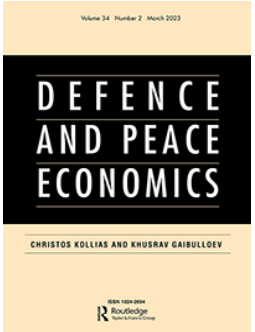

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Organisational Complexity of the Eurofighter Typhoon Collaborative Supply Chain

Ron Matthews and Rashid Al-Saadi

Centre for Defence Management and Leadership, Cranfield University at the Uk Defence Academy, Shrivenham, United Kingdom

ABSTRACT

The European Union (EU) promotes arms collaboration as a stepping-stone towards the evolution of an integrated European defence technology and industrial base. It will necessarily comprise prime contractors and their attendant supply chains, with the latter particularly important because they represent a refined regional division of labour, promoting efficiencies through skill-based specialisation. Paradoxically, however, Europe's largest military aerospace collaborative venture, the Eurofighter Typhoon, possesses a complex supply chain subject to political and institutional strictures, as well as potential inefficiencies. Partner nations prioritise national sovereignty objectives through duplicated assembly lines and work allocation arrangements based on juste retour (fair share) rather than market-driven competitiveness criteria. The purpose of this paper, then, is to explore Typhoon's supply chain complexity, especially the impact of juste retour policy. The findings from this analysis will highlight important policy issues influencing the future supply chain model of Europe's successor 6th-Generation fighter programme.

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Eurofighter typhoon; arms collaboration; defence supply chains; tempest fighter; juste retour

Introduction

In Europe, as elsewhere, the defence sector is politically sensitive and heavily regulated, with the nature and sources of weapons supply influenced by the host nation's history and politico-economic context. The region's defence industrial structure is characterised by prime contractors acting as high-value systems integrators located at the apex of critically important supply chains. The constituent firms are repositories of specialised and innovative engineering expertise accumulated through generations of investment into physical and human capital. Defence supply chains are highly diversified, comprising mostly 'commercial' small and medium size enterprises operating in an amorphous industrial sector under monopoly-monopsony market conditions. Not all defence suppliers are small, however. Rolls-Royce, for example, is a super-subcontractor in the field of military aero and maritime engines. The company also possesses a civil product structure, producing civil aero and marine propulsion components. This breakdown typifies the production structures of most other 'defence' subcontractors servicing the industrial needs of both the civil and defence economies (Maryellen, Kelley, and Watkins 1995, 52). Thus, defence supply chains contribute to national security not only through military output, but also through enhanced prosperity from cross-over economic and technical benefits impacting the broader economy.

However, weapon systems differ from commercial goods in the sense that they are designed to meet demanding military requirements, with their inherent complexity leading to comparatively higher rates of inflation. In recent times, several factors have been at play in accelerating acquisition

CONTACT Ron Matthews r.g.matthews@cranfield.ac.uk Cranfield University at the Uk Defence Academy

cost, but perhaps the dominant consideration is complexity. It is too simplistic to argue that weapons systems are R&D-intensive and therefore expensive; practical experience suggests that while the 'R' is expensive, the big cost driver is rather the specialisation associated with the 'D', compounded by low output scales.[1] A vicious cycle exists: the faster the cost growth of smart, stealthy and stand-off weapons, the greater the squeeze on procurement budgets, forcing reductions in production scale, and ultimately culminating in higher unit cost. Indeed, it has been demonstrated that the real unit cost of successive generations of combat aircraft has been around 10 percent per annum throughout the twentieth century, despite bouts of wishful thinking that this trend might be checked by changes in policies and practices (Kirkpatrick Hawk, 1995, 21; Kirkpatrick RUSI, 2019, 40). It is an inflationary spiral that is difficult to break, leading one observer to label the process as 'structural disarmament' (Callaghan Jnr. 1984), though the counter argument might be that militaries are getting more for their money, with the innovation process being driven by strategic competition.

The constant escalation of acquisition cost (Kleczka, Buts, and Jegers 2020, 130–32) has increased political pressure for more cost-effective acquisition strategies. One policy option that has found strategic, political and economic favour, especially in the high-cost military aerospace domain, is regional arms collaboration. Compared to national solutions, transnational technology-sharing is premised on the 'incontestable' logic that collaborative acquisition programmes, such as Tornado (Germany, Italy and the United Kingdom (UK)) and Eurofighter (Germany, Italy, Spain and the UK), act to shrink the financial burdens of participating countries. Practical experience, however, suggests otherwise.[2] Employing international arms collaboration means a problem is shared but not necessarily halved. The inherent complexity of work-share arrangements among partner nations forces arbitrary decision-making, inefficient supply chain structures and enduring work rebalancing that, counter-intuitively, elevate cost structures. Consequently, arms collaboration generates a lively debate between protagonists and antagonists, though, surprisingly, the debate has been confined to prime contractor relationships rather than the submerged supply chain component of the procurement iceberg.

This paper represents an attempt to fill the above intellectual void by offering a case study of the Eurofighter Typhoon's (henceforth, Typhoon) collaborative supply chain, described by a National Audit Office (NAO) Report 'as complex, and stretch[ing] across Europe' (National Audit Office – NAO 2011, 31). Transnational supply chain complexity has two interrelated elements (Rodrigues, Harris, and Mason 2015, 632): firstly, vertical collaboration – up and down the chain of supply, and, secondly, horizontal collaboration – between actors performing at the same level in the chain of supply (Barratt 2004, 32). Aerospace is selected as the sectoral focus because it is home to Europe's biggest collaborative venture, the Typhoon programme (National Audit Office – NAO 2001, 8). Yet, this paper's findings are also likely to resonate with multinational land and maritime collaborative ventures. Moreover, while this paper adopts a UK empirical perspective, all Typhoon's country partners are subject to the same institutional conditions, and thus the analytical findings are applicable across the Typhoon's entire multinational supply chain. The UK context is particularly interesting, though, because its defence supply chain is characterised by diversity, expansiveness (Dowdall 2004, 538) and underlying corporate relationship strategies that are judged to be both dynamic and highly sensitive (Croft et al. 2001; Johnsen, Howard, and Miemczyk 2009, 272). The paper begins by evaluating the scholarship underpinning military supply chains and international arms collaboration. The Typhoon case is then explored by reference to the evolution of powerful political relationships, governance mechanisms and underpinning industrial structures. Following this analysis, discussion turns to the supply chain implications of Europe's technological leap from the 4th-Generation Typhoon to its 6th-Generation successor, Tempest. A conclusions section brings the study to a close.

