU Institution, Body or Agency
EU Innovation Hub for Internal Security	Netherlands	EU Institution, Body or Agency
European Data Protection Supervisor (EDPS)	Belgium	EU Institution, Body or Agency
Directorate-General Migration and Home Affairs (DG HOME), Directorate Borders, Interoperability and Innovation	Belgium	EU Institution, Body or Agency
European Research Council Executive Agency (ERCEA)	Belgium	EU Institution, Body or Agency
European Research Executive Agency (REA)	Belgium	EU Institution, Body or Agency
European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)	Estonia	EU Institution, Body or Agency
European Defence Agency (EDA)	Belgium	EU Institution, Body or Agency
European Union Agency for Fundamental Rights (FRA)	Austria	EU Institution, Body or Agency
European Union Agency for Law Enforcement Cooperation (Europol)	Netherlands	EU Institution, Body or Agency
International Civil Aviation Organization (ICAO)	Canada	International Organisation
INTERPOL (International Criminal Police Organization)	France	International Organisation

Stakeholder	Country	Stakeholder category
United States Department of Homeland Security – Customs and Border Protection	United States of America	Extra-EU Border Management Authority
Project iMARS	France	EU-funded R&I project
Project D4FLY	Germany	EU-funded R&I project
Project TRESSPASS	Greece	EU-funded R&I project
Project eBorder	Portugal	EU-funded R&I project
Project H-unique	United Kingdom	EU-funded R&I project
Project PROTECT	United Kingdom	EU-funded R&I project
T3K-Forensics	Austria	Industrial producer of systems and components
Regula Forensics	Belarus	Industrial producer of systems and components
Gambit	Canada	Industrial producer of systems and components
Phonexia	Czech Republic	Industrial producer of systems and components
Biometric Solutions A/S	Denmark	Industrial producer of systems and components
Milestone Systems	Denmark	Industrial producer of systems and components
Easier	France	Industrial producer of systems and components
Idemia	France	Industrial producer of systems and components
Sopra Steria	France	Industrial producer of systems and components
SURYS	France	Industrial producer of systems and components
Thales	France	Industrial producer of systems and components
Ubble	France	Industrial producer of systems and components
VFS Services Ltd	France	Industrial producer of systems and components
SURYS	France	Industrial producer of systems and components
Cognitec Systems	Germany	Industrial producer of systems and components
Dermalog	Germany	Industrial producer of systems and components
Desko	Germany	Industrial producer of systems and components
Giesecke+Devrient	Germany	Industrial producer of systems and components
Jenetric	Germany	Industrial producer of systems and components
Mühlbauer Group	Germany	Industrial producer of systems and components
Secunet Security Networks AG	Germany	Industrial producer of systems and components
Veridos GmbH	Germany	Industrial producer of systems and components
Acticom GmbH	Germany	Industrial producer of systems and components
Widas Technologie Services GmbH	Germany	Industrial producer of systems and components
Raytrix	Germany	Industrial producer of systems and components
UniSystems	Greece	Industrial producer of systems and components
Keyless Technologies	Italy	Industrial producer of systems and components
Leonardo	Italy	Industrial producer of systems and components
Mastek	Italy	Industrial producer of systems and components
Fujitsu	Japan	Industrial producer of systems and components
NEC	Japan	Industrial producer of systems and components

Stakeholder	Country	Stakeholder category
Biometría Aplicada, S.A. de C.V.	Mexico	Industrial producer of systems and components
Cosmocolor	Mexico	Industrial producer of systems and components
IQSec, S.A. de C.V.	Mexico	Industrial producer of systems and components
Sissa Monitoring Integral	Mexico	Industrial producer of systems and components
InnoValor	Netherlands	Industrial producer of systems and components
Mobai AS	Norway	Industrial producer of systems and components
ITTI	Poland	Industrial producer of systems and components
Vision-Box	Portugal	Industrial producer of systems and components
Innovatrics	Slovakia	Industrial producer of systems and components
FacePhi Biometrics	Spain	Industrial producer of systems and components
SICPA SA	Spain	Industrial producer of systems and components
Veridas Digital Authentication Solutions	Spain	Industrial producer of systems and components
IQUADRAT Informatica SL	Spain	Industrial producer of systems and components
Speed Identity	Sweden	Industrial producer of systems and components
BWO Systems	Switzerland	Industrial producer of systems and components
OVD Kinegram	Switzerland	Industrial producer of systems and components
TECH5	Switzerland	Industrial producer of systems and components
Selfmetric	Turkey	Industrial producer of systems and components
Access IS	United Kingdom	Industrial producer of systems and components
Aurora-AI	United Kingdom	Industrial producer of systems and components
Polygon	United Kingdom	Industrial producer of systems and components
Flight Solutions International Limited	United Kingdom	Industrial producer of systems and components
GBG	United Kingdom	Industrial producer of systems and components
I-Evo Ltd	United Kingdom	Industrial producer of systems and components
iBeta Quality Assurance	United Kingdom	Industrial producer of systems and components
IDGateway	United Kingdom	Industrial producer of systems and components
iProov Ltd	United Kingdom	Industrial producer of systems and components
L-3 Harris ASA	United Kingdom	Industrial producer of systems and components
Onfido	United Kingdom	Industrial producer of systems and components
Rapiscan Systems	United Kingdom	Industrial producer of systems and components
SITA	United Kingdom	Industrial producer of systems and components
SNC-Lavalin Atkins	United Kingdom	Industrial producer of systems and components

