CRITICAL COMPONENTS AND MARKET DYNAMICS OF QUANTUM SENSORS

Towards European technology sovereignty in an emerging industry

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Authors
Clara Osorio Tamayo
clara.osoriotamayo@quantumdelta.nl

Julian Rabbie
julian.rabbie@tno.nl

Fokel Ellen
fokel.ellen@tno.nl

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1 Introduction

Quantum technology is rapidly maturing from academic lab setups to commercially available products and the contours of an emerging global market are starting to become visible. As one of Europe's leading quantum ecosystems, Quantum Delta NL (QDNL) believes that we have a responsibility to think ahead: what should the future quantum industry look like and how can we anticipate its impact on the economy, society and the global technology landscape?

Alongside quantum computing and quantum communication, quantum sensing is an often overlooked area that can be considered, in some respects, the most mature quantum technology. The extreme sensitivity of qubits to their environment, which forms a bottleneck for scaling up quantum computers, is in the case of quantum sensing the main asset that allows for radically new forms of measurements. This can be used for a wide range of applications in many different industries, such as energy, manufacturing, health and defence[1].

All of these applications require different types of sensors with distinct performance criteria, which can in turn be realised with multiple underlying hardware platforms (i.e. qubit modalities). Moreover, there is no clear, unifying technological goal that everyone in the field is working towards, in contrast to quantum computing and quantum communication networks. This makes it difficult to define a generic quantum sensor and efforts must therefore be focused on specific areas.

Within the Dutch ecosystem, three quantum sensing testbeds are being developed as part of QDNL's Catalyst Programme 3 (CAT-3). The goal of these testbeds is to accelerate the transition from lab to industry for three hardware platforms: cold atoms[2], optomechanics[3] and nitrogen-vacancy (NV) centres in diamond[4]. Achieving this goal requires a clear picture of the critical hardware components required for developing instruments based on these platforms, as well as the strengths and dependencies of the European ecosystem in terms of suppliers. In earlier studies we performed this exercise for quantum computing[5] and quantum communication networks[6], which resulted in a better understanding of how we can increase our strategic autonomy in this field and the identification of potential actions, such as policy interventions and investment opportunities. These results were also recognised and adopted on an international level[7].

In this study we expand the critical component analysis by including the broader market dynamics in which suppliers and quantum sensor developers operate. By structurally examining the forces at play in this market, we can gain useful insights into how we can support the development of a strong industrial ecosystem in the EU.

Combined, this white paper addresses a two-fold central question: **what are the critical hardware components of quantum sensing technology under development in the Dutch ecosystem and how is this linked to the broader market dynamics of quantum sensors?**

2 Methods and Results

Critical components

In order to map the critical hardware components for quantum sensors, we have first modified the canvas methodology that we developed for our previous two supply chain mappings[5,6]. The rows have remained unchanged, while we adapted the columns to system integration, control hardware and quantum device – see Figure 1. We then used this breakdown structure to map the critical components for each of the three testbeds in the Netherlands through a series of expert interviews and additional market research.

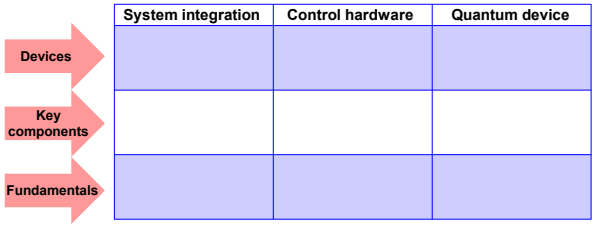


Figure 1: Canvas methodology for identifying critical components for quantum sensors. The columns depict three different hardware layers of a generic quantum sensor, while the rows contain layers of a supply chain: complete devices, key components contained within the devices and fundamentals such as raw materials and consumables.