Evolution of Collaborative Military Supply Chains

The concept of military supply chains emerged from the logistical challenges faced during WWII, which in turn induced advances in the parallel field of business logistics (Rutner, Aviles, and Cox 2012). Several decades later, the global communication revolution occurred, leading to improved modes of transportation and just-in-time methods of production, inventory and distribution. In 1995, these developments heralded the formal use of the term, 'supply chain', reflecting the integration of logistical and interdisciplinary functionality both within an organisation and across its network (Chen, Law, and Yang 2009). The concept of supply chains has attracted numerous interpretations. From the defence perspective, the UK's principal defence prime contractor, BAES, defines its supply chain as an integrated system of functions, people, processes, information and resources, that when combined, adds value to the two-way flow of goods and information between source and user.[3] Supply chains encompass both upstream and downstream networking activities (Lamming et al. 2000), and require collective management and open communications (Christopher 2016) in customer-supplier relationships (Lambert, Knemeyer, and Gardner 2004). According to Barratt (2004, 35) successful collaborative supply networks evolve a culture that encourages trust, open communication, mutuality and information exchange. The same author identifies cultural differences and a lack of trust as major negatives, hindering the identification of appropriate partners and adequate information exchange (Barratt 2004, 30–42).

It is argued that modern defence firms compete with their supply chains (Christopher 2016; Lambert, Knemeyer, and Gardner 2004), highlighting that effective supply chain strategy is increasingly recognised as a market differentiator, representing a major source of competitive advantage (Christopher 2016). As a means of developing long-term competitive success, the supply chain can balance conflicts between its functions (Stevens 1989), adjust for swings in demand (Shoshanah and Roussel 2013), build stronger partner relationships (Roh, Hong, and Min 2014), and integrate suppliers and customers (Cigolini, Cozzi, and Perona 2004). To pursue competitive advantage in an effective and transparent manner, appropriate governance structures must be put in place. Supply chain governance is a 'system of directing the behaviours and decisions of procurement within an organisation via legislative, executive and judicial processes' (CIPS 2018). However, McCarthy (2003) cautions that governance is more complex and demanding in the modern commercial environment, because supply chain leaders must adapt to the dynamic business environment.

The imperative to operate in a dynamic business environment poses no threat to contemporary defence supply chains because they comprise mostly commercial, highly competitive, companies (Shoshanah and Roussel 2013, 132). This feature represents just one of several similarities between military and commercial supply chains. Both must continuously invest in frontier product and process technologies to keep one step ahead of potential competitors (enemies). Another common thread is the obvious read-across between the military's rapid and creative responses to operational uncertainty and the commercial risks and unknowns faced by commercial businesses (Christopher and Holweg 2011). In peacetime, both defence and business supply chains pursue cost-efficient operations (Yoho, Rietjens, and Tatham 2013), involving common dangers, such as dependence on limited suppliers, long lead times, cyber threats and collaborative challenges. Moreover, although civil supply chains are more technologically reactive, due to faster development cycles, the military provides valuable lessons for its commercial counterparts. These lessons include the military's operational resilience in the face of diverse and uncertain threats, its ability to adjust from conventional warfare to highly manoeuvrable asymmetric military operations and its capacity to engage in peace support and disaster response efforts under mostly uncertain conditions (Ancker and Burke 2003, 18). In war, logistical pressures intensify and act to sharpen the differences between business and military suppliers, especially with respect to strategic objectives. The civil supply chain's goal is always profit maximisation to increase shareholder value. The defence supply chain, by contrast, aims to maximise military capability in support of national security.[4] Thus, while errors in civil supply chains can be financially damaging, in the military they can be catastrophic, resulting in injuries, destruction and death (Yoho, Rietjens, and Tatham 2013).

Collaborative Military Aerospace Supply Chains

To examine the unique nature and challenges of European military aerospace supply chains, characterised by the Tornado and Typhoon programmes, it is important to understand the scholarship on international arms collaboration. At the heart of this intellectual debate is the EU's emphasis on multinational collaboration, not solely on aerospace but also the land and maritime sectors. Industrial consolidation through collaboration is viewed as an evolutionary process, encouraging transition from fragmented national defence industries to an integrated European defence industrial base (Matthews 2018, 117). Defence-industrial convergence will create manifold economic benefits, and principal among these is the eradication of manufacturing duplication. This will lead to a higher critical mass of output, securing minimum efficient scales and reduced cost, with benefits accruing to both primes and sub-primes. In this regard, Hartley and Sandler (1995, 225) argue that increasing output from 100 to 1,000 units could produce 40 per cent cost savings. Additionally, collaboration induces learning economies, derived from worker specialisation and increased dexterity because of repetitive tasks during serial or flow assembly. Savings are determined according to an empirically proven model that predicts the man-hours required for unit aircraft production will decline by 20 percent for each doubling of cumulative output: an 80 percent learning curve (Hartley 1983, 51–2). In the specific context of Typhoon production, Hartley (2006, 12) estimates an average 85 percent learning curve from an intensive process of continuous learning. He further asserts (Hartley 2006, 22) that there are benefits associated with partner companies sharing experience and problem-solving knowledge, such that the Typhoon's collaborative EJ200 engine is a much better product compared to the case where only one company had developed the engine.