Stakeholder	Country	Stakeholder category
YOTI Ltd	United Kingdom	Industrial producer of systems and components
1Kosmos BlockID	United States of America	Industrial producer of systems and components
Aware, Inc.	United States of America	Industrial producer of systems and components
Bayometric	United States of America	Industrial producer of systems and components
Collins Aerospace	United States of America	Industrial producer of systems and components
Computer Projects of Illinois	United States of America	Industrial producer of systems and components
FaceTec	United States of America	Industrial producer of systems and components
Garud Technology Services	United States of America	Industrial producer of systems and components
HID Global	United States of America	Industrial producer of systems and components
Jumio	United States of America	Industrial producer of systems and components
Lapetus Solutions	United States of America	Industrial producer of systems and components
Leidos	United States of America	Industrial producer of systems and components
M2SYS	United States of America	Industrial producer of systems and components
Microsoft	United States of America	Industrial producer of systems and components
Mitek Systems	United States of America	Industrial producer of systems and components
MSite (Human Recognition Systems)	United States of America	Industrial producer of systems and components
Northrop Grumman	United States of America	Industrial producer of systems and components
Panoptic Systems Integration	United States of America	Industrial producer of systems and components
Princeton Identity	United States of America	Industrial producer of systems and components
Raytheon	United States of America	Industrial producer of systems and components
Tascent, Inc	United States of America	Industrial producer of systems and components
Trust Stamp	United States of America	Industrial producer of systems and components
WorldReach Software Corporation	United States of America	Industrial producer of systems and components
Salzburg University	Austria	Academic Institution
Katholieke Universiteit Leuven	Belgium	Academic Institution
Brno University	Czech Republic	Academic Institution
Palacký University Olomouc	Czech Republic	Academic Institution

Stakeholder	Country	Stakeholder category
Ecole Centrale de Lyon	France	Academic Institution
Eurecom	France	Academic Institution
Telecom Sud Paris	France	Academic Institution
Hochschule Ansbach	Germany	Academic Institution
Hochschule Bonn-Rhein-Sieg	Germany	Academic Institution
Hochschule Darmstadt	Germany	Academic Institution
Saarland University	Germany	Academic Institution
University of Bologna – Biometric System Laboratory	Italy	Academic Institution
University of Cagliari	Italy	Academic Institution
University of Sassari	Italy	Academic Institution
University of Groningen – Security, Technology and e-Privacy Research Group	Netherlands	Academic Institution
University of Twente	Netherlands	Academic Institution
Norwegian University of Science and Technology – Norwegian Biometrics Laboratory	Norway	Academic Institution
Gdańsk University of Technology	Poland	Academic Institution
Military University of Technology	Poland	Academic Institution
University Beira Interior	Portugal	Academic Institution
Laboratory for Multimedia Communications (Belgrade)	Serbia	Academic Institution
University of Ljubljana	Slovenia	Academic Institution
Universidad Autónoma de Madrid	Spain	Academic Institution
Universidad Carlos III de Madrid	Spain	Academic Institution
Halmstad University	Sweden	Academic Institution
University of Kent	United Kingdom	Academic Institution
University of Surrey	United Kingdom	Academic Institution
University of Reading	United Kingdom	Academic Institution
Lancaster University	United Kingdom	Academic Institution
Aberystwyth University	United Kingdom	Academic Institution
Bradford University	United Kingdom	Academic Institution
AIT	Austria	Research and Technology Organisation
IMEC	Belgium	Research and Technology Organisation
Estonian Forensic Science Institute	Estonia	Research and Technology Organisation
VTT Technical Research Centre of Finland	Finland	Research and Technology Organisation
Fraunhofer INT	Germany	Research and Technology Organisation
Fraunhofer IGD	Germany	Research and Technology Organisation
Fraunhofer Institute for Industrial Engineering IAO	Germany	Research and Technology Organisation
Fraunhofer HHI	Germany	Research and Technology Organisation

Stakeholder	Country	Stakeholder category
National Centre of Scientific Research "Demokritos"	Greece	Research and Technology Organisation
Consiglio Nazionale delle Ricerche (CNR)	Italy	Research and Technology Organisation
Baltic Institute of Advanced Technologies	Lithuania	Research and Technology Organisation
TNO – Nederlandse Organisatie voor Toegepast Natuur-wetenschappelijk Onderzoek	Netherlands	Research and Technology Organisation
Research and Academic Computer Network (NASK)	Poland	Research and Technology Organisation
Vicomtech	Spain	Research and Technology Organisation
Idiap Research Institute	Switzerland	Research and Technology Organisation
National Institute for Standards and Technology (NIST)	United States of America	Research and Technology Organisation
National Physical Laboratory (NPL)	United Kingdom	Research and Technology Organisation
International Air Transport Association (IATA)	Canada	Civil society and trade association
European Association for Biometrics (EAB)	Netherlands	Civil society and trade association
Biometrics Institute	United Kingdom	Civil society and trade association
British Standards Institution (BSI)	United Kingdom	Civil society and trade association
International Biometrics and Identity Association (IBIA)	United States of America	Civil society and trade association
Ormiston Consulting Services	Belgium	Consultant
Trilateral Research	United Kingdom	Consultant
Camtech Consulting	United Kingdom	Consultant
Critical Insights Consultancy	United Kingdom	Consultant
Eversheds Sutherland	United Kingdom	Consultant
ID Transnational Consultancy	United Kingdom	Consultant
JCour-Consulting	United States of America	Consultant
Proskauer Rose LLP	United States of America	Consultant
RAM Identity Strategies	United States of America	Consultant
ABC Inc.	United States of America	Consultant

