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The European defense market: Disruptive innovation and market destabilization

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Abstract

The global defense industry is shifting toward a new paradigm in which an emphasis on technology-driven capability development is being undermined by disruptive innovations emanating from the commercial sector. This evolution is likely to result in important effects on the defense market, lessening barriers to entry and turning upside down the approach to innovation. For the defense sector this entails that shifts in the organizational behavior of firms and military establishments are required if the full benefits of innovation are to be captured and integrated into defense capability development processes. This article analyses this shifting paradigm with the European defense market as a departure point. Briefly exploring the shifts in defense industrial processes since the 20th century, this article outlines the benefits of integrating the defense and civilian technological and industrial bases.

One branch of defense economics looks at defense equipment markets. Usually, this is done sector by sector and focuses on a category of capabilities so as to understand the viability of companies in a given market, the level of competition, or the effects of international sales. During the cold war era, defense markets were marked by a degree of stability, as underlined by the theory (or, at least, the story) of the military-industrial complex. Indeed, most changes in the equipment markets were related to issues such as market concentration, the balance between supply and demand, or export competition.[1]

But exogenous events can alter the functioning of defense markets beyond the endogenous behavior of firms or the policies of their customers, and this dimension of markets has been almost completely underestimated over the past decade or two. Markets have progressively given way to a new understanding, based on increasing levels of innovation in defense capabilities. Since the beginning of the 21st century three dimensions seem to have profoundly modified the dynamics of defense markets. First, some of the dominant technologies involved in aeronautics or land vehicles such as combustion engines, aerodynamics, alloys, avionics, composite materials, and communication systems have become increasingly difficult to improve. Second, due to the weight of asymmetric conflicts and disruptive innovation in terms of capabilities [e.g., hypervelocity or Anti-Access/Area Denial (A2/AD)], the demands on military forces have moved toward new kinds of capabilities and innovation. Third, the relationship between defense and manufacturing activities is evolving due to an ongoing transformation of the core dimensions of industry.

All these dimensions are intrinsically linked to innovations that affect both the demand and supply sides of the market. Therefore, it is impossible to understand the evolution of the European defense technological and industrial base without considering the dynamics of innovation in defense capabilities. In particular, defense innovation and disruptive technologies have the potential to alter systems design and manufacturing processes. Technologies such as robotics and artificial intelligence can lead to new defense technologies and industrial processes. European defense technological and industrial bases have been characterized by stability since the 1960s, since mergers and acquisitions did not truly modify the fundamentals of the industry. Today, however, one can expect that a radical transformation of the defense industrial base is possible and, to a certain extent, mandatory, if the needs of militaries are to be met. Thus, it is important to understand the fundamentals of this transformation.

To this end, this article is organized into three sections. First, it looks at the historical evolution of defense innovation and charts how the defense market has changed since 2000. Second, it analyses how military-industrial actors can behave within a context of transformation and disruptive innovation. And third, it moves to a broader analysis of industrial change. It examines how the European defense market can adjust given the industrial changes being experienced in many developed economies, often labeled as the Fourth Industrial Revolution or Industry 4.0. With an eye to the future, the article then concludes with reflections on how Europe could position itself in the global defense market in the coming years.[2]

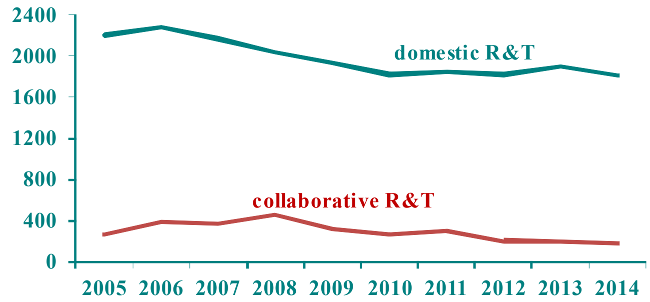

Figure 1: European defense R&T, 2005–2014 (EUR millions)
Source: Statistical database of the European Defense Agency.

The global defense industry is entering a new paradigm in which the current emphasis on technology-driven capability development is being undermined by disruptive innovations emanating from the commercial sector. This likely lessens barriers to entry and changes the sector's approach to innovation. Shifts in the behavior of defense firms and military establishments are required if the benefits of commercial innovation are to be captured and integrated into defense capability development processes.