However, collaboration is clearly more complex than national acquisition, and the above putative benefits must be weighed against what are termed 'collective action problems': the inefficiencies that arise due to increased complexity (Lorell and Lowell 1995). The fact is that while collaboration generates cost savings, there are also countervailing inefficiencies and costs associated with design differences and bureaucratic entanglement. These extra costs are encapsulated in the 1970's 'back-of -an-envelope' formula devised by the French haut fonctionnaire, Delpeche (1976, 33). The formula posits that the development cost of a cooperative programme exceeds that of a national venture by the square-root of the number of countries participating in the venture. A major reason for the relatively higher collaborative costs is that such programmes inevitably suffer from excessive delays (Hartley 2008, 310). In this respect, Delpeche further opines that the time required to complete a cooperative programme exceeds that of a national effort by the cube root of the number of participants.[5]

Moreover, while Europe's push for a common defence industrial base is premised on Adam Smith's concept of an international division of labour, the reality of regional-level specialisation is one in which commonality is undermined by the continuing prioritisation of national rather than European security.[6] The continued political reverence accorded by EU member states to national defence industrial sovereignty is anchored to the strategic reality that in war, security of supply is paramount. A reluctance to step away from sovereignty has meant minimal progress towards reducing unnecessary duplication among competing European arms suppliers through collaborative acquisition ventures. History demonstrates that partner states in major EU collaborative military aerospace programmes insist on separate assembly lines to protect and sometimes nurture high-value national industrial capabilities, notwithstanding the fact that duplicated manufacturing capacity adds considerable cost to collaborative acquisition programmes.

Case Study of the Typhoon

The Typhoon programme commenced in the early 1980s as a NATO Europe response to the military threat posed by the USSR and its Warsaw Pact allies. The four core partner nations (with Spain replacing France as one of the inaugural partners) agreed Typhoon's development programme in 1985, with the maiden flight in 1994 and operational deployment in 2003. The aircraft was initially intended to operate in an air-superiority role, but a common approach has diluted over time. While Germany, Italy and Spain still use the Typhoon in a (beyond) air-to-air role, the Royal Air Force (RAF) and its export customers, Saudi Arabia, Qatar and Oman, operate the British-designated Typhoon as a multi-role fighter (Bronk 2015, ix). Accommodating such design differences has induced operational compromises and associated delays, severely extending the Typhoon's life cycle so that it took around two decades for the aircraft to progress from concept to in-service; so long, in fact, that the aircraft's original air-to-air strategic role of countering the Soviet threat on the Central European front became redundant following the disappearance of the USSR and the associated Communist threat.

Programme delays have proved a major headache, but arguably the greatest inefficiency associated with the Typhoon collaborative programme, has been the absence of a genuine division of labour among partner nations. This has meant that production inputs, such as systems and subsystems, are not sourced based on industrial comparative advantage, but rather on ensuring that the work is equitably shared among the participating collaborative states (Sempere 2017, 334). Each member country's workshare is determined according to a concept termed juste retour: a fair return (inputs) in relation to the numbers of aircraft procured (outputs). It is a controversial concept, reflecting the reality of working in Europe; indeed, one observer argues it is akin to a cartel, where participants divide workshares between themselves, with any disagreements adjudicated not by corporate executives but by politicians (Moravcsik 1990, 74). At the highest systems level, juste retour translates into suites of work packages allocated to each of the four partner state's defence industries. Thus, for the UK, BAE Systems produces the aircraft's forward fuselage, foreplanes (canards), canopy/windscreen, spine assembly, vertical stabiliser (air-brake), inboard flaperons and stage one of the aft fuselage; Germany's Airbus is responsible for the centre fuselage; Italy's Leonardo, the left wing, outboard flaperons and the remainder of the aft fuselage; and Spain's Airbus, the right wing and the leading edge slats for both the left and right wings.[7]

The following UK examples provide a sense of the problems encountered during the early years of the Typhoon consortium: firstly, workshare requirements for the development of the Flight Control System ruled out a far cheaper technically compliant solo bid from the UK General Electric Company (GEC) in favour of a consortium proposal; secondly, the electronics for the Head-Up Display required UK drawings, but juste retour meant that the subsystems were produced in three different overseas locations before return to the UK for final assembly and testing; and, thirdly, Marconi, the leading UK company for systems development work, represented the only supplier possessing proven expertise and experience needed to design and produce the system, but was obliged to subcontract work to partner countries in order to meet workshare percentage requirements. Worse still, in its testing role, any components Marconi failed had to be returned to the foreign originating company for rectification before re-entering the testing loop (National Audit Office – NAO 1995, 6 & 21; February 2001, 76–77). Rigid adherence to juste retour ratios sacrifices supply chain efficiency and leads to cost increases of between 33–100 percent of a collaborative programme's potential cost (Heuninckx 2008, 11 & 18), and accounts for up to 96 percent higher costs compared to an equivalent national aircraft (De Vore 2011, 657; National Audit Office – NAO 2001, 16).[8]

On the upside, Typhoon's scale of production is impressive when compared to national output. As of May 2021, 572 aircraft have been delivered out of 662 total orders, including 511 aircraft from the four partner nations via four tranches and an additional 151 overseas export sales.[9] The lead nation

Table 1. Typhoon Production Tranches and Export Sales.

	Nations	Tranche 1	Tranche 2	Tranche 3A	Tranche 4	Total
Core Programme	United Kingdom	53	67	40	-	160
	Germany	33	79	31	38	181
	Italy	28	47	21	-	96
	Spain	19	34	21	-	74
Export	Austria	15	-	-	-	15
	Saudi Arabia	-	48	24	-	72
	Oman	-	-	12	-	12
	Kuwait	-	-	28	-	28
	Qatar	-	-	24	-	24
	Total	148	275	201	38	662

Source: Correspondence with BAES, 18 January 2021
Note: It was intended that Tranche 3 would be split into two delivery components, but 3B was abandoned due to reasons of unaffordability. Tranche 4 represents Germany's November 2020 procurement of 38 Quadrega Typhoons.

on a particular overseas marketing campaign is determined by partner countries based on judgements regarding which participating nations/industries possess the highest probability of winning the order.[10] This determination will be partially influenced by past, present and sometimes planned political alliances.[11] Aircraft destined for core nations or export customers have no impact on work allocation across systems development, equipment acquisition and installation.[12] However, the lead export company will assume prime contractor responsibility for aircraft mark-up, and this will bring with it the benefits of enhanced return on sales or investment, though with the downside of higher risk levels.[13] The breakdown of Typhoon orders among partner nations and export destinations is provided in Table 1.