Appendix 3 – List of attendees of the experts' consultation events conducted within this Research Study (First TF Workshop, Second TF Workshop and Delphi Survey)

Table 45: *List of attendees of the events of the Research Study (First TF Workshop, Second TF Workshop and Delphi Survey).*

No.	Stakeholder	Stakeholder Category	Country	No. of Experts	No. of participants to First TF Workshop	No. of participants to Second TF Workshop	No. of participants to Delphi Survey
1	Frontex RIU – Border Security Observatory	EBCG community – Frontex	Poland	6	6	6	6
2	Frontex RIU – Standards and Capacity Development	EBCG community – Frontex	Poland	2	1	2	2
3	Frontex RIU – Technology and Innovation	EBCG community – Frontex	Poland	1		1	
4	Frontex Centre of Excellence for Combating Document Fraud	EBCG community – Frontex	Poland	1	1	1	1
5	Belgian Federal Police	EBCG community – Border and Coast Guard National Authority	Belgium	1	1		1
6	Ministry of Interior of Estonia, IT and Development Centre	EBCG community – Border and Coast Guard National Authority	Estonia	1	1	1	1
7	Finnish Border Guard	EBCG community – Border and Coast Guard National Authority	Finland	1	1		
8	Ministry of Interior – DGPN/DCPAF	EBCG community – Border and Coast Guard National Authority	France	1	1	1	1
9	Information Centre of MOI	EBCG community – Border and Coast Guard National Authority	Latvia	1	1	1	
10	National Police Directorate of Norway	EBCG community – Border and Coast Guard National Authority	Norway	1	1	1	1
11	Poliția de Frontieră Română	EBCG community – Border and Coast Guard National Authority	Romania	1	1		1
12	Swiss Customs Administration	EBCG community – Border and Coast Guard National Authority	Switzerland	1	1	1	1
13	European Commission – DG HOME	EU Institution, Body or Agency	Belgium	1			1
14	European Commission – DG Joint Research Centre	EU Institution, Body or Agency	Italy	2	1	2	2

No.	Stakeholder	Stakeholder Category	Country	No. of Experts	No. of participants to First TF Workshop	No. of participants to Second TF Workshop	No. of participants to Delphi Survey
15	eu-LISA	EU Institution, Body or Agency	Estonia	2	1	2	1
16	Europol	EU Institution, Body or Agency	The Nether-lands	1	1	1	1
17	INTERPOL	International Organisation	France	1	1	1	1
18	ICAO – New Technologies Working Group	International Organisation	Singapore	1	1	1	1
19	U.S. Department of Homeland Security, Science and Technology Directorate	Extra-EU Border Management Authority	USA	1	1		
20	EU-funded Project – D4FLY – Veridos GmbH	Industrial producer of systems and components	Germany	1	1	1	1
21	EU-funded Project – D4FLY – Universi-ty of Reading	Academic Institution	UK	1	1	1	
22	EU-funded Project – D4FLY – Trilateral Research	Consultant	Ireland	1	1	1	1
23	EU-funded Project – eBORDER – Uni-versity of Bradford	Academic Institution	United Kingdom	1	1		
24	EU-funded Project – iMARS – Universi-ty of Twente	Academic Institution	Nether-lands	1		1	1
25	EU-funded Project – iMARS – Idemia	Academic Institution	France	1	1		
26	EU-funded Project – iMARS – KU Leu-ven Centre for IT & IP Law	Academic Institution	Belgium	1	1		
27	EU-funded Project – iMARS – EAB	Trade Association	France	1	1		
28	Norwegian University of Science and Technology	Academic Institution	Norway	1	1		1
29	Military University of Technology	Academic Institution	Poland	2	1	1	2
30	Halmstad University	Academic Institution	Sweden	1			1
31	IMEC	Research and Technology Organi-sation	Belgium	1	1	1	1
32	CNR-IIT	Research and Technology Organi-sation	Italy	1	1		1
33	Widas Technologie Services GmbH	Industrial producer of systems and components	Germany	1	1	1	1
34	Camtech Consulting	Consultant	United Kingdom	1	1	1	1

