Model-based Engineering and the Digital Thread

N A W Harrison[1,2]*, R I Whitfield[2], K A Odukoya[2], A L Powell[3]

[1] *BAE Systems, Maritime – Naval Ships, UK*
[2] *University of Strathclyde, UK*
[3] *YorkMetrics Ltd.*

* Corresponding Author: neil.a.harrison@baesystems.com

Synopsis

The digital thread is an emerging concept central to the continuing modernisation of naval shipbuilding. The digital thread is the backbone around which the knowledge of the product system is brought together and subsequently exploited. It is central to the cost-effective realisation of digital twins across the lifecycle. More so than ever before, this knowledge is codified in a large number of increasingly sophisticated digital models. These are now used through-life across the design, build, delivery and operation of naval systems, returning otherwise inaccessible insight into both systems and programmes.

These collections of digital models are typically diverse in nature, representing a wide array of unique and complementary views of the ship. They are usually created in a narrower design or system analysis context that often doesn't require them to run particularly efficiently or produce results that are easily digitally integrated or re-exploited. Yet they also nearly always have more value to offer shipbuilding projects and customers beyond their initial use. The challenge of creating and maintaining these models in a way that supports valuable re-exploitations is new and challenging for most in the shipbuilding industry, hence the growing interest in digital threads.

Multiple larger commercial design and analysis software environments offer 'out-of-box' kernels for digital threading. Additionally, emerging data standards and digital interchange conventions offer further building blocks. The methodologies and toolchains of data science and DevSecOps also contribute relevant solutions in the opportunity space. However, most digital twins and digital threads today are quite narrow and brittle, and do not cope well with novel usage, extension and change. Ship buyers and operators want the benefits of large, flexible, scalable and easily exploitable digital threads and twins, but are rarely the best positioned to fully architect and develop them.

Ship integrators, designers and builders – including the many combinations of partnerships involved in ship development today – have an important leading role to play in the continued development of digital threads and twins. There is much we can learn from other industries, including the civil engineering world that benefits significantly from the Building Information Management (BIM) standards and toolsets, and the automotive sector, which has several digitally mature businesses and toolchains. Big Tech companies also have a lot to offer in how they see and solve these problems. Additionally, there are several emerging technologies and approaches that are set to contribute to currently insolvent challenges, and we should adopt and drive these forward according to the needs of naval shipbuilding.

This paper presents an industrial perspective on what seems to be emerging as important in the incremental development of the scalable and flexible digital threads and twins of the future. It highlights important technology opportunities and addresses practicalities of collaborating on these technology-centric challenges. The aim in presenting this perspective is to team more broadly and effectively on these challenges and opportunities, accelerating the development of the next generation of digital threads and twins that will revolutionise both the delivery and user experience of future ship systems.

Keywords: Model-Based Engineering; Digital Thread; MBSE; Digital Twin; Digital Transformation; Naval Ships;

Authors' Biographies
Neil Harrison is a lead technologist at BAE Systems Maritime – Naval Ships and a part-time PhD candidate at the University of Strathclyde. **Kofoworola Adebowale Odukoya** is a PhD student at the University of Strathclyde in DMEM, researching consistency transfer of data across Architectural Frameworks. **Antony Powell** Antony Powell is founder of YorkMetrics Ltd. and an honorary visiting fellow at the University of York. **Robert Ian Whitfield** is a Senior Lecturer at the University of Strathclyde, delivering Systems Engineering Management research and knowledge exchange projects.

1. Why this paper?

The ongoing surge of digital disruption is a pressing invitation to revolutionise complex systems development. Today's maritime defence environment today is thick with complex systems, competing and collaborating in growing constellations across multiple domains and modes of conflict. Naval ships are important nodes in these networks and amongst the most challenging system development prospects.

Navies tend to buy ships in smaller batches that include engineer-to-order (ETO) aspects and they usually want to deploy the first of class rapidly into this fast-moving operational environment. These novel complex systems help navies gain critical operational advantages, which rest upon performances that arise by interaction of multiple emergent system properties. These can be difficult to fully predict and are sometimes only fully resolved by the measured behaviour of the finally realised integrated system, which is almost never a disposable prototype.

This is the nature of the awe-inspiring next generation of human systems. They are digitally intensive unique complex system of systems, both at the level of the product systems and the processes to realise them (a boundary that is growing increasingly blurred). The software-centricity of these systems also increases the opportunity to deliver new capability advantage and respond to new threats quickly; at (and ahead of) the speed of relevance.