Next, we placed a selection of the critical components we identified in a two-by-two matrix to showcase the overall results in a single picture (see Figure 2). The horizontal axis represents the *concentration of supply* and the vertical axis represents the so-called *EU-substitutability*. In short: the concentration indicates the number of suppliers and their market share. If a small number of suppliers have a high market share, the concentration of supply is high. The EU-substitutability is defined as the extent to which EU suppliers, based on the location of the company headquarters, can offer a substitute for a component. A high EU-substitutability implies that there is (a potential) capacity in the EU to produce a similar component. This matrix subdivides into four quadrants with specific characteristics and (policy) implications, which we also used in our previous studies on quantum supply chains. These are:

- **Monitor**: sufficient alternatives exist within and outside the EU. Response: monitor the situation and try to consolidate.
- **Increase**: there are few suppliers of the component, although they are already based in (or can be replaced with an alternative supplier within) the EU. Response: retain and increase the suppliers within the EU.
- **Investigate**: there are plenty suppliers, but they all reside outside of the EU. Response: investigate how to deal with the situation, e.g. by strategic investments to strengthen the supply in the EU ecosystem.
- **Mitigate**: few suppliers exist and there is little potential for finding a substitute within the EU. Response: mitigate this strategic dependency, e.g. by pursuing alternative technological solutions.

Using these quadrants, we can derive several valuable insights from our mapping.

Overall we can see that most components are positioned in the top two quadrants, which implies that these components can be sourced from EU suppliers. In particular, out of all the 70+ suppliers we identified (including potential alternatives), approximately 35% of suppliers are from the EU. If we extend this to the full European continent, we capture about half of the suppliers. The other half comes mostly from the US and Japan. Besides these two countries, there have been reports of other non-EU suppliers offering components of similar quality but with significantly lower prices and lead times. Especially towards commercialisation, where prices should be as low as possible to increase competitiveness, this could increase non-EU supplier dependencies and decrease our own market share.

We can also see that for quantum sensors based on optomechanics there are no components in the bottom-right quadrant, which means that there is less risk from a supplier perspective and we could develop this technology sovereignly within the EU.

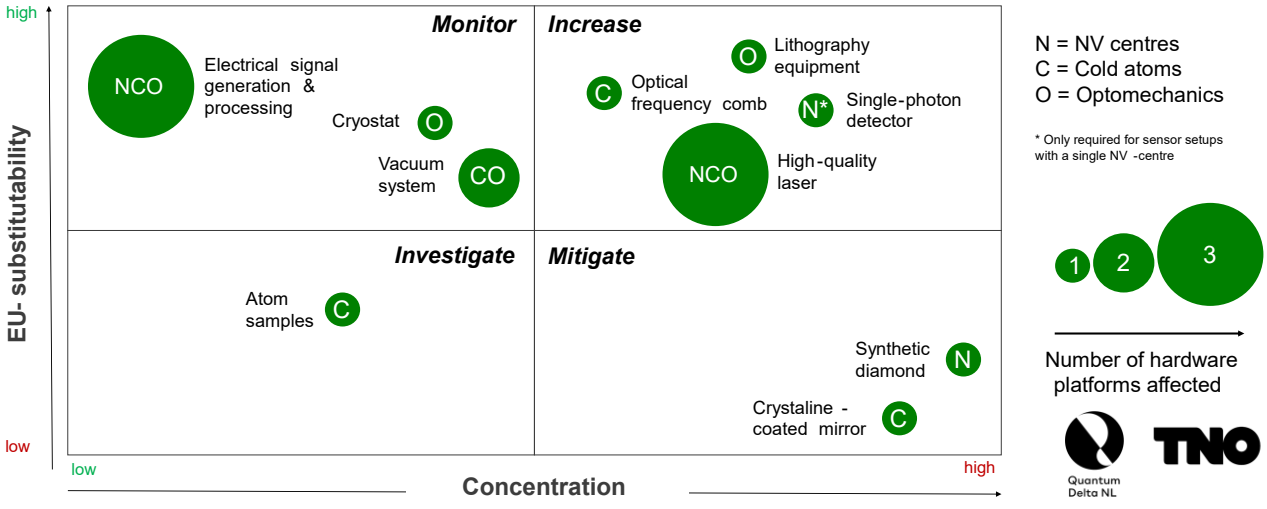


Figure 2: Result of the critical component mapping for quantum sensing in the Dutch ecosystem, where we present a selection of the hardware components we identified based on their market concentration and EU-substitutability. The size of the circles indicate the number of hardware platforms affected and the letters in the circle represent the platform(s) for which this component is used.