The total cost of the Typhoon programme since inception (early 1980s) to completion in 2030 is estimated to be around £37bn (Heinrich 2015, 343; National Audit Office – NAO 2011, 7–8). This figure includes the life cycle fixed costs of providing ground support and building infrastructure and the service costs of support and maintenance, with the latter estimated to account for 60 percent of total cost (Heinrich 2015, 343; National Audit Office – NAO 2011, 25). Above and beyond regular life cycle support, partner nations manage technological upgrading, involving continuous refreshment of Typhoon's capabilities in critical areas. This arrangement appears to work well, despite the dilution of national aerospace industrial clusters caused by the imperative of knitting together distant European suppliers into Typhoon's transnational supply chain. For instance, Rolls-Royce is interwoven with all its UK and European suppliers and research facilities to bring innovation to the market as opportunities arise.[14] Across Europe, the Typhoon programme supports 105,000 jobs among prime- and sub-prime companies, comprising approximately 40,000 workers in the UK, 20,000 in Germany, 20,000 in Italy and 25,000 in Spain, with most located in highly skilled aeronautical design and engineering domains (Hartley 2008, 310). A significant proportion of these skilled workers are engaged in civil-military development and production activities. For example, the civil-military workshare at Rolls-Royce is 50:50,[15] while across the Typhoon supply base, the ratio is more generally around 60 percent in favour of defence (Hartley 2006, 10). This civil emphasis suggests that the cross-threading benefits of technology spin-off and spin-on permeate the supply chain and potentially contribute to the growth of national economic prosperity.

Table 2. Typhoon ownership, prime contractor and workshare structures.

Country names	United Kingdom	Germany	Italy	Spain
Flags				
Prime contractors	BAE Systems	Airbus Defence and Space Germany	Leonardo	Airbus Defence and Space Spain
Workshares	37.5%	30%	19.5%	13%

Source: BAES internal report, 30 October 2020

The Typhoon programme has attracted huge investment, and while the juste retour mechanism for 'sharing' high value work among the four participating states is clear, the operational process is complex. Workshares were determined in 1985, when the Typhoon contract was signed. At that time, as illustrated in Table 2, the UK's procurement of 232 aircraft against a four-nation total of 620 aircraft, created a UK workshare of 37.5 percent; Germany's 180 aircraft procurement generated a workshare of 30 percent; Italy's 121 aircraft generated 19.5 percent; and Spain's order of 87 aircraft generated 13 percent. In 2009, there were further changes to the partner nations' acquisition profiles (for example, UK acquisition fell to 160 aircraft and Germany's declined by a proportionally smaller number to 143), but the workshare percentages remained unaltered.

Typhoon's Supply Chain: A Study in Complexity

Figure 1, below, offers a diagrammatic model of the Typhoon's unique hierarchical supply chain, comprising multiple layers of national governmental representation, governance structures, independent project management organisations and prime- and sub-prime industries. Typhoon's collaborative supply chain has several features which sets it apart from conventional commercial supply chains. Perhaps the most novel but obvious feature are the partner nations' defence departments sitting atop the supply pyramid and bearing the responsibility for making the ultimate procurement decision. Such decisions must be based on advice from military and industrial stakeholders in the home nations, which, in turn, is influenced by Typhoon's budgetary cost-capability-scale boundaries. Ministerial decisions are subject to the prevailing budgetary impacts of changing tranche volumes and midlife systems upgrades. Once higher-level inter-governmental agreement is reached, there is then a two-level governance architecture tasked with programme oversight and high-level management.

The first governance layer is provided by an organisation called NETMA (NATO Eurofighter and Tornado Management Agency). It acts on behalf of customer governments to check that prime contractors fulfil their contractual obligations, and as part of this process undertakes flow down

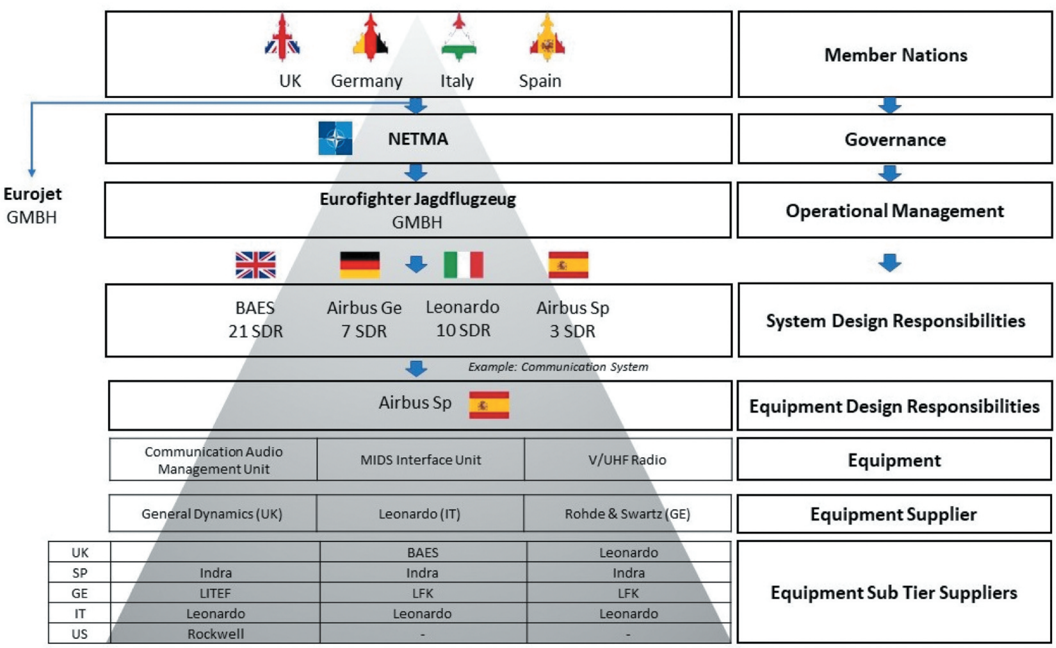

Figure 1. Typhoon Supply Chain. Source: BAES internal document, 29 April 2021

audits to ensure contractual compliance. As its title indicates, NETMA is a NATO organisation, providing high-level governance on the Typhoon programme through a Joint Steering Committee composed of two-star representatives from each partner nation. All decisions in this 'star-chamber' must be unanimous. NETMA is also responsible for settling the politically contentious issue of workshare. The issue is problematic because all four partner nations seek the highest input value in terms of developing/maintaining an indigenous high-technology aerospace sector. While juste retour determines the workshare percentages of participating nations, it does not specify the nature of the work packages that each partner receives. The disbursement of high value work packages is achieved through negotiation, partially based on industrial and technological competence, partially on experience gained through participation in predecessor aircraft programmes (e.g. BAES took the lead on Tornado fighter avionics and, logically, again took the lead on Typhoon avionic systems) and partially on political and industrial trade-offs.[16] Hence, juste retour increases costs as partner nations agree workshares in part through political bargaining rather than on economic efficiency criteria linked to competitiveness and comparative advantage (Hartley 2019, 244–45).