The naval ship is one of the first human systems to transition to this paradigm of development. Central to success in this new paradigm is access to a synchronous exploitable reservoir of product system insight and knowledge, and central to the creation of *that* is Model-based Engineering (MBE) and the digital thread. This paper explores the key opportunities this presents and how we might tackle them as a sector.

2. MBE and the digital thread

2.1. The rise of digital thread and twin

Digital thread is a relatively new term, emerging in literature around ten years ago (Figure 1). Its first mention in Gartner's technology blogs occurred in 2015, in a case study about the application of Product Lifecycle Management (PLM) 'to create a digital thread connecting product information with the supply chain' (Gartner, 2015). The idea of the digital twin is of a similar age and we use it 17x as frequently today (Figure 1).

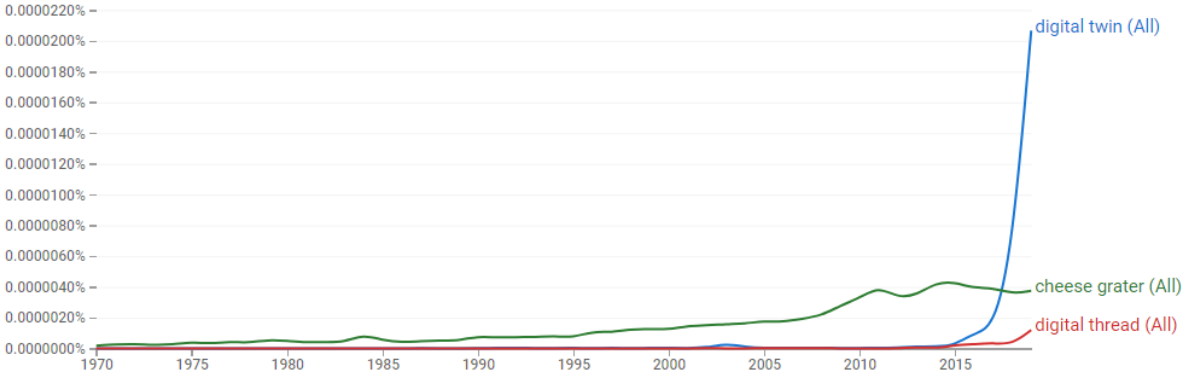

Figure 1: Frequency that terms occur in books by year of publish (Google Books Ngram, 2022)

We extend the term digital twin to mean anywhere in a digital system that insight into the performance of a real-world system and associated phenomena is generated by the combination of a computational model with some measurement data that is fed back from a realised system element in phenomenological conditions[1]. We consider all such arrangements to be digital twins irrespective of how synchronously, automatically or accurately the model-based insight correlates with real-world event, or how complete or exactly representative that realised system or its operational and phenomenological context is. In other words, digital twinning happens as soon as data acquired by sensing the real world is combined with a model, and it therefore starts early and happens extensively in the engineering of a complex system, which typically involves a large amount of validated modelling and simulation.

This naturally leads to an expansive definition of the digital thread as anywhere a data connection is made between two points in a digital system that enables some action or insight that wasn't previously possible. Therefore, and particularly in the development of a physically large and complex system, the idea of 'a' or 'the' digital thread is unlikely to be the most powerful conception; think of *digital threading* as the action of interweaving digital elements for advantage in the development and/or operation of a complex system.

[1] For the sake of brevity and directness of this paper, in place of referenced syntheses of the handful of terms that are key to the arguments of the paper we will simply present an (as far as we have verified) original plain English working grasp of them to be used herein.

2.2. *Where modelling comes in*

Modelling is the critical discipline in the creation of digital twins and therefore sets the most important and often under-satisfied requirements for the digital thread.

Computational models today are increasingly data-driven, as the fields of machine learning (ML) and artificial intelligence (AI) (often collectively referred to as the discipline of data science) continue to progress rapidly and merge into applied domains and toolsets. Whether we engage in: data-driven modelling with some obscured or 'black-box' element, assured as accurate by statistical thresholds, or; modelling through physically descriptive first principles, using calculus and Partial Differential Equation (PDE) solvers (sometimes referred to as 'white box'), or; the so called 'grey box' modelling combining characteristics from each – the validated model is the heart of the digital twin and the building block of effective MBE.