The drawbacks of a technology-driven defense industry

Innovation always has played a major role for military dominance but the 20th century was marked by a particularly rapid evolution of defense capabilities. Prior to world war one, soldiers could spend decades, even their whole careers, using the same equipment. But between the world wars, scientific progress and innovative defense systems emerged, merged, and solidified. This convergence bled over into the cold war era, a period of time characterized by a technological arms race in which arms-producing countries invested heavily in R&D to achieve dominance on account of technologies with incredible military potential.[3]

Since they are responsible for national security, militaries expect to have an industrial and technological base at their disposal to deal with crises (not just with security of supply). Some production units are seen as strategic resources and have to be preserved through continuous, follow-on contracts. The follow-on principle has two main consequences. It permits *technological continuity* in defense capabilities because of the growth potential of such technologies and, thanks to their mastery of the predominant technologies, it provides the main arms-producing companies with a degree of *commercial continuity* and stability. For instance, the French Rafale aircraft is a next-generation platform derived from the Mirage 2000. Its development was launched when the Mirage 2000 entered production in the late 1970s. The strong technological continuity between both systems was explicitly conceived for two reasons: to maintain strategic dominance through state-of-the-art systems and to preserve industrial capabilities.[4]

Continuity does not mean that significant improvements between two generations of platforms are absent. Major improvements do take place along a technological continuum and successive systems are positioned at the front-edge of many technologies that characterize the platforms they replace. But continuity does go some way to explain why the military-industrial complex "has endured for several decades, in some cases dating back to the second world war, despite the ebbs and flows, the booms and busts in defense spending." The follow-on principle introduces a procurement bias; it induces a tacit agreement among government, military, and defense companies, and it leads companies to promote the renewal of existing systems that are based on assets, technology, and know-how they already master.[5]

Already in the 1980s, however, it became clear that this model of interaction between militaries and firms resulted in several shortcomings. Even though advanced technologies can support missions and help maintain strategic dominance for arms-producing countries, defense R&D became increasingly expensive while generating fewer disruptive technologies. In 1985, one pair of authors calculated that the real unit cost of major arms systems had increased by 6 to 13 percent annually since the end of the second world war. Similarly, more than 20 years ago, another author pointed out that incremental defense R&D innovations within existing technology trajectories are increasingly difficult to achieve, and at increasing cost. Today, virtually all modern defense programs related to complex systems are encountering major challenges concerning either technological developments or budgetary targets.[6]

In part because of cost reasons, most arms-producing countries have become progressively unable to sustain a purely domestic defense industrial base. In Europe, this is reinforced by decreasing domestic budgets for defense R&D since the end of the cold war. But neither have European arms producing firms engaged in much cross-country cooperation to share the costs of developing new advanced systems. For example, data from the European Defense Agency (EDA) for domestic and collaborative R&T (research and technology) show a slight decline since the 2008 global economic and financial crisis which deeply affected European defense spending and led to the subsequent imposition of austerity policies. Both national and cooperative R&T is declining across this period. But the data also show that European countries appear unable to consistently engage in collaborative efforts (see Figure 1). They thus appear to maintain the domestically-based model of follow-on innovation inherited from the cold war.[7]

As defense R&T (as well as the larger rubric of defense R&D) investments have decreased, one wonders if continuing such investments is still useful for achieving the expected innovation levels. The defense economics literature shows that the effectiveness of defense R&D results from both the spending *level* on a given technology as well as from how this spending is *managed*. In fact, threshold effects result from the evolution of defense-related technologies. One pair of analysts who explored investments in integrative technologies in a dynamic optimization framework find that under nonlinear, convex development costs it is not optimal to build military forces using a myopic, short-term approach. In other words, it is difficult to transform the military within just a few years. Consequently, early investment in technology infrastructure is required because the entry cost is high and the transformation period ranges over more than a decade. If a country's investment in a given technology is too limited, it cannot expect to keep pace with the state of the art, and it is not worth investing in that technology in the first place. The EDA data shown in Figure 1 would seem to bear on this argument and suggest that defense R&D is not optimally used because resources are fragmented throughout Europe rather than pooled among committed countries to leverage scale effects.[8]

