System Interfaces and System Interoperability in a System-of-Systems Context

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ABSTRACT

For a system-of-systems it is of paramount importance that all its constituting systems or system elements are operating together to fulfil the purposes of the system-of-systems successfully according to the system-of-systems' goals. In this paper, the system-of-systems context is interpreted at the boundaries of organisational responsibility. As far as the NATO is concerned, the boundary between the military forces and the armament industry providing weapon systems and associated services is in the focus.

In the first place, each weapon system has to fulfil the operational requirements allocated to it. The company that has awarded the contract concentrates their efforts primarily on satisfying the contract specification. The contract specification contains primarily the operational requirements, but also other constraints. Among these constraints, more or less detailed system interface requirements shall ensure a smooth integration of the weapon system into the system-of-systems. However, rather detailed system interface requirements demand a high management effort and may impose a risk for system interoperability. This paper will identify the root causes of these risks. Possible solutions for risk mitigation are considered, too.

From a system-of-systems point of view it is equally important that all the various weapon systems work together as expected. That means system interoperability is an issue of the military forces beyond the primary interests of the armament industry and the correct implementation of system interfaces. In the era of network-centric warfare, there is a high demand for excellent information exchange capabilities. This paper describes the NATO approach to system interoperability and its evolution over time.

1 INTRODUCTION

Specialisation, workshare and standardisation are the constituting principles of sophisticated industrial civilisations. In this investigation of system interfaces and system interoperability, a review of specialisation, workshare and standardisation marks a reasonable starting point. Throughout history different human societies have implemented these principles in various ways. Even in the era of globalisation, many variations for organising an economy exist and evolve further in parallel, keeping some local and regional traditions. In the seventy years of NATO history, an evolution is observable how to cope with the three principles. This paper will review the past and will set the NATO practices into context. Based on the status-quo, opportunities for improvement are investigated throughout this paper.

In a second step, the System-of-Systems (SoS) context is analysed. The ambivalence of the term system-of-systems will be explained by following the meaning shifts in systems engineering methodology over the last twenty years. It is not the goal to provide a final definition of the term system-of-systems in general. Just some unique characteristics of system-of-systems will be considered below as far as supportive to the further flow of thoughts on system interoperability and system interfaces.

With these prerequisites, the next logical step is to turn to system interoperability issues in general. The NATO focus on system interoperability will be considered especially. Relevant system interoperability standards will be addressed briefly.

Finally, we will dive deeper into the topic of system interfaces. The challenges how to define and how to manage system interfaces are manifold. In this lecture the focus is set on the nature of system interfaces in general looking for various system interface categories and their implications for engineering systems participating in SoS. How to manage system interfaces during development beyond the application of fully pre-defined interface standards will be considered in a second paper on architecting systems for participation in a SoS context.

2 SPECIALISATION

From the three principles specialisation, workshare and standardisation, the specialisation principle is considered here first. Specialisation and market economies evolved together. Ancient subsistence economies invented markets to exchange a surplus of goods not needed for self-consumption. The actors on these markets were hunters, gatherers and early farmers. With increasing wealth, market volumes grew. Opportunities to make a living from offering specialised goods and services arose. History provides sufficient evidence for the dependency between wealth and technological advance. The ancient Roman Empire with many achievements forgotten afterwards accumulated extraordinary wealth. Similarly, the industrial revolution in England coincided with exploiting the richness of the British Empire at the peak of its power.

Strong motivational forces contribute to specialisation. As humans we want to live in a meaningful world, and each individual wants to be meaningful by oneself. Motivational psychologists see in this a specific human motivation not shared with other species. They see it caused by our knowledge and awareness that the life of all biological beings have an end [9]. Self-expression in fine arts and also in all kinds of purposeful arts provide a chance to perpetuate the individual's impact beyond one's own lifespan.

A further motivational force is the satisfaction gained from experiencing self-control and autonomy [20]. To excel in a particular discipline provides us with feelings of independence and pride. Experiencing self-control and autonomy feels good for our self-esteem. Concepts like the existence of a free will and individual freedom are linked to this motivational system. Considering Darwin's evolution theory, the motivation for self-control and autonomy corresponds to the survival of the fittest. This could explain the competitive aspects many humans link to self-control and autonomy. Striving for excellence is an important factor for societal evolution. Competitive markets provide the means to let it happen.