Differing work package responsibilities raise questions about whether transaction costs are minimised in the supply of Typhoon wings, fuselage sections, subassemblies and systems that are shipped to each of the four partner assembly lines. Such complexity creates an imperative to develop an economic, as well as an engineering, 'systems-of-systems' model, with the requirement that member states fund only the workshare of domestic industry, thereby minimising payments across national boundaries. Facilitating this system, NETMA operates an offset-billing process in which periodic debits and credits of Typhoon shipments are calculated. When necessary, adjustments are made, either in cash or additional workflow, to account for the net differences between agreed partner nation workshare targets. This ensures that, at the conclusion of a contracting period, cost-share equals work-share equals off-take. NETMA is an important high-level governance body, and at this late stage in Typhoon's lifecycle, the supply chain is stable, and NETMA's governance role is minimal.[17] However, this is not to deny challenges exist, with the organisation suffering from three major weaknesses: a lack of delegated authority, squeezed empowerment in terms of programme management and limited accountability.[18] These problems are partially caused by organisational silos among the various stakeholders, limiting information flow and undermining long-term consensus planning. NETMA additionally suffers from the lack of a common long-term strategy focused on Typhoon's future evolution, which is partially caused by the varying sophistication of participating nations' national planning apparatus.[19]

The second layer of governance is provided by the four national aerospace prime-contractors (Airbus GE, Airbus SP, BAES and Leonardo) through an organisation called Eurofighter Jagdflugzeung GmbH. This organisation also operates as the coordinating authority on the aircraft's design, production and upgrade activities, acting as the primary interface between the European industrial partners and the customer through NETMA. Accordingly, Eurofighter Jagdflugzeung GmbH is responsible for programme management, with a remit to secure high levels of transparency and operational performance. However, inevitably, the involvement of four sets of national decision-makers compounds the complexity of decision-making, governance and industrial interaction. Thus, Eurofighter Jagdflugzeung GmbH faces the same organisational limitations as NETMA, particularly with respect to its constrained mandate and empowerment. A further weakness is the lack of universally acknowledged standardised processes backed by comprehensive documentation, leading to work variances due to the differing personal preferences and organisational cultures of partner nation industries.

As Figure 1 illustrates, positioned within the Typhoon supply chain is a parallel high-level organisation responsible for the management of the aircraft's EJ200 engine development, production, maintenance and sales. It possesses a similarly complex partnering arrangement, incorporating, for example, Rolls-Royce's EJ200 supply chain that comprises 67 dedicated companies working alongside a mesh of traditional UK suppliers and EJ200's European and non-European partners.[20] Both the aircraft and aeroengine international consortia are co-signatories with NETMA on the

Typhoon's principal development contracts, ensuring that integrated design and performance specifications are achieved. Nevertheless, these governance and project management organisations suffer from excessive levels of bureaucracy, colourfully described as organisational 'treacle'.[21]

English is employed as the common language in the reporting structure, but there are translation and bureaucratic delays from innumerable meetings between representatives of the respective member countries' Ministries of Defence. One National Audit Office report – NAO (1995, 28–32) noted that in a single calendar year, some 585 meetings between partner companies were planned, though 796 were actually held. The planned and additional meetings and associated administration burden creates bureaucratic 'drag', with four separate layers of national management entwined within Typhoon's committee meetings, often attracting up to 60 attendees, all in search of consensus. Inordinate delays are caused by several factors, including duplication of meetings on similar topics, the inability of low-level meetings to reach decisions – necessitating escalation of decision-making to higher hierarchical strata and excessive customer and industry attendees at forums – stalling progress until consensus and alignment are achieved.[22] Indeed, it has been estimated that up to two years is required to finalise contracts before development work can begin, pushing the capability development envelope, from concept to embodiment, to seven years.[23] Delays caused by bureaucracy represent just one, albeit major, impediment to the smooth functioning of the collaborative model. Wider politico-economic challenges that impact on the Typhoon's complex supply chain framework, are listed in Table 3.

As highlighted earlier, a distinctive feature of Typhoon's supply chain, including the EJ200 consortium, is that work is not allocated on the basis of competitive efficiency, but rather on workshares determined by the controversial juste retour formula. Work is allocated across a transnational network of interconnecting national supply chains comprising over 400 European companies, driven by the ultimate objective that each partner nation enjoys workshares valued at pre-agreed input-output-cost ratios.[24] Juste retour workshare percentages apply horizontally, between partner countries, and vertically, via percentage allocations cascading down through three supply chain levels of activity, covering System Design Responsibilities (SDRs), Equipment Design Responsibilities (EDRs) and Installation Design Responsibilities (IDRs). This 'design, procure and install' process works to ensure that ultimately the UK receives 37.5 percent of the work, Germany 30 percent, Italy 19.5 percent and Spain 13 percent, as highlighted in Table 2. There are 42 SDRs in total, with BAES (UK) 'owning' 21, Leonardo (IT) 10, Airbus (GE) seven and Airbus (SP) three.[25] These SDRs represent the highest value and skill domains on the Typhoon programme, and, hence, are regarded as the technological 'crown jewels', actively sought by partner nations. Accordingly, all partner country prime contractors retain as much of the SDR work as possible, outsourcing the EDR and IDR work.[26]

Table 3. Flaws in the Framework: Typhoon's Collaborative Supply Chain.