Beyond the technology argument one needs to probe the cost argument to understand the limits of today's defense R&D. Specific market features lead armed forces to struggle with a situation in which rising unit costs result in a symmetrical reduction of quantity. Reports from public audit offices in France (Cour des Comptes), the United Kingdom (National Audit Organisation), and the United States (Government Accountability Office) show that governments or their militaries often choose immature or unproven technologies even if they jeopardize the delivery of capacities and when the technology specifications are not essential for achieving most military requirements. A systematic bias in defense procurement favors quality even if this results in a reduced quantity of systems. An industrial environment is nurtured in which enterprises are encouraged to promote advanced technology rather than minimize unit costs. Today's upward drift in R&D costs thus continues to reflect the business model that has characterized the defense industry since world war two. Much of the blame should be put on the technology-centric paradigm that defines the essence of this industry.[9]

The endless quest to stay on the technological frontier becomes less sustainable when the underlying technologies mature. Today's major defense capabilities rely on technology born from the 1920s (e.g., aeronautics) to the 1960s (e.g., electronics, computer science). But because incremental performance comes with complex solutions, technological uncertainties, and numerous problems during the development stages, it has been suggested that any 5 to 10 percent of additional performance results in a 30 to 50 percent increase in extra cost. For various kinds of platforms, procurement costs have increased at an intergenerational real-cost growth rate of 4 to 8 percent. The desire to procure next-generation technology is a key driver of cost escalation, which to a large extent explains the dynamics behind one of Augustine's laws.[10]

In our view, the currently predominant defense technologies have reached a cost plateau. As it becomes increasingly difficult to improve on already-achieved performance *within a given technology envelope*, any additional improvement inevitably comes with higher marginal cost and limited operational benefit. R&D efforts concentrated on the marginal increase of technological performance absorb a large share of investments. To address the capability needs of armed forces, this does not mean that there is no need for innovation in the field of defense. It just means that the core question should not be *if* but *how* to innovate. Simply targeting all available R&D resources on the improvement of *existing* systems (technology envelopes) appears not only difficult but inadequate and inappropriate in regard to the effective needs.[11]

Additionally, the defense technological and industrial base (DTIB) can no longer operate in a vacuum whereby it develops capabilities with limited interaction with the rest of the economy. Many commercial sector innovations possess potential applications to defense systems. As defense-related technologies themselves have reached a plateau, the industry has to look for technological inputs from outside the DTIB and focus on (re)combining existing component knowledge through innovative knowledge architecture. In their foreword to a recent book on *Creative Disruption*, William Lynn and Adm. James Stavridis note: "Google's recent acquisition of Boston Dynamics, a DARPA-funded organization that develops some of the world's most innovative robots, served the Pentagon with an unsettling notice: the centre of gravity in cutting edge, military applicable research is shifting abruptly away from the defense establishment to relatively new commercial firms with loads of cash to invest."[12]

'Ostriches' cannot survive in a transformative market

The defense sector is not immune to the broader technological evolution taking place in the commercial sector. Disruptive innovation may alter the defense sector in profound ways. Technologies such as nano- and biotechnologies, robotics, artificial intelligence, and new forms of advanced manufacturing can greatly affect the development of new and existing weapons technologies. Advanced manufacturing in particular may play a significant role in how the defense sector functions in the future. Innovative new production processes, such as 3D/4D printing and ongoing miniaturization, challenge existing processes and the manufacturing time scale. They may lead to more resilient and flexible components, could provide more production flexibility in general, and could possibly lead to mass manufacturing right on the battlefield.[13]

If it is correct to suggest that disruptive innovation is about "new suppliers dealing with new customers," challenging questions are raised for a defense sector traditionally marked by monopsony. Importantly, disruptive innovation affects both military and defense-industrial transformations, but these do not necessarily coincide. Adaptation need not be synchronized and thus can disrupt established customer-supplier relations in the defense sector. So the challenge of the sector lies not only in the task of generating innovative products *per se* but also in its ability to adapt new commercial technologies for the benefit of its military customers.[14]

An additional challenge is that new technologies tend to have a knock-on effect for services and business models, too. They do not always imply a concomitant shift in business models, of course, but it is important to note that government agencies and firms can alter policy and business practices, respectively, in response to disruptive innovation. Since the defense sector traditionally has not been as responsive to innovation as the commercial sector has been, much scope exists for military-industrial actors to rethink the ways in which they generate, capture, and use new knowledge.[15]