Leaving the details of the research on motivation psychology behind, we may just conclude that humans love to do what they are able to do best. Usually, we prefer to advance in these areas even more following a path of strengthening our strengths.

On this road, we see an explosion of human knowledge. Further details are revealed in each discipline. Discipline specific terminologies are enhanced and lead to languages only little understood beyond the particular discipline's boundaries. Coincidently, a further segmentation of knowledge disciplines is observable. Each new discipline is creating their own body of knowledge published in narrow-banded journals and discussed in numerous conferences where the discipline specialists meet. Inter-disciplinary communication suffers. Sometimes it becomes even questionable which benefits may finally result for human culture and the planet.

As far as technical systems are concerned, this is of course a strong argument for promoting integrative disciplines like systems engineering. However, each attempt for integrating knowledge from various disciplines is faced with a number of fundamental problems:

- Due to discipline specific terminology and language, mutual understanding is hampered in general. Some terms used by a particular discipline may be unknown. Other terms may be borrowed from common language, but may be overloaded with extended, limited or different meaning. Further terms may be used by several disciplines, but may have got a particular connotation in specific discipline terminology. Similarly, each discipline may use specific phrases and sentences that are hard to decipher by non-discipline members.
- Distinctions introduced by a particular discipline may be meaningless to other disciplines. The creation of knowledge is widely aiming for revealing details enriching the understanding of the properties and behaviour of a given investigated subject. Differences become visible. To name them, new terminology distinctions and categorisations are introduced that are not eligible to non-discipline members.
- Problem solutions found by a particular discipline are not valued and are not considered by other disciplines as neither the problem is understandable nor the quality and dependencies of the solution are assessable. Especially in cases where solutions from different disciplines are in a competitive relation, the generation of a compromise with a balanced solution acceptable to all disciplines may be cumbersome, and may take a lot of effort and time.
- When working together, the necessity for corrective action due to a new problem found by a particular discipline may be denied by other disciplines as they cannot see the problem at all. Especially in case of limited resources, the initiation of corrective action may then be postponed. Thus, issues that may be solved easily, if the full available lead time would be utilised, may develop into crisis, overspending and delays.

These problems mark the downside of far-reaching specialisation. There are no simple measures to get rid of them. Claiming common sense and majority voting does not work as representatives from each particular discipline are always a minority in multi-disciplinary efforts. Demanding a common language that is understood the same way by all disciplines involved leads to ignorance of some essential knowledge of particular disciplines. All this is a burden for organising workshare with multi-disciplinary interaction in an economy successfully.

3 WORKSHARE

The organisation of workshare is a paramount societal challenge. Wealth and survival of a society are highly dependent on how material and immaterial resources are utilised effectively and efficiently to cope with an ever changing environment. A high level of specialisation leads to pluralistic societies with a large number of individual and institutional players. The modern age has seen various solutions for ruling a society politically and economically. Almost none of the solutions survived for long and without crises. Conclusively, the organisation of workshare seems to be a tricky subject with no optimal solution appropriate under all circumstances.

This section will start with a historical survey about the workshare cultures in Europe and beyond. Two extreme poles are identified. In between a wide range of workshare cultures may exist amalgamating elements from both extremes. The evolution of NATO procurement policies is evaluated according to this scheme. We will see that NATO reacted on developments in the economic environment that to a remarkable extent resulted from military funded technical achievements. Next, a taxonomy of products is introduced in order to identify associate risk levels and to allow the derivation of a number of guidelines how to organise and manage workshare appropriately in various scenarios.

3.1 A Historical Review on the Organisation of Workshare

During the medieval age, the European cities became the hot spots for the evolution of all trades and crafts. Independent cities gained far reaching self-rule and self-administration. Italian cities as for example Venice developed into rich and powerful trading powers. Their access to the Mediterranean allowed an extension of their trade relations to the Middle East, central Asia and China. Wealth and knowledge were gained including the recovery of ancient Greek knowledge leading to advances in finance, science, technology and arts. Still viewed from today, the blossoming of the Italian renaissance is a hallmark in history.