Appendix 4 – Taxonomy of biometric technologies

Figure 21: *Taxonomy of biometric technologies.*

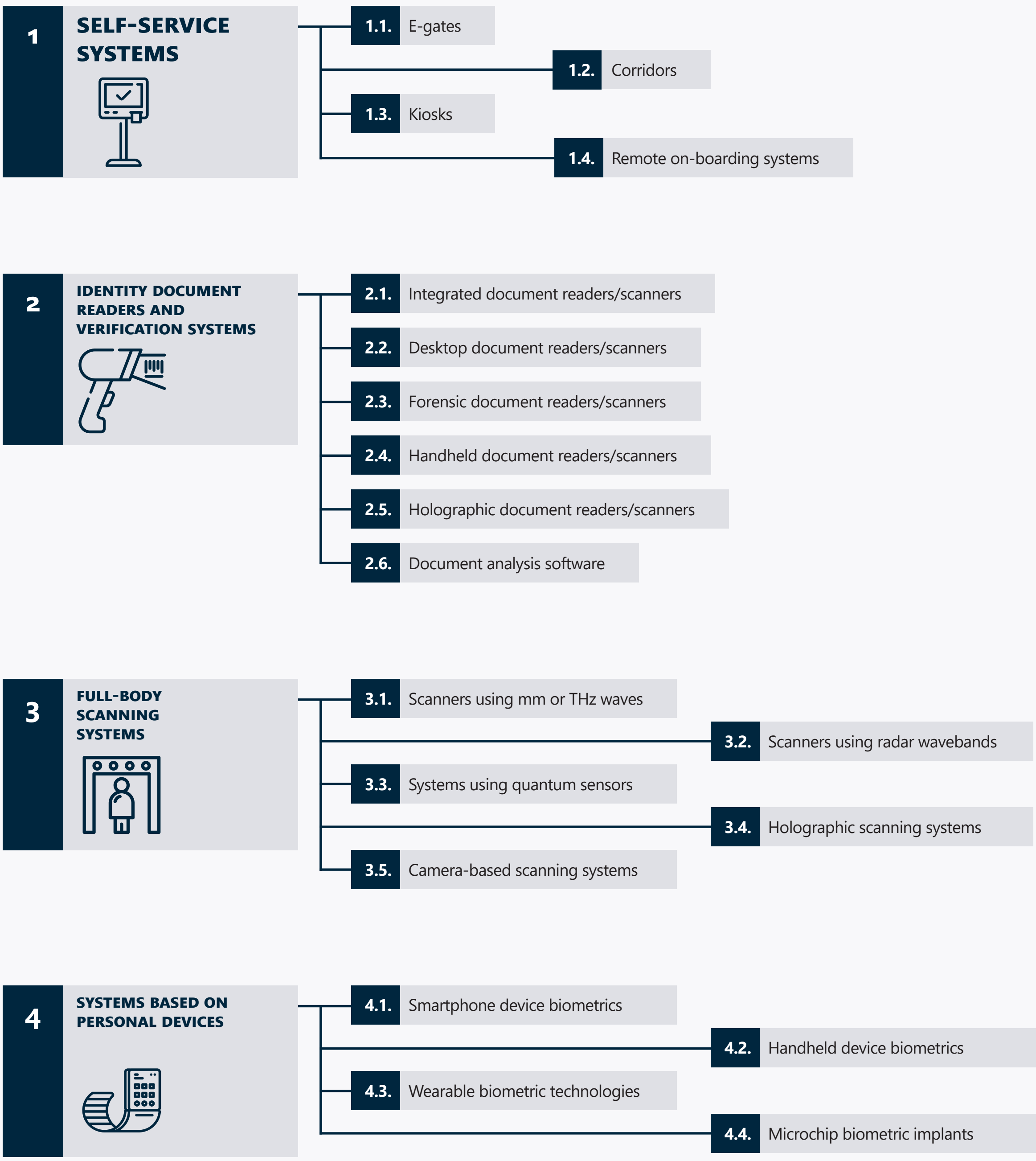
- **1 BIOMOLECULAR BIOMETRICS**
  - **1.1.** DNA biometrics
    - **1.1.1.** DNA phenotyping
    - **1.1.2.** DNA profiling
    - **1.1.3.** DNA sequencing
    - **1.1.4.** Techniques for collecting DNA samples
  - **1.2.** Other biomolecular biometrics
    - **1.2.1.** Hand bacteria identification
- **2 MORPHOLOGICAL BIOMETRICS**
  - **2.1.** Face recognition
    - **2.1.1.** Thermal infrared face recognition
    - **2.1.2.** Near-infrared face recognition
    - **2.1.3.** Video-based face recognition
    - **2.1.4.** Image-based face recognition
    - **2.1.5.** 3D face recognition
  - **2.2.** Friction ridge recognition
    - **2.2.1.** Thermal friction ridge recognition
    - **2.2.2.** Near-infrared friction ridge recognition
    - **2.2.3.** 3D friction ridge recognition
    - **2.2.4.** Contactless friction ridge recognition
    - **2.2.5.** Contact-based friction ridge recognition
    - **2.2.6.** Fingerprint recognition
    - **2.2.7.** Palmprint recognition
    - **2.2.8.** Footprint recognition
    - **2.2.9.** Finger-knuckle-print recognition
  - **2.3.** Iris recognition
    - **2.3.1.** Iris recognition in the NIR spectrum
    - **2.3.2.** Iris recognition in the visible spectrum
    - **2.3.3.** Iris recognition at a distance
  - **2.4.** Vascular pattern recognition
    - **2.4.1.** Retina recognition
    - **2.4.2.** Sclera/Episclera recognition
    - **2.4.3.** Finger vein recognition
    - **2.4.4.** Palm vein recognition
    - **2.4.5.** Back-of-hand vascular recognition
    - **2.4.6.** Wrist vein recognition
  - **2.5.** Physiological signals biometrics
    - **2.5.1.** Heart-rate variability
    - **2.5.2.** Electrocardiographic signals
    - **2.5.3.** Phonocardiographic signals
    - **2.5.4.** Photoplethysmographic signals
    - **2.5.5.** Encephalographic signals
    - **2.5.6.** Acoustic properties of the ear canal
  - **2.6.** Hand geometry recognition
    - **2.6.1.** Contact-based hand geometry recognition
    - **2.6.2.** Contactless hand geometry recognition
  - **2.7.** Other minor morphological biometrics
    - **2.7.1.** Dental biometrics
    - **2.7.2.** Tongueprint recognition
    - **2.7.3.** Ear print recognition
    - **2.7.4.** Periocular recognition
    - **2.7.5.** Skin texture recognition
    - **2.7.6.** Cranial suture scanning
    - **2.7.7.** Rugoscopy
    - **2.7.8.** MMW and THz wave body imaging