Despite the fact that prime contractors focus on high-value activities such as systems integration and defense R&D, the traditionally closed-off form of technology development within the defense sector no longer reflects present and future market realities, and most military establishments do not possess a monopoly on technology advances anymore. Given that most disruptive technologies now emanate from the commercial sector, emphasis should be placed on breaking into the commercial R&D realm. Crucially, defense industry and governments must refocus their energies on *technology integration* rather than *technology production*. This is no easy task but heralds a complete shift in the required behavioral and/or organizational dimensions of defense procurement and defense innovation if the defense sector is to benefit from disruptive innovation. Also note the inherent misalignment between the standard time-horizon for defense procurement (10 to 30 years) and the break-out of disruptive technologies (usually far fewer years). The required behavioral shift presumes that military-industrial actors can effectively integrate disruptive technologies into ongoing procurement developments as and when they emerge.[16]

For military-industrial actors, the advent of disruptive technologies emanating from the commercial sector poses a three-pronged challenge: first, how to integrate disruptive technologies into existing or planned capabilities in an effective and time sensitive manner; second, how to adjust organizational behavior to capture commercially-driven innovations; and third, how to foster relations between the military establishment and nondefense commercial firms and their research clusters (e.g., high-technology firms in Silicon Valley). None of these are easy to address and the second and third, especially, take on great relevance in a context where the broader industrial landscape is being reshaped. While the dual-use concept has been around since the cold war era as a way of linking defense and commercial efforts, the term veils the complex relationship between defense and commercial innovation. A successful relationship between the defense and commercial sectors requires each to understand better the socio-technical bias and approach of the other. This presumes willingness and ability to learn and to change behavior. Innovation is not merely and simply about inventing and producing technologies; it is equally—if not more so—about the learning processes of an organization itself.[17]

The new behavior that is required can be illustrated by thinking about decisionmaking within the procurement system. Traditionally, the hierarchical structure of defense ministries and procurement agencies has meant that individuals such as high-ranking military officials shape the military's attitude toward new military innovations. But having gatekeepers in place to encourage, direct, or dissuade technology integration in the defense sector runs counter to much of the literature and practice of Open Innovation, an organization's ability to combine internally- and externally-sourced ideas. Based on decentralized and fairly evenly distributed innovation management within firms, this form of innovation is a major challenge for a defense sector used to secrecy, the guarding of innovation, and maintenance of hierarchical control over decisionmaking.[18]

That said, a number of large and medium-sized defense economies are transitioning toward a more open approach to defense innovation. For example, the United States' Third Offset Strategy seeks to drive investment in paradigm-breaking technologies and to shift the mentality of the DoD. For multiple reasons, including the need to decrease overall personnel spending, the DoD is presently trying to bring its defense and civilian bases closer together. In addition to the work of DARPA, the establishment of a "civ-mil" innovation interface—called the Defense Innovation Unit Experimental (DIUx)—is opening hubs in places such as Palo Alto (California), Boston (Massachusetts), and Austin (Texas) to profit from commercial technology advances. The DoD believes that investment in technologies such as autonomous systems, robotics, and directed energy weapons will give the U.S. a military edge over its actual and potential adversaries and allow its forces to combat the proliferation of precision-guided weapons and A2/AD ‘bubbles’.[19]

Yet despite this drive toward more integration between the commercial and defense technological and industrial bases, the DoD faces significant challenges in harnessing the disruptive abilities of firms located in places such as Silicon Valley. For one thing, many high-tech firms are cautious about what closer links with the DoD will do for their public image. For instance, when Google bought Boston Dynamics—a DARPA-funded organization—it ensured that none of its newly acquired robotics projects were being used for DARPA programs. Indeed, Google pledged never to pursue military contracts. Another challenge relates to intellectual property rights (IPRs). A dual-use system of innovation may leave space for an IPR regime that stimulates defense-commercial collaboration, but designing a regime that allows commercial firms to secure IPRs in a context where military establishments are loath to share IPRs is extremely challenging.[20]