Engagement with the different business models adopted by each of the individual business partners
Changing national requirements
Divergent budget cycles
Export controls (e.g. recent license restrictions on sales to Saudi Arabia)
Managing US origin content and overhead cost
Speed of decision-making
Political interference
Protection of IP and commercial interests
National security protections
Agreeing work-share arrangements
Agreeing export policy
Agreeing outsourcing and offshoring arrangements with third parties
Storage and protection of data
Operating under an international MOU/Treaty which fails to reflect the environmental dynamics of geo-politics, commerce and technological change

Source: Rolls-Royce senior executive, 20 October 2020
Note: Flaws not ranked in order of importance

Embedded within the 42 SDRs are five Industrial Joint Teams (IJTs) allocated across the four partner industries. The IJTs are principally focused on systems design and the integration of avionics, Flight Control, Utility Control, Structure, and Weapons Integration. The avionics IJT, for instance, is owned by BAES and is one of the largest, with around 120 mostly professional in-house staff.[27] The IJTs were established with the tri-fold objectives of aligning systems design across the multiple subsystems, reducing information segregation across partner nations and exploiting potential synergies through knowledge sharing. However, progress in achieving these goals has been compromised, as earlier mentioned, by weak empowerment from Eurofighter Jagdflugzeung GmbH.[28] As a consequence, cross-national IJTs are heavily influenced by host partner nations, whose parochial interests act to stall wider horizontal and vertical industrial engagement. Once the allocation of SDR and IJT systems has been agreed, selected downstream companies are awarded Equipment Design Responsibility. At the EDR level, companies across the four partner countries are tasked with designing nearly 800 line-items.[29] The workshares can be decomposed into 348 equipment subsystems to BAE Systems, 204 to Leonardo, 148 to Airbus GE and 79 to Airbus SP.[30] Non partner countries, France and the US, are respectively allocated an additional three and five EDRs, representing a significant 12 percent value share, overall.[31]

Figure 1 offers the example of the Communications SDR allocated to the Spanish Defence and Space company, Airbus SP. Typifying partner country efforts to keep as much high value work within their respective economies, Spain keeps all SDR work within Airbus SP, and similarly, captures all three Communications EDRs, comprising the Communication and Audio Management Unit (CAMU), the Multifunctional Information Distribution System (MIDS – a NATO data communication link, governed by the US and utilised by air forces in which Washington is prepared to share the cryptographic keys) and the Transceiver and Antennas Unit (V/UHF Radio). In this Communications SDR example, Spain's three prime suppliers comprise General Dynamics (UK) for the CAMU, Leonardo (Italy) for the MIDS and Rohde and Swartz (Germany) for the V/UHF Radio. Drilling down still further, the Team-Lead for the V/UHF Radio (Rhode and Schwartz) will define the equipment specification and flow this downstream to the sub-tier suppliers, Leonardo (UK and Italy locations), Indra (Spain) and LFK (Germany). Airbus SP will manage the manufacturing requirement, and once the supplier builds, tests and ships the radio, the IDR company will install it into the aircraft, as part of the 'final assembly' IDR work, at locations across Europe.[32] Interestingly, the UK prime supplier is the American-owned General Dynamics, which qualifies for a juste retour workshare allocation because it acquired a company that was UK-based.

Each of the three equipment suppliers procure from their respective equipment sub-tier supply chains before they integrate, test and ship to the respective IDR locations. This again represents an artificial distribution of work requiring constant monitoring to ensure strict juste retour targets are achieved, with the arbitrary nature of the process inevitably leading to higher costs. Below the prime-supplier level, tens of thousands of components, low-cost fittings and basic raw materials are sourced from industries within the partner states and from non-partner countries (e.g. BAE Systems buys materials and low value manufacturing parts from the US), and none of these purchases will be captured in the juste retour workshare calculus. Tenders for this relatively low-value work are conducted via open cross-border competition, leading to actual or potential leakage to non-partner countries.[33] Compounding these problems is the fact that only a small percentage of Typhoon contracts are incentivised.[34] However, quality is assured, because every piece of equipment received via 'payment on delivery' is certified through a Certificate of Conformance, and similarly high-value supply chain-to-prime suppliers which receive 'advance payments' are also certified.[35]

Life after Typhoon

Typhoon's organisational and management model is a political construct, representing a tricky balancing act between member country economic considerations and longer-term capability planning. Consequently, the aircraft's future product strategy has suffered, and has contributed to the discontinuation of Typhoon's partnership structures for the successor Future Combat Aircraft System (FCAS). However, there are other factors at play, including, unsurprisingly, a consensus that juste retour represents a poor substitute for competitive supply relations and an alternative business process was necessary.[36] Additionally, there exist political discord that goes back to the relative failure of Europe's two major defence powers, France and the UK, to deliver on the lofty military and defence-industrial collaborative ambitions embodied in the 2010 Lancaster House Treaty. Instead of closer cooperation in these areas, strategic and technological rivalry re-emerged. France sought to safeguard the notion of 'strategic autonomy', and because of this, BAES became embroiled in a competitive struggle with Dassault (Marrone and Nones 2019, 6). Moreover, Brexit acted to exacerbate the already fractured Euro-UK politico-economic relationship. The result has been rapprochement between Paris and Berlin, symbolised by a 2016 agreement to explore joint development of a 6th-Generation FCAS. Finally, France feared a re-run of its absence in the Typhoon project and to assuage this prospect sought technological leadership of the FCAS. If control of critical technologies was not possible via cooperation, then it would be achieved through competition. Hence, the Typhoon consortium partners took divergent 'political' paths in design of two separate 6th-Generation fighter aircraft, with Germany, Spain and fellow Airbus partner, France, competing with the UK, Italy and Sweden.