Further, NV-based quantum sensors generally operate at room temperature and therefore do not require a cryostat as critical component, which is the case for NV-based systems that are used for communication and computing. Single-photon detectors are moreover only used in setups that require a single NV centre, in contrast to ones that require an ensemble of NVs[8]. Finally, even though both optomechanics and cold atoms require vacuum systems to operate, the latter also does not require a cryostat, as the atoms are cooled through laser cooling[9].

Compared to our previous two exercises on quantum computing and quantum communication, we notice some overlap with certain components identified here: lab-grown diamond, cryostats and high-quality lasers. A supplier disruption for one of these components could thus have significant impact across the quantum technology field. On the other hand, an important difference is that field-programmable gate arrays (FPGAs), which are fundamental for computing and communication, are not required for these sensor types. Even though you need fast processors for quantum sensors, there is no need for the extremely high-end ones for which we had identified a non-EU supplier dependency.

Market dynamics

Even though it is important to be aware of supplier dependencies, this is only part of the broader market dynamics that companies have to deal with. In order to analyse other relevant factors, we use the Six Forces framework[10], based on the well-known Porter's Five Forces model[11]. Next to supplier power, this model includes customer power, internal competition, new entrants, substitutes and complementors (see Figure 3).

This framework can help both technology developers and critical component suppliers that operate in the quantum sensor market to better understand and analyse their environment, highlighting both risks and opportunities. This is in turn key to foster EU supply chains and obtain "indispensable leverage" over time for this critical technology[12]. Through a series of interviews with leading international companies in the defence, space, manufacturing and energy sectors that are actively developing and/or adopting quantum sensors for their operations, we have analysed the effects of these six forces in more detail.

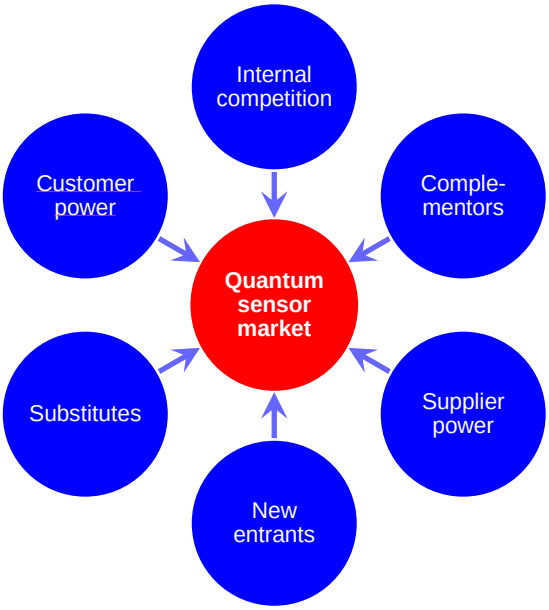


Figure 3 Six Forces framework.

Supplier power

This is in part covered in the previous paragraph and ultimately depends on the hardware platform of the quantum sensor. Since most hardware components are niche products with small markets, supplier power is high due to a lack of alternatives. This is especially true for components in the bottom-right quadrant ("mitigate") of Figure 2, as the few available suppliers are further away geographically.

Another issue caused by a lack of alternatives is the high cost of switching when a certain component is not available anymore. Since there are currently no widely adopted standards in the quantum sensor market, interoperability between components is far from certain and significant redesign might be required to incorporate a substitute component.

Overall, high supplier power can result in high costs and long lead times. This can be reduced by forming strategic partnerships with suppliers, developing standards and (to the extent possible) diversification, preferably with suppliers in multiple geographic areas.