The free imperial cities of the Holy Roman Empire exercised self-governance through a system of guilds representing all trades and crafts. To sustain and grow a system of apprenticeships and journeymen maintained and increased the conduct of practice in the particular trades and crafts beyond the scope of each particular city. Mercantilism in France under Louis XIV brought a new facet to the French kingdom by centralising the governance including the central control of all trades and crafts.

Colonialization and imperialism provided some European powers with further wealth. In England, the wealth fuelled the industrial revolution and a business model to extract raw materials from colonies and manufacturing these materials to high-value goods that partly, through restrictive trade arrangements, were sold back into the colonies. Liberal and capitalist governance models became dominant in the western world. In opposition, socialists and communists designed a governance model that in reality led to a central planning economy. Although the western model has outlived the soviet model, today's globalised economy is still not free of crises.

In addition to this European centred narrative, it is also of interest how economic development has taken place in European colonies. On no occasions Europeans have taken existing civilisations on a par with their own culture. In some areas, the existence of other cultures including their economic systems has just been denied. North America and wide areas of Africa are examples where Europeans have taken such a green-field approach [4, 15]. Industrialisation in these economies was introduced by individual craftsmen who emigrated from Europe. These people had to build up whole infrastructures by themselves as they could not rely on a network of local support from other crafts and municipal governments. Under these circumstances a specific understanding of entrepreneurship and patriarchal governance evolved.

3.2 Workshare Organisation from Market Opportunistic to Green-Field Approaches

Of course, the historical review above is rather brief. In-depth studies of how workshare was organised in each particular case could reveal more detailed conclusions. But from what is said, two extreme cases of workshare organisation can be identified.

One of the extremes may be called market opportunistic by relying completely on products, services and infrastructure that are already available. Let us look as a few examples illustrating the concept. Umbrellas may be invented for rain protection. With the idea to use umbrellas also for sun protection a new market opportunity may occur. The post-it stickers are another famous example. The appropriate adhesive was available from research failing its objectives. Just the idea to combine the adhesive with small-sized paper created a new source of income. Important is the innovative idea itself that need not to come from the producer. However, after such an innovative idea has proven to be successful a further evolution with improved products may take place. For example, a sun umbrella may be designed more light-weight than a rain umbrella. Or, post-it stickers may be offered in further colours than yellow and other sizes.

The antipode to the market opportunistic approach is the green-field approach. For the green-field approach, the value generation depth is nearly endless. Workshare opportunities are scarce. There is no supporting infrastructure and many technologies may needed to be invented first. Of course, also this extreme does not occur in reality, but some human endeavours come close to it. Human space flight is one of the most prominent examples.

In practice, the organisation of workshare is somewhere between the two poles. It may be an exercise to the reader to sort the examples from history on this scale. In general, market opportunistic approaches have a tendency of low risk, short lead times and less costs. Risks, lead times and costs tend to increase remarkably at the other end of the scale. The human capabilities may be too limited to plan and to control all aspects in a green-field approach. The failure of central planning economies provide ample evidence for this judgement.

3.3 The Evolution of NATO Procurement Policies

Traditionally, NATO procurement policies have been close to a green-field approach. According to von Clausewitz all warfare is driving to extremes utilising and sometimes overstressing all resources of a society [4]. Following this path, military demands became a driving force in technology development for certain periods in history. The Second World War and the decades afterwards followed this pattern. In many sciences and technological fields, military technology has been a forerunner: materials and their processing, electronics, software, embedded systems and network technologies - to just name a few of the important contributions of military technology investments to overall technical progress. Operations research and systems engineering established themselves as important disciplines [21]. Documenting all these technologies and their appropriate application has led to a voluminous body of specifications and standards. All the disadvantages of a green-field approach were experienced. Delays of delivery, over-spending and weapon systems not matching contracted expectations are common themes with many military procurement projects.