Following the established pattern, we take a broad view of what constitutes MBE as the use of computational representations of the product system for advantage across the development lifecycle. This definition has softer emphasis on whether any given model-based advantage is 'Engineering' and consequently MBE could also be described as model-based product development – a term more seldom used in the literature. By definition (and purposefully so), this grasp of MBE encompasses the use of models to automate the generation of software (e.g. for embedded electronics), which is often known as Model-Based Design (MBD).

Finally on terminology, for simplicity and to respect the desideratum of Systems Engineers, we consider MBE as interchangeable with Model-Based Systems Engineering (MBSE). In some pockets of literature and practice, MBSE is considered to mean only or primarily the architectural modelling of the classical concepts of Systems Engineering methodology (e.g. requirements, functions, logical system decomposition, etc.) using languages like SysML and modelling conventions like the NATO Architecture Framework (NAF). As we hold an inclusive grasp of the activities considered to be Systems Engineering, MBSE comes to include the natural breadth and depth of modelling involved in the successful realisation of complex systems, and becomes synonymous with MBE.

2.3. *Why these ideas matter*

The state of the art in MBE today results in the use of a wide array of models to engineer complex systems and create digital twins. These models demand ever increasing quantities of data and processing power; this is where the idea of digital threading becomes vital. Digital threads are the infrastructural technologies and associated methodologies that handle the logistics of moving data to where it adds value. Digital threads don't solely exist to transfer data to and from models and digital twins (and product development activities involving modelling don't necessarily need digital thread technology per se), but models are the highest value pathway for data to flow back to business decisions, and consequently the two ideas have more impact when applied together.

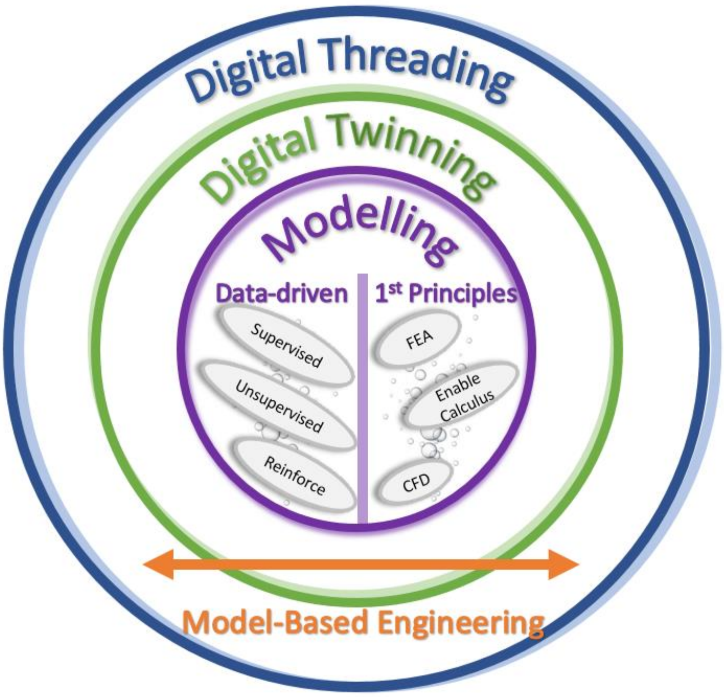

Figure 2: Modelling, digital twinning, digital threading and MBE

The development of a complex system is a knowledge-centric process in which MBE and the associated digital methodologies of threading and twinning are key. A large number of representations of the same system are created, concurrently and successively, by a socio-technical collaborative process. The ability of an enterprise to do this competitively today depends on an extensive 'digital machine' that coheres the efforts of the many people involved. This digital machine is faster and more reliable when constructed out of automated, resilient and interoperable components. Any component that requires human intervention to keep it working in the face of some change slows the end-to-end process down to the speed of those human responses.

Without any digital thread infrastructure, this slowing happens every time new data is acquired. The same is true if we hold models outside of some kind of digital twin management framework; every time we want the insight that new data holds, we again slow down to the speed of human intervention for answers. If instead we handle all of these elements in an automated digital platform of digital thread and twin technologies, these things can happen instantly, limited only by how truly event-driven that system is and what computing power is available.

Before these kinds of integrated digital machines were possible, customers had no choice but to pay for the manual effort required to shepherd the knowledge about the product into actions and outcomes. Today we expect the acceleration of digital in all that we do. It's ubiquitous in the world of consumer tech and of growing ubiquity in the world of manufacturing and systems engineering. If you found yourself unable to climb your stairs at home, you might be surprised if the stair-lift sales rep arrived with an Augmented Reality (AR) system and design representation that can be adapted on the fly to fit your unique staircase: this is precisely what Stannah Lifts have implemented, allowing unrivalled customer experience and rapid 'one-click' manufacturing of bespoke designs (PTC, 2022).