It is not just the U.S. that is investing in defense innovation through closer collaboration with the commercial sector. Evolving defense innovation patterns in China, Israel, Japan, and South Korea also are important. For example, reform of China’s defense innovation model began in the late 1980s with a view to fusing its civilian and military technological and industrial bases. (A prevalent element of its innovation effort has been to copy from other countries.) While its military development has not traditionally been at the high-end of the technology frontier, this fusion has led to an R&D push that has seen the rapid development of aviation capabilities such as the Shenyang J-31 stealth fighter. China's innovation model is geared toward leap-frog advances in the military domain based on an undisclosed amount of investment in defense R&D and copycat strategies. While China may require a few more decades to fully exploit science and technology, an emerging strategy has been to initiate a science education system aimed at inculcating science throughout the public system as well as to rapidly establish new commercial R&D hubs.[21]

Faced with increasing global competition in the defense innovation domain, Europe also must grapple with the military-technological evolution underway. The challenge for Europe is that its defense industry remains fragmented and that it suffers from chronically low investment on collaborative defense R&D. Interestingly, recent steps taken by the European Union (EU) to start investing in defense research has given rise to new possibilities for European defense innovation. While still on a relatively small scale when compared to the U.S., the EU is looking to invest EUR3.5 billion in defense research from 2021 to 2027. As a pilot to its defense research efforts, the EU has invested EUR1.4 million in three programs related to urban combat intelligence, detect-and-avoid sensors for autonomous systems, and autonomous nonlethal dissuasion technologies. Should these projects prove worthwhile, the intention is to invest a EUR90 million over 2017-2019 in further programs. The real added-value of this funding will emerge if investments lead to an integration of Europe’s defense and commercial technological and industrial bases.[22]

Adjusting the defense sector to the overall transformation of industry

Innovation remains at the core of defense capability development. Even though the DTIB is no longer entirely driven by the trajectories of old technology envelopes, nor quite as subject to long-term planning constraints as in the past, new threats emerge and actual or potential foes can rely on a large and rapidly expanding knowledge base to create innovative military capabilities or threats. Therefore, the DTIB must reinvent itself so that it can respond in a timely and effective way to requests the military forces may express. This again raises the question of the convergence between the DTIB and civilian industry. Indeed, this question arose first in the late 1980s and early 1990s when the concept of the DTIB emerged. With the end of the cold war, defense budget cuts led to a crisis in the arms industry and resulted in industrial overcapacity. Although important, budgetary aspects turned out to be a short- to medium-term issue that masked the industry’s long-term structural deficiencies. Segregation from the rest of the economy engendered inefficiencies and failures.[23]

Civilian and military technological regimes are supposed to have intrinsic properties that distinguish them from each other, primarily because specific user interests impose different technology requirements. This separation was reinforced by strict segregation of defense firms from the global economy to prevent the Soviet Union and its allies from accessing state-of-the-art western technologies. But protection also deprived the industry from receiving the benefits of civilian research and manufacturing. The concept of the DTIB was a means to help overcome segregation by favoring convergence with the civilian industrial and technological base. This one-sided approach was not entirely successful because convergence was thought of as a safeguard strategy rather than as a systemic transformation to really merge the defense and commercial industries. Today’s DTIBs do have better leverage over civilian technologies and the commercial sector, and while these interactions contributed to the greater integration of civilian technologies into defense systems and to lower production costs, they did not, however, lead to an overall transformation of the fundamentals of DTIBs, both in conception and in production.

To an extent, the current setup of European DTIBs (as for most other arms-producing countries) corresponds to the optimal use of the industrial approach that resulted from the Third Industrial Revolution. It is characterized by a quite linear development approach in which technology evolutions are structuring a generation-based conception of systems, leading to a kind of planned obsolescence. Additionally, large sunk costs associated with system conception and production setup due to the complexity and specificity of related technologies imply that efficiency relies on industrial techniques of mass production whereby homogenous products are produced in large quantity, leading to volume-based barriers to entry. All this would favor incumbent companies and the follow-on principle approach. The key challenge, then, lies in adjusting the DTIB to a Fourth Industrial Revolution, one that is likely to induce radical changes over all dimensions of industrial activities. In a word, the defense industry must change if it wishes to respond to the expectations of the military and to the ways civilian industry operates. No longer can systems conception be based on planned obsolescence resulting in decade-long developments. And production volumes have decreased so much in DTIBs that mass production techniques appear less effective and very expensive.[24]

As a defense-oriented Industry 4.0 emerges, the rules of the defense market game are bound to change. The past stability of the DTIB was possible because incumbent companies were protected from competition by strong barriers to entry that prevented newcomers from breaking into defense markets (particularly hit-and-run strategies were near impossible to pull off). In terms of systems development and production, these barriers were ontologically linked to characteristic features of Industry 3.0 which have become a legacy, or even an outright burden, as DTIBs generally do not rely on the best industrial approach and practices to address military needs.