Over time, many military technologies developed after the Second World War were utilised in non-military applications. This resulted in a number of game-changing consequences. Market volumes for these technologies increased. Wide-spread commercial interests let to further technology improvement funded by commercial enterprises spending a multitude of military technology development and procurement budgets. Smaller production shares became allocated to military applications. Military procurement agencies lost some of their importance and influence on further industrial progress as customers. Satisfying specific military requirements for dual-use products started to get less attention by industry. For example, there were cases that some design flaws, bugs and errors in microprocessor designs were discovered. For the high volume variant marketed for general purposes, the lithographic masks used for production were updated in due time. For the military variant, a service bulletin was published to avoid certain instructions as enterprise management opted against frequently re-qualifying the microprocessor design according to military standards.

These developments demanded a reaction to military procurement policies. Although the changes and considerations evolved over a longer time period, the decision of William Perry – then the Secretary of the US Department of Defense (DoD) – in 1994 to demand the utilisation of commercial-off-the-shelf (COTS) products whenever available became a memorable turning point not only for military procurement in the United States. All other NATO nations and NATO itself adopted their procurement policies accordingly.

However, the directive for utilising COTS is simple and clear, but in many occasions the implementation of this policy was not as easy. Requirements for military applications have to consider warfare conditions that are not regularly found in commercial applications. Nuclear hardening requirements are a good example. To survive nuclear threats the design of microprocessors and other small scale electronic circuitry have to adopt certain measures. Additional material layers increasing the resistance on the wafer are in many cases a suitable measure. Thus, military specifications still demanded specific product variants.

The immediate impact of the so called Perry initiative was the cancellation of many military specifications and military standards. Other standards became deprecated, and were aimed to be superseded by improved or new standards published by civil standardisation bodies including ANSI, EIA, IEEE, IEC and ISO. For good reasons, these measures have been a good starting point for adjusting the organisation of workshare in NATO. But it became a cumbersome process. Even today – twenty years later – this transition has not come to an end, and the lessons mentioned above and many more had to be learned. In the end, the resulting changes were actually more limited than expected. Even today the procurement policies of the US DoD are closer to a green-field approach than a market opportunistic approach. The system life cycle applied by the current Defense Acquisition Management System provides some evidence for this finding, see Figure 1 [6].

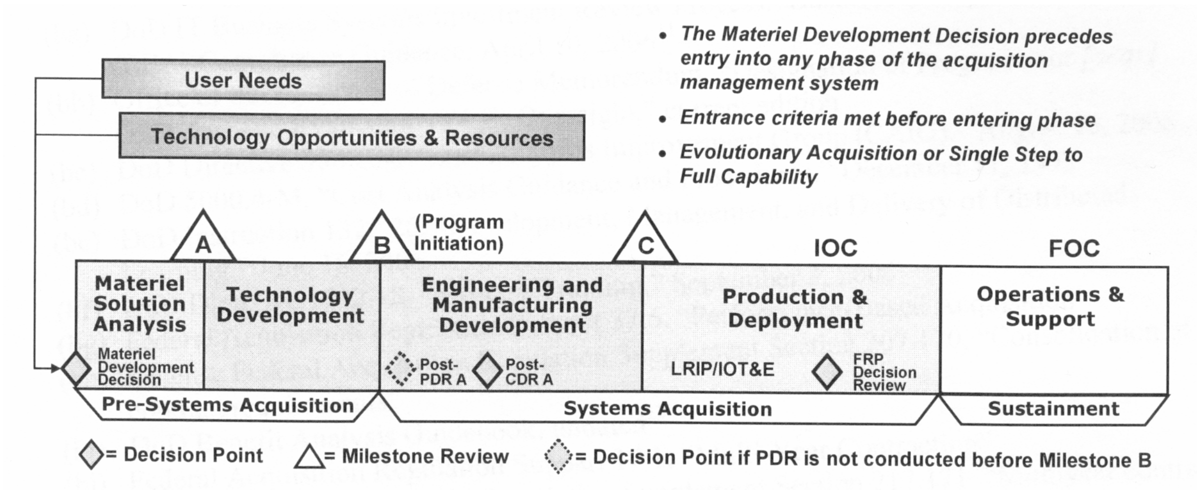

Figure 1: The US Defense Acquisition Management System [6].