How many stages of product development and realisation like this are in your organisation, your close partners, and those you sell to and buy from? How many representations of the design could be better digitally exploited? How many sensors and effectors could be integrated to achieve more accurate and responsive realisation of tailored system designs? As additive manufacturing becomes increasingly prevalent, why transport parts long distances and hold extensive inventories?

Models and data are at the centre of all of this: the methodologies by which we manage them and multiply the value they add are key capabilities for high performance enterprises that produce excellent products.

3. Digital thread: an idea whose time has come

3.1. A naval shipbuilding journey to date

Ideas like MBE and digital thread are newer than the technologies that deliver them. Computer design tools have been applied in ship design for over four decades and the work of realising naval systems has become increasingly digital, data-driven, model-centric and computationally intensive.

Today in BAE Systems Maritime – Naval Ships we have made significant progress with business digitalisation. A significant investment in digital threading has culminated in an extensively realised PLM[2]-centric digital thread implementation (McKendry, 2022). In that same timeframe, we have also developed a solution for off-boarding ship systems sensor data and converting it into live operational insight (BAE Systems, 2016). We've grown our MBE capability alongside this too, increasing the use of architectural modelling to de-risk the engineering of marine systems (Tudor, 2019) and the use of integrated generative modelling tools for fast and comprehensive concept design studies (Hifi, 2022).

We also increasingly use models in the management of the enterprise architecture (EA), including through the application of The Open Group Architecture Framework (TOGAF) modelling convention. This has been part of transitioning to more of a 'data as a service' model through Data Warehousing (DW), Enterprise Transformation Layer (ETL) services and establishing a microservices-like internal environment for data contributors and consumers. Such agile EA foundations are crucial to continue to develop in tandem as we drive the digital capabilities and offerings of the business.

The growing comprehensiveness and adoption of cloud offerings are another potential significant ingredient to make the handling of data, models and computing more seamless, automated and extensible. Additionally and complementarily, several large software vendors now offer substantial integrated toolchains for engineering and manufacturing. These cloud elements can be allied with the adoption of model and data standards, to further exploit the agility and interoperability of 'turn-key' solutions.

Most of the methods above partner one way or another with the latest class of umbrella data science platforms, which make it possible to infuse AI and ML across the whole digital process, reinventing how we solve the digital problems in our enterprises and disrupting the product system paradigms themselves. In summary, there are a spectrum of components that can be employed in your unique 'digital machine' to make model-centric and data-

[2] Product Lifecycle Management

driven enterprise operations viable and effective; working out what is significant for each enterprise's unique digital environ and where to start is a perennial challenge.

3.2. Where are we heading next?

While much of the future seems uncertain, digital disruption looks set to continue.

AI will continue to break boundaries and drive the cutting edge of digital technology in ways we cannot fully predict or plan for. Consider the example of Robotic Process Automation (RPA), which grew by 30% more than the rest of the software segment in 2020 (Ray *et al.*, 2021). This form of automation leapfrogs more traditional back-end information systems integration and being beholden to software vendor development pipelines to improve how tools can be used, creating a brand new layer of automation in the enterprise to speed and integrate digital operations. RPA agents will continue to become more capable, with powerful upgrades in vision, decision-making and human-machine interfacing. Enabling RPA to solve the enterprise's problems that it is fit to without degrading the resilience and agility of the digital infrastructure is a non-trivial challenge.

Or look at containerisation. Kubernetes grew by 70% in adoption in 2021 (CNCF, 2021), including finding application in complex defence systems (Air Combat Command Public Affairs, 2020). Coupled with the growing software-centricity of complex systems, this technology trend is radically speeding how we manage the deployment of systems capability and continuous upgrades into operation. It is also disrupting how we manage enterprise architecture, affording better exploitation of compute and slicker management of blends of totally virtual systems with Hardware In the Loop (HIL) and Rapid Control Prototyping (RCP), for more representative testing and faster systems development.