3 BEHAVIOURAL BIOMETRICS

- **3.1.** Keystroke recognition
  - **3.1.1.** Dynamic keystroke recognition
  - **3.1.2.** Static keystroke recognition
- **3.2.** Gait recognition
  - **3.2.1.** Gait recognition based on video sensors
  - **3.2.2.** Gait recognition based on radar sensors
  - **3.2.3.** Gait recognition based on floor sensors
  - **3.2.4.** Gait recognition based on wearable sensors
- **3.3.** Handwriting recognition
  - **3.3.1.** Dynamic handwriting recognition
  - **3.3.2.** Static handwriting recognition
- **3.4.** Speaker recognition
  - **3.4.1.** Text-dependent speaker recognition
  - **3.4.2.** Text-independent speaker recognition
  - **3.4.3.** Vocal resonance recognition
- **3.5.** Other minor behavioural biometrics
  - **3.5.1.** Complex eye movement patterns (eye-tracking)
  - **3.5.2.** Oculomotor plant characteristics

Appendix 5 – Taxonomy of biometrics-enabled technological systems

Figure 22: *Taxonomy of biometrics-enabled technological systems.*



5 MOVABLE SYSTEMS

- **5.1.** Mobile (non-autonomous) checkpoints
- **5.2.** Semi-autonomous robotic systems
- **5.3.** Autonomous robotic systems
- **5.4.** Systems for the seamless recognition of persons in transport

6 LARGE-SCALE IT SYSTEMS THAT DEPLOY BIOMETRIIC COMPARISON COMPONENTS

- **6.1.** Traveller information and entry-exit systems
- **6.2.** Visa and travel authorisation systems
- **6.3.** Biometric central databases for border control and law enforcement

7 VIRTUAL TRAVELLER IDENTITY SCHEMES FOR BIOMETRICS-ENABLED TECHNOLOGICAL SYSTEMS

- **7.1.** ICAO "Digital Travel Credential" (DTC)
- **7.2.** IATA "Travel Pass"
- **7.3.** WEF "Known Traveller Digital Identity"
- **7.4.** Proprietary schemes
- **7.5.** Digital Trust Frameworks

Appendix 6 – Glossary of basic terms and definitions

This section provides a concise list of basic terms and definitions regarding biometrics, EU border management and patents. It is not an exhaustive glossary, as its main purpose is to provide a description of some basic concepts and clarify the meaning of some of the terms used within this document.

The section is divided into the following two parts:

- **Terms and definitions related to biometrics and EU border management.** If not otherwise indicated, the following terms and definitions were extracted from the *Schengen Borders Code*[65] and the International Standard ISO/IEC 2382-37:2017,[66] where further details, concepts and definitions can be found.[67]
- **Terms and definitions related to patents.** If not otherwise indicated, the terms and definitions described in this part were extracted from EPO's online glossary[68] and USPTO's online glossary[69].

The following list of terms and definitions is presented in alphabetical order. Words that are in ***bold*** are defined in this list. Every time a word is written in *italic* in a term/definition, it means that its definition is also included in the list. Words that are not in bold neither italic are to be understood in their natural-language sense.

a) Terms and definitions related to biometrics and EU border management

- ***Access control***: refers to the mechanisms that monitor, prevent, and manage accesses to essential resources, from buildings to network data repositories.[70]
- ***Biometric*** (adjective): of, or having to do with, *biometrics*.
- ***Biometric acquisition process***: *biometric capture process* and additional processing to attempt to produce a suitable *biometric sample*(s) in accordance with the defined policy. In addition to the biometric capture process, a biometric acquisition process may include segmentation, quality control, and other pre-processing steps.

65 European Commission, Regulation (EC) No 562/2006 of the European Parliament and of the Council of 15 March 2006 establishing a Community Code on the rules governing the movement of persons across borders (Schengen Borders Code), 2006.

66 ISO, International Standard ISO/IEC 2382-37:2017 – Information technology – Vocabulary – Part 37: Biometrics, 2017.

67 Other relevant references regarding the subject field of biometrics that might be of interest to the reader are those in:
ISO, International Standard ISO/IEC 19795-1 to 10: Information technology – Biometric performance testing and reporting – Part 1 to Part 10, 2006.
ISO, International Standard ISO/IEC TR 24741:2018 – Information technology – Biometrics – Overview and application, 2018.

68 https://www.epo.org/service-support/glossary.html

69 https://www.uspto.gov/learning-and-resources/glossary

70 A. Alexandrou, "Physical Security: Interior Applications – Doors, Access Control", Encyclopedia of Security and Emergency Management, Springer International Publishing, 2018, pp. 1-8.