Customer power

On the other side, customer power might be the strongest force hindering the commercialisation of quantum sensors. The bottleneck lies in the current lack of clear added value of quantum sensors. For most

applications, existing (classical) sensors already offer competitive solutions and customers need to be convinced that quantum sensors can provide an advantage in a specific area. This can for example be increased sensitivity or the ability to operate in harsher environments, but in general this will be highly context-dependent. Moreover, only a small group of potential end users are currently aware of quantum sensing technology. Due to its wide range of hardware platforms and applications, the entry barrier for getting acquainted with this field can be high.

This barrier can be lowered by focusing on industries with high market values, such that a small relative advantage can result in high absolute profits. Examples are subsurface imaging for mineral exploration and improved global navigation systems. Another approach is to focus on the non-monetary value that quantum sensors could bring, such as increased safety, health, reliability or scientific capabilities. This will shift the focus from a short-term return on investment (which is challenging) to a long-term added value.

An example is GPS-independent navigation using quantum sensors, which can provide strategic military advantage next to the commercial opportunities it brings[13]. The increased attention and budgets in the defence domain in Europe can moreover in general be leveraged to further develop quantum sensors for military applications, which could then be adapted for civilian use.

For critical component suppliers, system integrators can have substantial market power by being able to set the requirements of the products and services their customers supply. By focusing on the interoperability of components and by developing strong relationships with these integrators, suppliers can increase the adoption of their products.

Internal competition

The internal competition between quantum sensor companies can be fierce, given the small market that multiple players aim to serve and the fact that this market is driven by a technology push. This can both be competition between companies that offer a sensor based on the same hardware platform, as well as competition between different hardware platforms for the same application. At the same time, some quantum sensors are still in an early R&D phase, for which collaboration with entities operating in the same domain can be key to advance their capabilities. Many companies will, however, seize any opportunity to create an income stream individually to justify the high investment required to develop the technology.

Market growth can ultimately reduce internal competition. Current estimations project that the market for quantum sensors will grow to $1 billion by 2030, which will further increase to $7 billion by 2040[14]. If more end users are willing to adopt quantum sensors, there will be more room for multiple suppliers to operate in the same sector. However, the increased market uptake will likely also increase the number of new entrants over time, resulting in more competition.

For component suppliers, internal market competition is a generally healthy dynamic that drives down price and stimulates innovation. However, governments can choose to interfere in these markets by incentivising to buy critical components within the EU, either directly through procurement regulations or indirectly by providing subsidies. This can increase the EU-substitutability of these components over time.

New entrants

Given the technical complexity of quantum sensors, the absence of a clear (short-term) market and the abundance of classical substitutes, there is a significant barrier for any company aiming to enter the quantum sensor market. This can be made even more complex in industries that have strict regulations, such as the health or space industry, where it can take substantial effort to make instruments qualified for operations.

Nonetheless, new quantum sensing startups continue to be established as the years progress[15]. Although the majority of investments were first focused on the US and the UK, in recent years venture capital investments in European quantum sensing companies have increased and sometimes even surpassed the deal activity in North America[16].

A route to safeguard companies from the threat of new entrants is to properly protect their intellectual property and build up a strong knowledge and market position over time. Many companies seem to be aware of this, given that the compound annual growth rate of quantum

sensing patents filed in 2017 – 2022 was higher than the one for quantum computing and communication in the same period[15].

New entrants that provide critical components within the EU can be required to mitigate the risk of those that are currently in the bottom-right quadrant of Figure 2. The position of the components would then shift to the top-left due to these additional EU suppliers. At the same time, foreign new entrants can undermine the market position of component suppliers in the top-right quadrant, for which we currently have a strength. The competitive environment of key European suppliers should thus be monitored over time in order to ensure that we retain this leverage.