Another source likely to continue to disrupt is progress in understanding cognition and its interaction with the development of larger, more sophisticated, pre-trained neural networks. Imagine you were shown a state of the art text-to-image generator or deep fake video 10 years ago; what seemingly impossible feat will we have manifested 5 years from now? Or consider even the level of the identity of this technology space as "digital". The first quantum computing operation was completed in the 1980s, 42 years ago (Benioff, 1980). Today quantum computing can be bought on demand in the cloud for $1.60 per runtime second on IBM's 27-qubit Falcon R5 processors (IBM, 2022). As quantum becomes more relevant and prevalent, digital will drop away as a definitive way of referring to computing: the terminology, processes and possibilities will shift.

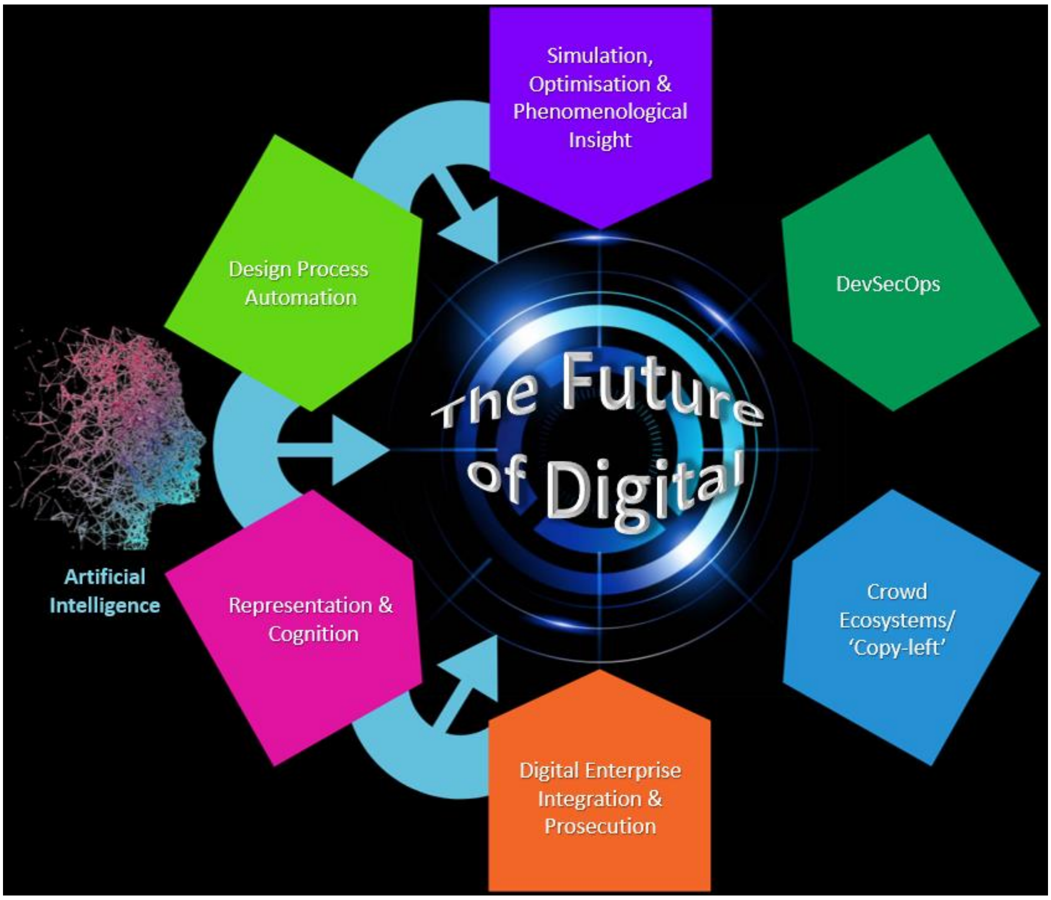

Figure 3: Some key emerging trends that shine light on where digital disruption may be heading next

There are more tantalising possibilities further unfolding in the cross-over between Mixed Reality (MR) and software-defined control systems (Madden and BAE Systems, 2019), and the overlap between design and operational realms and systems now reaches far beyond traditional training systems or data-driven predictive maintenance. There is opportunity to crush development lifecycles and break operational systems into well-understood modules that can be upgraded independently to rapidly respond to changing operational needs (Team Defence Information, 2019). This opens up opportunities for more open architectures and ecosystems, something in the best interests of all contributing in the value chains, and something BAE Systems is working on today for future air systems (UK Ministry of Defence, 2022).