Technology development is still a separate system life cycle phase preceding the actual development for each weapon system acquisition. In a market opportunistic approach, technology development would be less related to the procurement of a particular weapon system, but on technology investment decisions made by an enterprise or in concerted action within a supply chain in order to minimise risk by not putting all eggs in one basket. However, with this approach the US DoD follows its traditions that can be traced back to the first half of the nineteenth century when rifle production for the US Army was centrally controlled by the DoD. It was a milestone of the industrial revolution to allow the assembly of parts from various manufacturers with little effort for harmonisation and no need for re-working parts in the final assembly stage [5].

NATO itself and the other NATO countries had to adopt to the changes introduced by the US. US military specifications and military standards were widely used in military procurement programmes throughout NATO. To rely further on cancelled and deprecated military specifications and standards became more and more questionable as those documents were not maintained and updated anymore. However, in some cases they remained in use for quite some time as referenced documents in military procurement programmes launched after 1994.

Overall, procurement policies of NATO member countries lost their coherence after 1994. To a wide extent this was an impact of the Perry initiative. The end of the cold war had an essential impact as well. European NATO members were looking for a peace dividend and reduced their defence spending. Strengthening common military procurement in the European Union on one hand side and more diversity of national procurement policies on the other developed in parallel. The promises for savings following a COTS approach were welcomed to reduce the military procurement budgets.

In Germany the intentions for changing procurement policies in the direction of a market opportunistic approach were far reaching. The intention was to transfer the responsibility for inventing the appropriate technologies for future weapon systems to a wide extent to industry. Technical competencies on the government side could then be reduced. In case of an actual need for new weapon systems, the military procurement agency would then approach industry to check and review their offers. In 2001 the new procurement policies were released. Since then the procurement policy document called Customer Product Management (CPM) has been updated twice [2]. CPM focuses on the procurement process within the German Ministry of Defence. The organisation of workshare between government and industry is considered briefly only. This may be not fully adequate for governing innovative military procurement programmes. The technical expertise on the government side was reduced.

All procurement policies have more or less in common that they favour one kind of procurement processes fitting all the needs. When searching for balanced approaches between the two extremes, the green-field approach and the market opportunity approach, a taxonomy of products would be helpful. In the following, three categories with a number of sub-categories are proposed as starting point for further considerations for the tailoring of procurement processes.

3.4 A Product Taxonomy for Product Procurement

Category I comprises existing products that may be selected for military procurement. The options for decision are just accept and buy, or reject and don't buy. Many products falling in this category may be technologically rather simple. They may be new, innovative and unique, or selected from a multitude of diverse market offers. Category I products are real COTS products. Buyers of Category I products have no direct influence on the development of the products they procure. However, there is the supply and demand feedback loop regulating the market. Nevertheless, the enterprise developing and producing the Category I product is free in their decision making and is fully responsible. The buyers of Category I products are fully responsible to integrate the procured products into their systems successfully. In case of dissatisfaction they may blame the producer only in the legal boundaries of product liability and product safety regulations.

In traditional, green-field oriented military procurement the demand to re-use so called Government Furnished Equipment (GFE) is a further example for Category I products. In this case, not the military procurement agency is in charge of successfully integrating the GFE, but the industrial enterprise that has to integrate the GFE in their systems.

Category II products differ from Category I products by offering a number of options to be selected or ignored by buyers. Otherwise, the products are market available and may be sold from stock or may be individually manufactured according to particular customer demand. In other words, Category II products may be either manufactured according traditional mass production principles or according to lean manufacturing principles. A wide range of products fall into Category II. The total quantity of product items is nearly irrelevant. Passenger cars sold by the millions may fall in this category as well as a few plants of the same type in the chemical industry. As long as the manufacturing of the product does not involve additional development activities changing product characteristics and alterations to the production processes, Category II products are true COTS products.