Transformation of innovation expectations and of industry fundamentals lead to a level playing field in which the fastest and most adaptive firms can secure potential defense market contracts. In the absence of unbearable sunk costs, entry in defense markets is likely to become contestable, at least for an increased share of defense acquisition. It therefore seems likely that in-depth transformation of the DTIB will be painful, especially for incumbent companies. Of course, even as the creation of an Industry 4.0 DTIB approach appears essential, it cannot be taken for granted that non-DTIB companies will in fact be interested in serving the military (as the Google example referred to earlier illustrates). It would therefore seem necessary that states set up industry and technology policies that support both the transformation of current defense-oriented firms and that attract purely commercial ones to the field of defense capabilities.

Increased convergence of the defense and commercial technological and industrial bases will be a key element in the renewal of the defense sector. This is especially true in Europe. We mentioned the Third Offset Strategy promoted since 2014 in the U.S., but this does not necessarily open the U.S. market to European companies. European DTIBs could be put in jeopardy without an equivalent initiative on its side of the Atlantic. However, one can expect recent European initiatives to be leveraged, even though its resources and ambitions will be well below the massive efforts mobilized in favor of the United States' Third Offset Strategy.[25]

Conclusion

The Europeanization of defense R&D efforts and a more European approach to consolidating the European DTIB could help Europe adjust to the emerging Industry 4.0. The EU has overcome some of its decades-long aversion to investment in the defense sector, for instance with an initial EUR1.4 million investment in swarms, robotics, sensors, and autonomous systems launched in 2015. These initial defense research investments are designed to test whether EU institutions can work effectively on defense research and whether they can develop an IPR-regime that works for Europe's defense market. Should these initiatives succeed, the plan is to integrate a fully-fledged European Defence Research Programme (EDRP), worth potentially EUR3.5 billion over 2021-2027, into the EU's Multiannual Financial Framework. All this is still at an early stage but, if calibrated correctly, shows great potential to reshape the European defense market.

EU-level investments may make it possible to encourage convergence of Europe's defense and commercial markets by influencing the types of defense capabilities developed and by encouraging much closer collaboration between traditional defense firms and broader, civilian, actors such as research institutes. There will, however, be limits to what EU investments in defense research can achieve. First, EU efforts should not replace national investments in defense R&D: this is precisely why EU investments should be co-financed in order to secure buy-in from member states. (While the policy objective of the European Commission may be to move in an evolutionary way toward a single European defense market, and while EU defense research spending may evolve in this direction in the future, at present the amount of money being tabled by the Commission—EUR90 million until 2020—would not be enough to cover national spending on defense R&D.) Second, it will take time before EU investments in defense research can change the mentality of military-industrial actors in Europe. Adopting a more open behavioral and organizational approach to defense innovation will need time to succeed and cannot rely solely on EU investments.

Longer term, good opportunities to seriously augment the EDTIB may be on the horizon. The European Commission's European Defence Action Plan (EDAP) has not only stressed the importance of the defense procurement and defense transfer directives, but it has also tabled the idea of having a European Defence Fund (EDF). The EDF would support EU member states with defense capability development with a view to linking up defense research efforts with broader defense capability programs. This may provide a financial incentive for European countries to work closer together. Bringing together the EDF and any future EDRP could become vital ingredients for any deep transformation of the EDTIB.