The issue of unstructured data is still one of the lesser-mentioned tricky problems in the world of digital thread and twin. We are reaching out to the bleeding edge in this area to overcome the ontological and structural hurdles, and take inspiration from successes in parallel fields, such as progress by researchers working in the biomedical field at the University of Manchester (Zerva *et al.*, 2021). And we are actively working to develop technologies and techniques to exploit graph technologies and manage the evolution of enterprise semantics over time. Without the ability to see and influence the structure and rigour of description in use across the enterprise globally, we never know exactly how digital threading interventions gel with the wider context and rank in terms of value return. This is the subject of cutting-edge research with YorkMetrics and is an area we are also exploring through a pilot of the OpenCAESAR approach, which was developed at NASA JPL.

4. Naval shipbuilding and the cutting edge of digital

4.1. The significance of brownfields

It doesn't matter when an organisation invests or how much of their digital systems they can modernise in one go, because digital disruption will continue and intensify in unpredictable ways across multiple fronts every enterprise will find themselves building with second-hand parts before long.

As more enterprises come to benefit from the orchestration and integration of large discontinuous digital domains comprised of data, software, models and infrastructure (of varying capabilities, ages and states of upkeep), these will naturally become the highest value enterprise management opportunities. Being able to do this in an incremental and scalable way will become pivotal to being fit for the future of digital. Most of us in shipbuilding already work with sizable brownfield digital environments and while this can feel debilitating, succeeding in this setting trains the competence, adaptability and means-ends focus necessary to deliver solutions amongst the unrelenting waves of digital disruption.

Some elements of naval systems can have both long operational and development lifecycles. They typically involve a discontinuous progression of design expression that is generated by the many teams realising different elements and design perspectives of the system. Each of these expressions can have high complexity in-of-itself and by product of its dependency on others; they are usually created across more than one disconnected inhomogeneous enterprise environment (due to commercial, geographical and security constraints).

We are headed for a future where all complex systems developers and operators work in these kinds (increasingly overlapping) brownfields of equivalent complexity. This is being driven by systems becoming more data and software driven, increasingly incorporating AI and autonomous elements, changing product paradigms and further intertwining things. Emerging examples include:

- Self-driving cars managed at network levels;
- Distributed power generation and consumption in a grid of micro-grids;
- Waging mixed threshold mutli-domain warfare across related attack targets and surfaces, and;
- Multilateral comprehension of the state of health (and how to heal) planet Earth's living ecosystems.

This isn't about freely wandering digital realms where data is readily discoverable and amenable to sense-making, or can be easily processed to make it so along one-directional flows out to models and decision-aides. Nor is it about connecting recently developed digital piece-parts into 'all-singing, all-dancing' omnipotently architected environs. Not to denigrate progress spearheading new technologies and ways of working in environments *without* the brownfield complex system constraints and confounding factors; it generates many useful components to use in the future, but it also often neglects these less headline-grabbing factors to the challenges being experienced.

What's being demanded is the ability to craft on-the-hop, historically sensitive, present-day-impact focussed, temporary but resilient, re-manufacturable digital machines. Given this brief, it's worth considering what can be learnt from the advent of hackathons where tactical, smart, 'hacky' solutions are incentivised. Looking to BAE Systems' surprise win in developing predictive analytics for a fleet of C130 aircraft by pulling from different information systems in different security domains in 24hrs at the Defence and Security Accelerator (DASA) 2019 Hackathon (BAE Systems, 2019), it is possible to conclude that teams familiar with digital brownfields similar to the problem context gain differentiating advantage. Or that winning advantage is bestowed by having a blend of:

intimate understanding of what is important to the customer and the problem domain (including its typical datasets and associated product knowledge), along with; expertise in relevant digital technology and what it can enable, while bridling any preconceived solutions to the problem – but the winning advantage here was more than both those things.

4.2. The evolving role of primes

Prime integrators are uniquely positioned to play a pivotal role in the coordination of product system knowledge. Digital competence in the execution of this role is of advantage to everyone involved in realising, using or supporting and upgrading complex systems in the modern digital age.

Consider how Big Tech companies bring relevant contributions to the work of building digital machines that connect and enable the extended enterprises delivering complex naval systems of systems. To deploy this technology effectively requires intimate understanding of: the extent and nature of available product system data, information, knowledge and wisdom; the art of the possible in the product system domain, and; how to bring these two things together to advance the goals of the system user. Big Tech solutions provide significant acceleration across these areas, but Big Tech companies are not best positioned to also supply all the necessary contextual awareness. This also isn't most efficiently or perspicaciously added by the system user or customer alone either; there is a role that present system primes can continue to step up to.