- ***Biometric capture***: obtaining and recording, in a retrievable form, signal(s) of *biometric characteristic*(s) directly from individual(s), or from representation(s) of *biometric characteristic*(s).
- ***Biometric capture process***: series of actions undertaken to affect a *biometric capture*. Process of collecting or attempting to collect a signal(s) from a biometric characteristic, or a representation(s) of a biometric characteristic(s), and converting the signal(s) to a captured biometric sample set.[71]
- ***Biometric capture subject***: an individual who is the subject of a *biometric capture process*.
- ***Biometric characteristic***: biological and behavioural characteristic of an individual from which distinguishing, repeatable *biometric features* can be extracted for the purpose of *biometric recognition*.
- ***Biometric claim***: claim that a *biometric capture subject* is or is not the bodily source of a specified or unspecified biometric reference.
- ***Biometric data***: *biometric sample* or aggregation of biometric samples at any stage of processing, e.g., biometric reference, biometric probe, *biometric feature*, or biometric property.
- ***Biometric data subject***: an individual whose individualised *biometric data* is within the *biometric system*.
- ***Biometric enrolment***: the act of creating and storing a *biometric enrolment data record* in accordance with an enrolment policy. The use of 'registration' as a synonym for 'enrolment' is deprecated since it has a different meaning in the signal processing community.
- ***Biometric enrolment data record***: data record attributed to a *biometric data subject*, containing non-biometric data, and associated with biometric reference identifier(s).
- ***Biometric feature***: numbers or labels extracted from *biometric samples* and used for comparison.
- ***Biometric identification***: process of searching against a *biometric enrolment database* to find and return the biometric reference identifier(s) attributable to a single individual.
- ***Biometric mode***: combination of a *biometric characteristic* type, a sensor type, and a processing method. Determining what constitutes a single type of sensor, processing method, or *biometric characteristic* will depend on convention. For example, current convention is that images of ridge patterns from both thumbs and fingers represent a single *biometric characteristic* type, i.e. fingerprints. With respect to sensors, infrared and visible bandwidth sensors are considered different types, but visible bandwidth sensors are considered a single type despite imaging red, green, and blue bandwidths.
- ***Biometric recognition (or biometrics)***: automated recognition of individuals based on their biological and behavioural characteristics. Biometric recognition encompasses *biometric verification* and *biometric identification*.
- ***Biometric reference***: one or more stored *biometric samples*, biometric templates or biometric models attributed to a *biometric data subject* and used as the object of biometric comparison.

71 C. Busch, "Standards for Biometric Presentation Attack Detection", Handbook of Biometric Anti-Spoofing. Advances in Computer Vision and Pattern Recognition., Springer, Cham, 2019.

- ***Biometric sample***: analogue or digital representation of *biometric characteristics* prior to *biometric feature* extraction.
- ***Biometric system***: a system for the purpose of the *biometric recognition* of individuals based on their behavioural and biological characteristics.
- ***Biometric verification***: process of confirming a *biometric claim* through biometric comparison.
- ***Biometrics***: automated recognition of individuals based on their biological and behavioural characteristics. The terms 'biometrics' and '*biometric recognition*' can be considered synonyms. The more general meaning of biometrics encompasses counting, measuring and statistical analysis of any kind of data in the biological sciences including the relevant medical sciences.
- ***Border check***: check carried out at *border crossing points* to ensure that persons, including their means of transport and the objects in their possession, may be authorised to enter the territory of the Member States, or authorised to leave it.
- ***Border control***: activity carried out at a border, in accordance with and for the purposes of the Schengen Borders Code, in response exclusively to an intention to cross or the act of crossing that border, regardless of any other consideration, consisting of *border checks* and *border surveillance*.
- ***Border crossing point***: any crossing-point authorised by the competent authorities for the crossing of *external borders*.
- ***Border surveillance***: surveillance of borders between *border crossing points* and the surveillance of *border crossing points* outside the fixed opening hours in order to prevent persons from circumventing *border checks*.
- ***Emotion analysis***: also referred to as "emotion detection" or "emotion recognition", is the task of processing a specific stream of *biometric data* of an individual in order to classify the underlying emotional state.[72]
- ***External borders***: the Member States' land borders, including river and lake borders, sea borders and their airports, river ports, sea ports and lake ports, provided that they are not *internal borders*.
- ***First-line check***: *border checks* on persons carried out at EU *external borders* may be divided into two stages: every person undergoes a first-line check to verify entry requirements. As a general rule, persons may remain inside their vehicle during such checks, unless circumstances require otherwise. At land and sea borders, Article 9 of the Schengen Borders Code encourages the creation of separate lanes, either designated for EU, European Economic Area (EEA), and Swiss nationals or for travellers from other countries. If a more thorough verification is required, a passenger is referred for a *second-line check*, usually carried out in special rooms or offices. After a first- or a second-line check, travellers may be allowed to enter the country or be refused entry and told to return to the country from which they came.[73]

72 S. Xefteris, "Behavioral Biometrics in Assisted Living: A Methodology for Emotion Recognition", Engineering, Technology & Applied Science Research, vol. 6, no. 4, pp. 1035-1044, 2016.

73 European Union Agency for Fundamental Rights, "Fundamental rights at land borders: findings from selected European Union border crossing points", Luxembourg, Publications Office of the European Union, 2014.