The UK programme was launched in 2018 with £2bn of government and industry funding through a newly formed Combat Air Acquisition Programme (CAAP). This was aimed at designing, developing, manufacturing and supporting a technology demonstrator for the newly named Tempest fighter. The UK-led programme appears to have gained the greatest development traction compared to its rival FCAS; the aim being to replace the 4th-Generation Typhoon five years ahead of the Franco-German launch timescale (Brzozowski 2019). Industry has committed to supporting the UK MOD in achieving this target, but the timelines are ambitious, including down-selection and contracting of the collaborative partnering option by late 2021, confirmation of final investment decisions by 2025 and initial operating capability by 2035.[37] Tempest is already well into the conceptualisation phase, with Roblin (2020) stating that 2,500 workers are already engaged on Team Tempest. Indeed, it is predicted that between 2026 and 2050 full manufacturing will sustain around 20,000 highly skilled jobs (Lea 2020a). The aircraft will feature numerous innovative features. For example, the piloted version will have a virtual 'avatar' co-pilot to free the pilot of numerous responsibilities, with both the piloted and unpiloted versions possessing the capacity to process 10,000 times the military theatre data of the Typhoon (Fisher 2020a).

The business framework intended to deliver the Tempest programme will be different from the Typhoon's acquisition programme. For example, it is anticipated that the Tempest partnership will quicken the pace of generating and maturing technologies, thus contributing to affordability. To reduce costs and eliminate delays, Tempest has been designed from the 'inside-out', focusing on software in a bid to exploit artificial intelligence and 'plug-in' technologies, rather than the traditional model of 'outside-in', in which sensors and weapons would be added via the slow and expensive construction of hardware (Tovey 2020). It is anticipated that the affordable Tempest fighter will positively influence exportability. Existing Middle Eastern Typhoon customers, such as Oman, Qatar and Saudi Arabia, will be important elements in the business equation, because they will be expected to seek replacements for their future ageing fighter fleets. Significantly, BAES acted as the prime contractor on all three of these overseas sales programmes.

The UK MoD is actively engaged in supporting the Tempest supply chain, which incorporates 'heavyweight' industrial partners such as BAES, Leonardo, Rolls-Royce and MBDA as well as several hundred supplier companies and other organisations, including universities. This formative supply chain presently operates within a European collaborative framework, with potential future participation from the Netherlands (Roblin 2020). Non-European collaborators are speculated to include Japan, India, Saudi Arabia and Turkey (Lea 2020b; Marrone and Nones 2019, 109). Whatever the eventual permutation of partners and suppliers, Tempest's supply chain will be fundamentally transformed through the induction of Stratasys into the supply structure, producing around 30 percent of aircraft components through additive manufacturing (3D printing) with a further 50 percent robotically assembled on BAES' assembly line (Davies 2020; Hollinger 2020). This represents a step change in technological capability compared to the Typhoon, which uses only one percent additive manufacturing and zero robotics in production operations (Hollinger 2020). Although BAES' current use of 3D printing technology, by product value, is minimal, the company has used the technique for more than 20 years, and its adoption is now widespread and growing, primarily through rapid prototyping in the manufacture of 'standard components' on Typhoon aircraft (Davies 2020). Typhoon's UK shop floor is currently acting as an experimental test bed to gauge the effectiveness of these advanced technologies in the transition from 4th- to 6th-generation fighters.

Other future impacts can be speculated to include shrinkage of BAES' military aerospace supply chain, because instead of outsourcing components, there will likely be a partial return to vertical integration. BAES is planning that 3D printing and robotic technologies will reduce by half the cost and time involved in producing a complex fighter aircraft; indeed, remarkable economies have already been modelled, including a reduction in production time from about two years to just two months for one large system located in Tempest's rear fuselage (Hollinger 2020). However, the use of these fourth industrial revolution technologies will lead to the loss of traditional skilled aerospace engineering workers, such as machinists and fabricators, who weld sheet metal and assemble complex components and systems. Moreover, non-traditional firms located outside the aerospace sector can be expected to form part of the supply chain. For example, Rolls-Royce's more efficient and longer-range advanced future power propulsion units will produce substantial additional amounts of heat. To store and re-channel this additional energy into Tempest's 'directed-energy-weapons', Williams Advanced Engineering, a division of a motor racing company, has joined the Tempest supply chain to provide batteries, energy storage and cooling technology, all first deployed on a motor racing track (Tovey 2020).

Challenges remain, however, including the principal risks driving delay and cost, such as modifications, mid-life upgrades and proprietary software that will continue to exist in Tempest's new exploratory 'end-to-end' supply chain. These risks add weight to the gloomy prediction that Tempest's unit production cost will be consistent with the historic inflationary trend of successive next-generation combat aircraft. Compared to the planned 'affordable' but eventually expensive F-35, carrying a $100 million unit cost tag, even with the benefits of scale, the Tempest will have a shorter production run and incorporate more advanced technology suggesting an even higher unit cost.[38] Moreover, due to the huge investment burden involved in developing a modern fighter platform possessing the flexibility to integrate technologies not yet invented and face threats as yet unknown, there is the distinct possibility that in the future, Europe's two FCAS programmes will merge (Fisher 2020b). History, though, is replete with examples of political rivalries, such as Typhoon versus Rafale, dominating economic logic.

Conclusion

The aim of this article has been to explore organisational complexity within international collaborative military aerospace supply chains, taking Europe's Typhoon fighter as a case study. The topic, though under-researched, is nevertheless important, because collaboration is viewed as an acquisition option that can dampen rising defence equipment costs. Of related contemporary policy significance is the fact that high-technology supply chains can fuel civil-military innovation, contributing to both economic prosperity and military security. For these benefits to arise, however, there must be convergence of inter-organisational cultures between multi-national participants to remove obstacles to information flow, transparency and strong governance. The Typhoon experience reflects a political construct of its time, demonstrating numerous organisational, political and structural frailties, including cultural dissonance, excessive bureaucracy, interminable delays, technical compromise, inadequate governance, cost-plus contracts and the persistence of information silos. One major contributing factor to these flaws resides in the institutional mechanism, juste retour, which is used to determine participant workshare. Evolution of an efficient international division of labour is hampered by the arbitrary inclusion into the supply chain of relatively inefficient companies simply to achieve pre-agreed national work quotas. The Typhoon juste retour process that allocates work into its supply chain creates a remarkable degree of inter-organisational complexity. The design and manufacturing process comprises work packages allocated horizontally across a multinational network of prime- and sub-prime companies with three vertical tiers of activity incorporating 42 SDRs, 800 EDRs and innumerable IDRs. Inevitably, each of the partner country primes vies for project management of high-value SDRs and once in possession, monopolises ownership of downstream EDR work packages.