Simultaneously, and for many of the same reasons, neither Big Tech nor the customer is best positioned to independently manage the technology development coming up through Small Medium Enterprise (SME) tech disruptors. Academia has a role to play here too, and once again better in concert with the other relevant perspectives than trying to create an independently held conception of the opportunity space and its solutions, which often develop through frank conversation and close work-sharing. Consortia, such as standards development groups, also have a role to play, but if they are the only cohering force jointly developed solutions will always lag the need and tend to either address only part of a given challenge or the whole by significant reduction of its dimensionality. There is much primes are uniquely positioned to do to connect and enable these naturally interacting parts.

However, focussing on the value of strengths in the current paradigm and hackathon winning advantage might be a misleading way to try to understand what will be significant for digital mastery in the next wave of tech disruption. Both analysing the role of primes and looking at success in hackathons implies that a single player can deliver a significant in situ advancement in the new paradigm. This is a direct consequence of how hackathons are configured, rarely do we see spontaneous collaboration and combinatorial unfolding (Madden and BAE Systems, 2019). In the sprawling and broiling complexity of the real world, best results will very rarely be reached by any sole actor trying to solve the whole problem space in isolation.

4.3. The importance of ecosystems

Let's take the example of the idea of an "integrated multi-domain PLM" (Siemens, 2021) and whether this can be bought off-the-shelf. To answer this, it might be revealing to consider what knowledge is being integrated.

In the case this is knowledge from engineering domains that are well established and codified into system modelling paradigms and computational solvers, then the software vendor adds value by packaging this into an easily managed environment with a modern UI and exploitable data, as well as providing a conduit for cross-pollination across industries. The role of making tooling accessible and intuitive can be understated; engineers' practical ambition for design exploration and analysis is often shaped by the capabilities of the tools in their hands. And many integrated modelling and simulation environments provide ways to traverse from 3D design definition in a CAD environment to its analysis and optimisation in a CAE environment seamlessly, including publishing the products of both directly into a configuration management supported project data environment.

However, what about when the complex system product technology or application requires a type of system definition or analysis that is not very well established, codified or supported in the tool out-the-box? Supplementing these externally governed, tightly controlled proprietary blocks of digital capability – built on preconceived and sometimes preclusive ontologies – is a demanding task. The most common approach is to break free completely, sometimes into other variably compatible software tools or into home-grown design tools and solvers. This usually also requires some ontological evolution, or more intimate management of the ontology or available actions within the off-the-shelf big vendor block, and there is a trade-off here as the degree of 'lifting the hood' on the software tool unpicks the benefits of its emplacement within the enterprise's digital twin and thread.

So both today and as we move into the future, best progress is enabled by everyone stepping up to their natural role and not beyond it. In the case above, multi-domain PLM that is only architected and configured by the software vendor will fall short of what we want to do because of the inseparability of the complex system development goal and shaping of the description system to get there. As to where we go next; engineering organisations will continue to want the accelerations of central software vendors (likely increasingly so), so we need more sophisticated interfaces and partnering arrangements to unlock the most significant benefits for all. This is true for all relationships between the aforementioned relevant parties in the digital ecosystem (Figure 4).