Substitutes

The most obvious substitute for quantum sensors are their classical counterparts, which can have a better SWaP-C (size, weight, power and costs) for certain applications and are already integrated into existing systems. For example, the optomechanical sensors that are developed within the Dutch ecosystem have to compete with existing micro-electrical-mechanical system (MEMS) sensors, which are commercially available. These MEMS sensors can moreover be used to measure multiple physical quantities for different applications, such that they can even be considered a substitute for quantum sensors based on other hardware platforms than optomechanics as well. Along the same lines, two quantum sensors based on two distinct hardware platforms that can be used for the same application can in turn also be considered substitutes. For example, magnetometers based on NV centres and atomic vapour cells can both be used for GPS-independent navigation[14].

Once a customers is committed to the development of a certain quantum sensor for the longer term, the threat of substitutes likely diminishes due to high switching costs (see *Supplier power*). In general, the threat from substitutes can further be reduced by clearly defining and communicating the unique added value a certain quantum sensor can bring.

Complementors

Complementors are additional products or services that are sold on top of a core product to increase its overall value. Quantum sensors are in practice always part of a larger integrated system and/or infrastructure, so complementors can in this case for example be other (classical) sensors, interfaces, software models and vehicles.

Technology developments in the quantum computing and communication domain can indirectly support the development of quantum sensors (and vice-versa), since the underlying hardware platforms can be the same. For example, NV centres in diamond can be used to build quantum processors, quantum memories and quantum magnetometers. Innovative solutions in the computing or communication domain, such as miniaturisation through integrated photonics technology, could thus be transferred to the sensing domain. Creating strategic alliances with companies operating in a different pillar (i.e. computing or communication) but with the same underlying technology could therefore result in a win-win situation in which there is no competition in serving the same set of end users.

In the longer term, developments within these neighbouring domains can also unlock new quantum sensing applications. For example, advanced quantum communication networks can enable distributed quantum sensing applications, and (distributed) quantum sensors can be used to directly train quantum machine learning algorithms without having to translate to classical data in between[17].

Complementors are moreover a great way for critical component suppliers to strengthen their market position by offering additional products and services on top of their hardware products. This in turn increases the added value for customers and fosters long-term relationships.

All in all, an analysis of the market forces at play for quantum sensors can help to identify concrete barriers and interventions for companies and critical component suppliers operating in this domain. This can in turn optimise their business strategy and increase their competitiveness, which is key to realising a leading and strategically autonomous European quantum sensing industry.

3 Conclusions

We mapped the critical hardware components for quantum sensing in the Dutch ecosystem, which we coupled to a broader analysis of the market dynamics at play for quantum sensors using an extended version of Porter's Five Forces framework.

Our critical component analysis provides strategic insights into the strengths and dependencies in terms of suppliers for the testbeds in the Dutch ecosystem. Overall the component suppliers are well represented in the EU, especially for optomechanical quantum sensors. A natural extension of these results would be to include more hardware platforms[18], as well as an analysis of which critical components are required for different applications. Moreover, the required components will likely change over time as quantum sensors will be miniaturized and commercialized, so it is important to revisit and update this mapping regularly.

Using the Six Forces framework, we then analysed how supplier power, customer power, internal competition, new entrants, substitutes and complementors shape the quantum sensor market. This enables us to better understand the risks and opportunities for both quantum sensor companies and critical component suppliers that are operating in this sector.

The frameworks applied here allow for a better understanding of the quantum sensing ecosystem in the Netherlands, the EU and beyond. Since the field of quantum sensing is very broad, future research could analyse the market dynamics for a specific company, type of quantum sensor or application in more detail.

Moreover, quantum sensing companies do not operate in a vacuum and are part of a larger ecosystem in which academia, governments and research institutes also play a major role. A so-called innovation orchestrator can increase the interconnectedness between these actors and create a shared vision, which they can jointly use to accelerate the necessary steps required to bring quantum sensing technology to market[14,19].

We would like to extend our gratitude to all the experts who shared their time and insights with us, and we look forward to all the exciting developments within this industry in the years to come.

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Quantum
Delta NL

Quantum Delta NL
Elektronicaweg 10
2628 XG Delft
The Netherlands

info@quantumdelta.nl

www.quantumdelta.nl