Although the Typhoon supply chain, characterised by juste retour, drives sub-optimal collaborative behaviour, incurring substantial cost inefficiencies, it is an industrial construct that over the decades has functioned smoothly, suffering surprisingly little politico-economic intervention and interruption. Once work allocation percentages have been agreed and defence-industrial sovereignty demarcation lines negotiated, inter-organisational structures, relationships and trust have been allowed to mature. The passage of time has enabled greater efficiencies at the micro-industrial level and more intensive defence-industrial integration at the macro-European level. Germany's 2020 procurement and potential further sales opportunities indicate that the Typhoon model will be around for decades to come. Yet, Europe's successor 6th-Generation FCAS programme will comprise competing ventures, splitting the market in two. There is little in the way of an economic or strategic rationale to commend this divisive approach, but, ultimately, affordability pressures may oblige the two FCAS programmes to merge. If this happens, it will create a consortium one-third larger than that of Typhoon, and an attenuated inter-organisational supply chain structure of even greater complexity. The policy imperative calls for a business model that prioritises economic efficiency over national sovereignty, but this is easier said than done.

Notes

1. Correspondence with a BAES executive, 29 April 2021
2. Rafale, for instance, is probably more expensive than the Eurofighter, but the cost equation is heavily influenced by domestic and overseas sales.
3. Interview with a BAES executive, 12 February 2020
4. In reality, the comparison is more nuanced. The profit maximisation objective will also apply to corporate defence contractors, such as those in the UK, where the entire defence industrial base, save for nuclear weapons, is in the commercial sector. Logic dictates that even government-owned defence firms would also aim to operate efficiently.
5. It should be noted that while Delpeche's formulae impress with their precision, and finds currency among defence economists, they are without empirical validation.
6. Note, however, that Moravcsik (1991) expresses the opposite view, i.e. that autarchy in complex weapons systems has not been an enduring dominant preference of politico-military elites in Europe since the 'military revolution.'
7. Correspondence with a BAES executive, 29 April 2021
8. Although juste retour has been the dominant workshare methodology employed on major European transnational collaborative ventures, policymakers recognise its inherent inefficiencies and thus alternative approaches have been adopted. For example, OCCAR is a six nation European through-life management body that pursues cooperative defence equipment programmes. It uses qualified flexible voting on critical decisions ensuring faster decision making, and renounces what it describes as the analytical calculation of industrial juste retour. Instead, it employs a 'global balance' approach, defined as the pursuit of an overall and flexible multi-programme/multi-year balance of workshare against cost share.
9. Correspondence with a BAES Eurofighter executive, 17 May 2021
10. Interview with a BAES executive, 6 March 2019
11. Interview with a BAES executive, 6 March 2019
12. Interview with a BAES executive, 29 April 2021
13. Interview with a BAES executive, 6 March 2019
14. E-mail correspondence with a senior Rolls-Royce executive, 20 October 2020

15. E-mail correspondence with a senior Rolls-Royce executive, 20 October 2020
16. Interview with a BAES executive, 6 March 2019.
17. E-mail correspondence with a senior Rolls-Royce executive, 20 October 2020
18. Anonymous Eurofighter supplier executive, 22 July 2020
19. Anonymous Eurofighter supplier executive, 22 July 2020
20. E-mail correspondence with a senior Rolls-Royce executive, 20 October 2020. Note that 18 percent of Rolls-Royce's EJ200 supply chain is non-European.
21. Anonymous Eurofighter supplier executive, 22 July 2020.
22. Note that while Spain only accounts for a 13 percent workshare in the programme, it has an equal voice (veto) at the negotiating table.
23. Anonymous Eurofighter supplier executive, 22 July 2020
24. Interview with a BAES executive, 6 March 2019
25. Interview with a BAES executive, 6 March 2019. It should be noted that there is an additional 'weapons' SDR in which the lead role is shared across all partner nations; however, as BAES assumes responsibility for the majority of weapons' lead roles it has become convention for this SDR to be assigned to the British company, increasing its SDR allocation to 22 and the consortium total to 42.
26. Interview with a BAES executive, 12 February 2020
27. Interview with a BAES executive, 12 February 2020
28. Anonymous Eurofighter supplier executive, 22 July 2020
29. Correspondence with a BAES executive, 29 April 2021
30. Interview with a BAES executive, 12 February 2020
31. Interview with a BAES executive, 12 February 2020
32. E-mail correspondence with a BAES executive, 18 January 2021
33. Interview with a BAES executive, 12 February 2020
34. Anonymous Eurofighter supplier executive, 22 July 2020
35. E-mail correspondence with a BAES executive, 18 January 2021.
36. The Tempest's organisational structure has yet to be determined. There are three options. Firstly, continue with a NETMA-type dedicated project-based agency that benefits from specialisation. However, its high level of bureaucracy and rigid juste retour workshare methodology creates delays and increased cost. OCCAR, by contrast, is an international cooperative procurement body where work goes to the most efficient participating member state's industry, with imbalances corrected across subsequent procurement programmes. There is no guidance on how this concept works in practice, save for an initial Treaty statement that action will be taken if workshare falls below 66% of financial contribution in any programme. Although this might be viewed as 'kicking the can down the road', OCCAR appears attractive to major European states and currently manages 16 complex defence equipment projects, including the A400M and more recently the Boxer multi-role armoured vehicle programme. A third organisational structure is that of the US-led eight country (after the 2019 removal of Turkey) Joint Strike Fighter consortium, which employs a workshare solution based on 'arms-length' competition. In practice, this works against the interests of the smaller partners which struggle to compete against the scale and R&D capability of US and UK defence contractors. All three project management approaches thus appear to exhibit implementation problems, begging the question as to whether a perfect workshare model exists.
37. Correspondence with a BAES Eurofighter executive, 30 October 2020.
38. Correspondence with Professor David Kirkpatrick, 19 June 2020; also see, RUSI Journal, June 2020, 40.

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