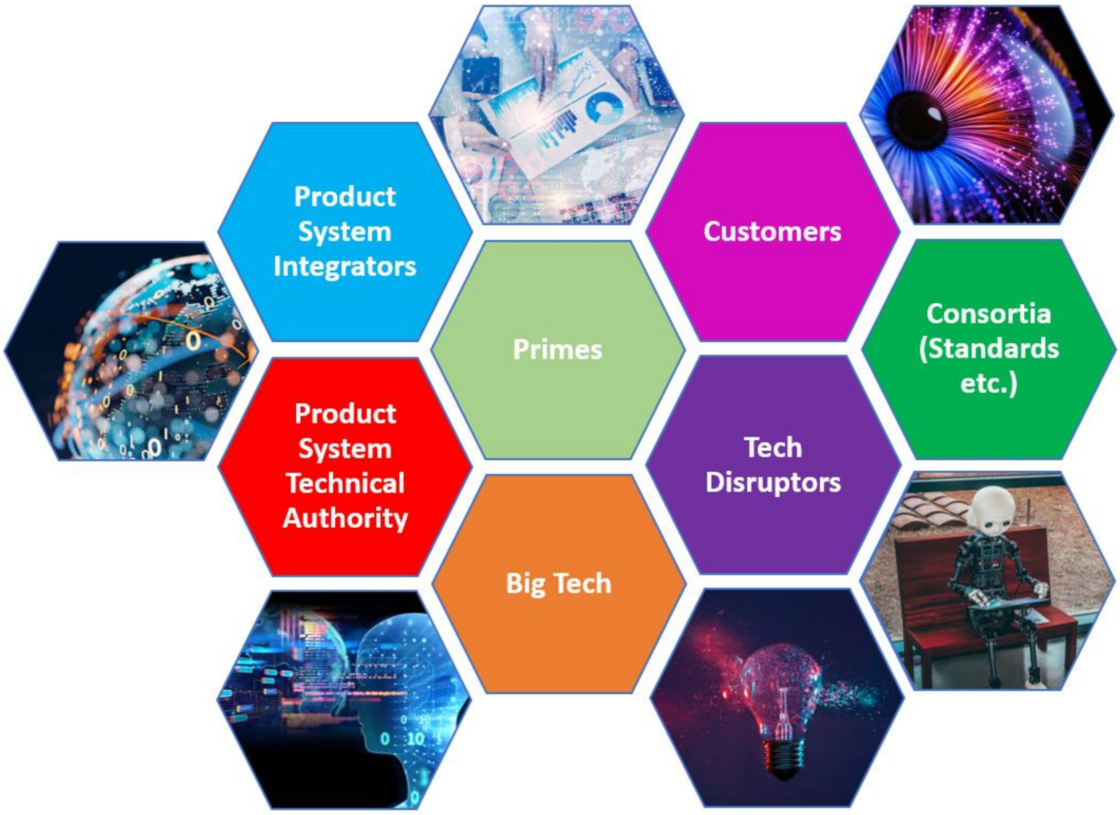

Figure 4: The cooperating actors in a healthy complex systems digital ecosystem

5. Conclusion

The unfolding digital paradigm shift is an existential crisis for all organisations. Teams around the world are ruthlessly ploughing ahead into this brave new world, rapidly making ways of working and things we're making uncompetitive or obsolete. One of the highest stakes arenas for this is defence, and right behind this is probably big companies, so the threat to naval products and enterprises is real and present.

We want to pivot to the new paradigm and allow the natural strengths of each player in the ecosystem to combine, producing the speed and directness of the hackathon but on inherently collaborative open-ended challenges and opportunities. This isn't something that anyone has fully cracked yet, but there are many vectors starting to point in this direction. One of the problems is that too many of us are still trying to do it in isolation because we all sense there are important opportunities here. If we don't team in the way expressed above, it seems unlikely that we will be able to make this transition.

We've started trying something different in BAE Systems. Our Digital Programme (Thread and Twin) at the sector level across Maritime & Land is a team dedicated to realising this next generation of business methodology and technology. This is complemented by a reorganisation to bring together our digital powerhouses into the new Digital Intelligence. Our focus is to develop mutually beneficial open-minded bilateral partnerships across the digital ecosystem, for example with our strategic partner universities.

Wherever it is in our gift, we are unblocking the path ahead, for example when it comes to intellectual property and commercial enablement, i.e. making sure we have real and attractive present-day reasons to solve the thorny problems that changing digital technology is bringing to the surface. And internally, the Digital Programme is an example of 'just getting on with it' by tackling the problems as they arise and seeking solutions to work at pace. This involves connecting the people who can get things done, by breaking down siloes across the whole group and stopping solving the same problem twice. It is about 'thinking big' while being incrementally oriented, through more optimistic and open-ended methods of managing projects and working with partners to address high-value problems that benefit the whole enterprise.

5.1. Inclusion

In the new age of open digital ecosystems that produce complex systems, we will only achieve success by stepping away both from locking in customers and from locking out potential co-creators. In both cases, we are more aligned in what and how we want to realise new systems and capabilities than we are at odds. All parties bring valuable expertise to the problem space and we want to team in the most natural relationships, so that together we can move at the speed of relevance and usher in the mind-blowing next generation of digitally-enabled systems.

This is the future that is invited by the new digital world unfolding around us right now. It is challenging to reach out to, because the digital tech won't stand still as we realise these new ways of working together. Together as a co-creative ecosystem, we can find our way to powerfully combine the vital perspectives and contributions we each bring and realise this as yet unimagined generation of digital solutions.

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