Finally, the EU has signaled important policy initiatives that could be elaborated further in the future. As a follow-up to the EU Global Strategy published in June 2016, the High Representative/Vice President presented the Security and Defence Implementation Plan to EU member states. It not only calls for an EU Innovation Initiative to manage potentially disruptive technologies, but also foresees the creation of a Coordinated Annual Review on defense that may see closer coordination of defense planning among European countries. Elsewhere,[26] we have called on the EU to coordinate the technology roadmaps of member states, not only to improve coordination and cooperation, but to also provide valuable foresight for future technological and industrial trends. It seems that the EU is now well-placed—provided political will exists—to push for closer European cooperation in the defense-industrial domain. If Europe is to manage disruptive innovation and market destabilization then such efforts cannot come too soon. Otherwise non-European companies will not only compete with European firms on international markets but even in Europe itself.[27]

Notes

1. Military-industrial complex: Adams (1989).

2. Industry 4.0: Schwab (2016).

3. Whole careers and emerging convergence: Wright Mills (1956). Scientific progress: See the ample literature on the so-called Revolution in Military Affairs: Henrotin (2013).

4. Follow-on principle: Kurth (1972). Rafale: This does not mean that there is no major innovation or new technology in the Rafale, just to say that launching this program did not result from a strategic or technological imperative.

5. Technological continuum: See, again, Henrotin (2013) on the Revolution in Military Affairs. Military-industrial complex: Some authors limit the concept to capitalist economies but it has also been applied to planned economies since it is not necessary that a country relies on market/capitalist mechanisms to generate a military-industrial complex. While the channels differ, the results are quite similar in terms of power and resource capture. Quote: Kurth (1993, p. 307).

6. Real unit cost: Kirkpatrick and Pugh (1985). Another author: Serfati (1995).

7. R&T is part of R&D. It includes basic research, applied research, and advanced technology but not capability development. While it would be useful to have R&D data, the EDA only releases detailed figures on domestic and collaborative spending for R&T.

8. One pair of analysts: Setter and Tishler (2006, 2007).

9. Unproven technologies: For instance, it is often held to be true that the armed forces of the U.K. seek the best kit—proven U.S. frontier technology systems—but that the U.K. government then overrides with political pressure to "buy British", supporting local jobs and investment. In the U.S., GAO assessment of major, complex defense systems over at least the past decade argues that the DoD pushes for the launch of production even as key technologies have not yet reached maturity. The F-35 is an emblematic example. Systematic bias: Rogerson (1990). Nurtured: Serfati (1995).

10. Technological frontier: Gansler (1989, p. 218). Rely on technology: Bellais and Droff (2016). It has been suggested: Adelman and Augustine (1990); Augustine (1997). Various kinds of platforms: Kirkpatrick (2004, 2008); Davies, *et al.* (2012). Augustine's laws: Law 16 states that defense budgets grow linearly but unit cost of new military aircraft grow exponentially. He writes: "In the year 2054, the entire [U.S.] defense budget will purchase just one tactical aircraft. This aircraft will have to be shared by the Air Force and Navy 3½ days each per week except for leap year, when it will be made available to the Marines for the extra day" (Augustine 1997, p. 107).

11. Plateau: Bellais and Droff (2016).

12. FitzGerald and Sayler (2014, p. 5).

13. Hammes (2015).

14. Quote: Christensen (1997). On disruptive transformation, see Dombrowski, Gholz and Ross (2002, pp. 16).

15. Knock-on effect: Markides (2006). Scope to rethink: Börjesson and Elmquist (2012, p. 189).

16. The paragraph relies on Stowsky (2004).

17. Presumes: Pierce (2004, p. 1). Socio-technical bias: te Kulve and Smit (2003).

18. Traditional hierarchical structure: Jungdahl and Macdonald (2015). Open Innovation: Mortara and Minshall (2011). Innovation management: Chesbrough (2003).

19. Simón (2016).

20. Google pledged: Fiott (2016). IRPs in dual-use context: Bellais and Guichard (2006).

21. China: Cheung (2009, p. 17). Leap-frog and copycat: Hannas, Mulvenno, and Puglisi (2013). Defense R&D: Middleton, *et al*. (2006). Science education: Song (2008). R&D hubs: Walsh (2007).

22. Fiott and Bellais (2016).

23. Gansler (1989); Chesnais and Serfati (1992).

24. Planned obsolescence: Bellais and Droff (2016). Fourth industrial revolution: Brynjolfsson and McAfee (2014).

25. Not necessarily: Fiott (2016).

26. Fiott and Bellais (2016).

27. Defense planning: Council of the EU (2016, pp. 5, 23).

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