- ***Internal borders***: include the common land borders (including river and lake borders) of the Member States; the airports of the Member States for internal flights; sea, river and lake ports of the Member States for regular internal ferry connections.
- ***Personal recognition***: for the purposes of the present work, it is considered a synonym of *biometric recognition*.
- ***Scanning***: within this document, this term is associated with the process of executing a *biometric capture*.[74]
- ***Second- line check***: further check which may be carried out in a special location away from the location at which all persons are checked (*first-line check*).

b) Terms and definitions related to patents

- ***Assignee***: the recipient of a transfer of a patent application, patent, trademark application or trademark registration.
- ***DOCDB patent family***: a collection of patent documents considered to cover a single invention. The technical content covered by the applications is considered to be identical. Members of a patent family will all have exactly the same priorities. This type of patent family was considered in *Patentometric and Bibliometric Analyses*.
- ***Dominant design***: a single architecture that establishes dominance in a product category. A *dominant design* is a concept that wins the allegiance of the marketplace, the one to which competitors and innovators must adhere if they hope to command a significant market.[75]
- ***European patent***: a patent that can be obtained for all the EPC contracting states by filing in a single application with the EPO in one of the three official languages (English, French, or German). European patents granted by the EPO have the same legal rights and are subject to the same conditions as national patents granted by the respective national patent office. A granted European patent is a "bundle" of national patents that must be validated at the national patent offices of the countries selected by the applicant for it to be effective.
- ***Examiner***: specialist patent office staff whose job is to evaluate the patentability of inventions claimed in patent applications.
- ***Inventor***: a person who contributes to the conception of an invention.[76]
- ***Patent application***: request for patent protection of an invention, filed in a patent office.
- ***Patent attorney***: a qualified professional representative, appointed to act on behalf of an applicant to draft a patent application and/or accompany the application through the various stages of the patent grant procedure.[77]
- ***Patent office***: a government body which controls the issue of patents.[78]

74 No definition is given for "scanning" in ISO, International Standard ISO/IEC 2382-37:2017 — Information technology — Vocabulary — Part 37: Biometrics, 2017.

75 J. Utterback, "Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change", Boston, MA, Harvard Business School Press, 1994.

76 Definition provided by the Research Team.

77 See the definition of "European patent attorney" provided by EPO (https://www.epo.org/service-support/glossary.html)

78 Source: https://ec.europa.eu/competition/sectors/pharmaceuticals/inquiry/preliminary_report.pdf

- ***Patent*:** a legal title that gives inventors the right, for a limited period (usually 20 years), to prevent others from making, using, or selling their invention without their permission in the countries for which the patent has been granted.

Appendix 7 – Key Players within capability domains

Table 46: *List of key players (marked with ✔) for each key technological cluster (KTC).*

Stakeholder category	Name	Country	KTC A	KTC B	KTC C	KTC D	KTC E
Industrial producer of systems and components	Dermalog	Germany	✔	✔	✔	✔	✔
Industrial producer of systems and components	Innovatrics	Slovakia	✔	✔	✔	✔	✔
Industrial producer of systems and components	TECH5	Switzerland	✔	✔	✔	✔	✔
Industrial producer of systems and components	Thales	France	✔	✔	✔	✔	✔
Industrial producer of systems and components	Polygon	United Kingdom	✔	✔	✔		
Industrial producer of systems and components	Giesecke+Devrient	Germany	✔	✔	✔		
Industrial producer of systems and components	Idemia	France	✔	✔	✔		
Industrial producer of systems and components	secunet Security Networks AG	Germany	✔	✔	✔		
Industrial producer of systems and components	Speed Identity	Sweden	✔	✔	✔		
Industrial producer of systems and components	Vision-Box	Portugal	✔	✔	✔		
Industrial producer of systems and components	Veridos GmbH	Germany	✔	✔	✔		
Industrial producer of systems and components	Gambit	Canada	✔				
Industrial producer of systems and components	I-Evo Ltd	United Kingdom	✔				
Industrial producer of systems and components	Jenetric	Germany	✔				
Industrial producer of systems and components	T3K-Forensics	Austria	✔				
Industrial producer of systems and components	Mobai AS	Norway		✔	✔	✔	✔
Industrial producer of systems and components	Aurora-AI	United Kingdom		✔	✔		
Industrial producer of systems and components	Cognitec Systems	Germany		✔	✔		
Industrial producer of systems and components	FacePhi Biometrics	Spain		✔	✔		
Industrial producer of systems and components	Veridas Digital Authentication Solutions	Spain		✔	✔		
Industrial producer of systems and components	iProov Ltd	United Kingdom		✔			

Stakeholder category	Name	Country	KTC A	KTC B	KTC C	KTC D	KTC E
Industrial producer of systems and components	Keyless Technologies	Italy		✔			
Industrial producer of systems and components	Selfmetric	Turkey		✔			
Industrial producer of systems and components	SITA	United Kingdom		✔			
Industrial producer of systems and components	ubble	France		✔			
Industrial producer of systems and components	Raytrix	Germany		✔			
Industrial producer of systems and components	Onfido	United Kingdom			✔		
Total number of industrial producers of systems and components			**15**	**22**	**17**	**5**	**5**
Academic Institution	Hochschule Darmstadt	Germany	✔	✔	✔	✔	✔
Academic Institution	University of Bologna – Biometric System Laboratory	Italy	✔	✔	✔	✔	✔
Academic Institution	Laboratory for Multimedia Communications (Belgrade)	Serbia	✔	✔	✔		
Academic Institution	University of Cagliari	Italy	✔	✔	✔		
Academic Institution	Lancaster University	United Kingdom	✔				
Academic Institution	Ecole Centrale de Lyon	France		✔	✔		
Academic Institution	Eurecom	France		✔	✔		
Academic Institution	Halmstad University	Sweden		✔	✔		
Academic Institution	Katholieke Universiteit Leuven	Belgium		✔	✔		
Academic Institution	University of Twente	Netherlands		✔	✔		
Academic Institution	University of Reading	United Kingdom		✔	✔		
Academic Institution	University of Ljubljana	Slovenia		✔	✔		
Academic Institution	Military University of Technology	Poland		✔	✔		
Academic Institution	University Beira Interior	Portugal				✔	✔
Total number of Academic Institutions			**5**	**12**	**12**	**3**	**3**
Research and Technology Organisation	Fraunhofer IGD	Germany	✔	✔	✔	✔	✔
Research and Technology Organisation	Idiap Research Institute	Switzerland	✔	✔	✔		
Research and Technology Organisation	TNO Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek	Netherlands	✔	✔			

Stakeholder category	Name	Country	KTC A	KTC B	KTC C	KTC D	KTC E
Research and Technology Organisation	AIT	Austria	✔				
Research and Technology Organisation	VTT Technical Research Centre of Finland	Finland	✔				
Research and Technology Organisation	Fraunhofer Institute for Industrial Engineering IAO	Germany		✔	✔		
Research and Technology Organisation	National Institute for Standards and Technology (NIST)	United Kingdom		✔	✔		
Research and Technology Organisation	Estonian Forensic Science Institute	Estonia		✔	✔		
Research and Technology Organisation	National Centre of Scientific Research "Demokritos"	Greece		✔			
Research and Technology Organisation	Research and Academic Computer Network (NASK)	Poland				✔	✔
Total number of Research and Technology Organisations			5	7	5	2	2
EU-funded R&I framework programme	Horizon Europe	Belgium	✔	✔	✔	✔	✔
Total number of EU-funded R&I framework programmes			1				
EU Institution, Body or Agency	Directorate-General Joint Research Centre (JRC), Directorate Space, Security and Migration	Belgium	✔	✔	✔	✔	✔
EU Institution, Body or Agency	EU Innovation Hub for Internal Security	Netherlands	✔	✔	✔	✔	✔
EU Institution, Body or Agency	European Data Protection Supervisor (EDPS)	Belgium	✔	✔	✔	✔	✔
EU Institution, Body or Agency	Directorate-General Migration and Home Affairs (DG HOME), Directorate Borders, Interoperability and Innovation	Belgium	✔	✔	✔	✔	✔
EU Institution, Body or Agency	European Research Council Executive Agency (ERCEA)	Belgium	✔	✔	✔	✔	✔
EU Institution, Body or Agency	European Research Executive Agency (REA)	Belgium	✔	✔	✔	✔	✔
EU Institution, Body or Agency	European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)	Estonia	✔	✔	✔	✔	✔
EU Institution, Body or Agency	European Defence Agency (EDA)	Belgium	✔	✔	✔	✔	✔
EU Institution, Body or Agency	European Union Agency for Fundamental Rights (FRA)	Austria	✔	✔	✔	✔	✔
EU Institution, Body or Agency	European Union Agency for Law Enforcement Cooperation (Europol)	Netherlands	✔	✔	✔	✔	✔
Total number of EU Institutions, Bodies or Agencies			10				

Stakeholder category	Name	Country	KTC A	KTC B	KTC C	KTC D	KTC E
INTERPOL (International Criminal Police Organization)	France	International Organisation	✔	✔	✔	✔	✔
Total number of International Organisations					1		
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Austria	Austria	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Belgium	Belgium	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Bulgaria	Bulgaria	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Croatia	Croatia	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Cyprus	Cyprus	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of the Czech Republic	Czech Republic	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Denmark	Denmark	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Estonia	Estonia	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Finland	Finland	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of France	France	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Germany	Germany	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Greece	Greece	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Hungary	Hungary	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Ireland	Ireland	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Italy	Italy	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Latvia	Latvia	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Lithuania	Lithuania	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Luxembourg	Luxembourg	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Malta	Malta	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of the Netherlands	Netherlands	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Poland	Poland	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Portugal	Portugal	✔	✔	✔	✔	✔

Stakeholder category	Name	Country	KTC A	KTC B	KTC C	KTC D	KTC E
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Romania	Romania	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Slovakia	Slovakia	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Slovenia	Slovenia	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Spain	Spain	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Sweden	Sweden	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Iceland	Iceland	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Liechtenstein	Liechtenstein	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Norway	Norway	✔	✔	✔	✔	✔
EBCG community – Border and Coast Guard National Authority	Border and Coast Guard Authorities of Switzerland	Switzerland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex Research and Innovation Unit (RIU)	Poland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex RIU – Border Security Observatory	Poland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex RIU – Technology and Innovation	Poland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex RIU – Standards and Capacity Development	Poland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex Centre of Excellence for Combating Document Fraud	Poland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex Fundamental Rights Office	Poland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex ETIAS Task Force	Poland	✔	✔	✔	✔	✔
EBCG community – Frontex	Frontex Liaison Officers (FLOs)	Poland	✔	✔	✔	✔	✔
Total number of EBCG community members (=End users)			39				
Civil society and trade association	European Association for Biometrics (EAB)	Netherlands	✔	✔	✔	✔	✔
Total number of Civil society and trade associations			1				

Further Reading

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Annexes

- **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

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