However, there is a grey area in practice. Sometimes a few changes of the manufacturing process and some product improvements demanding developing activities to change product characteristics may be introduced to satisfy the particular needs even better. For this reason, Category II products may be sorted into a number of sub-categories. The Sub-Category IIa is reserved for the true COTS products. In Sub-Category IIb isolated alterations of options in the manufacturing process are found. Demanding a specific colour for a car that is not available from the standard colour palette is a typical example. Military forces may like to express their brand by a particular olive-green colour of all their cars. At first sight, this may be a rather simple case to cope with for some extra costs. But what happens, if the pigments of the olive-green paint does demand another pre-treatment of the metal surface than the colours from the standard colour palette. Or, if for camouflage a painting scheme of more than one colour is demanded by the customer. Further adjustments to the production process may be necessary to satisfy the customer-defined option. This additional risk justifies to define a separate Sub-Category IIb beyond real COTS products for capturing customer specific adjustments of production processes.

A further Sub-Category IIc is proposed for cases in which development activities become involved for customisation options for a particular customer in additiion. If a customer wants to select two options that are not intended to be applied together, a compatibility check may demand further verification and validation activities. Think about that both options have a high electrical power consumption. Then, an analysis and some testing may be required to ensure that the specific configuration including the basic product plus all actually selected options does not overload the power generation system.

In other cases, even design changes may occur. Demanding a specific colour with certain pigmentation may be overloaded with expectations for signature reduction not only in the visual spectrum, but also in the infra-red spectrum. Thus, the option for the particular colour may introduce explicitly or hidden a new requirement. A few changed or additional requirements may have even a deeper impact on the whole design. If the requirement for a truck is changed for being capable to drive through water 100 cm deep instead of water 80 cm deep, some equipment may need to be moved to other locations in the truck. Installation fixtures, electrical wiring and further technical aspects may need a re-design. Consider a further example related to electro-magnetic compatibility (EMC). In a war theatre scenario, much higher EMC threat levels may be encountered as considered for trucks in civil scenarios. Adjusting the design will affect all electronic equipment and all wiring. The whole system architecture of the basic truck may be not well suited to cope with higher EMC threat levels.

All claims for Sub-Category IIc products for being merely COTS products will not satisfy the expectations for cost-efficiency and low technical risks associated commonly with COTS products. Instead regarding cost and risk levels Sub-Category IIc may come close to Category III products.

Category III comprises all products that are developed and produced on customer demand. In general, it makes not too much sense from a customer perspective to invest in the development of products that are already available on the market. Thus, Category III products tend to strive for innovation exploiting a mix of new technologies and already available technologies to provide new products with features and functions that have been unseen before. As the risk levels to bring a Category III product into being may become high, risk management becomes a dominant management activity. The actual maturity and further progress of the technologies envisaged and exploited for a particular product are important risk indicators. Today, the Technology Readiness Levels (TRLs) proposed by NASA are in common use for assessing product maturity [15]. TRL assessments may be applied to the whole product or individual technologies needed for system elements on any level of the system architecture. Because the TRLs are established already, there would be nothing gained from defining sub-categories for Category III products in parallel.

It would be wrong to state that Category III products bear always the highest risks compared with the other product categories. Sub-Category IIb and Sub-Category IIc may in fact bear higher risks, especially when the true nature of the procurement process is camouflaged by a claim of a COTS style procurement. In contrast, the procurement of Sub-Category III products may run quite smooth with no big surprises when all system elements have already achieved high TRLs. In this case, we are indeed close to the market opportunistic pole.

What distinguishes Category III products from the other categories is the fact that the customer and the producer have the opportunity of close interaction even during early system life cycle phases. That makes customer and producer into risk sharing partners. Customers have the chance to influence the product's evolution at a number of milestones seeking new opportunities and assisting in avoiding some pitfalls of unintended product features and behaviours. Producers get early feedback regarding their designs and could approach the customer when some of the plans turn out to be too ambitious.

Of course, this all happens within a framework of contractual relations with monetary, legal and time constraints. Thus, customer and producer have also to maintain their individual interests. Producer organisations are obliged to make profit in order to survive and prosper. This limits the willingness to approve all new ideas and complaints from the customer side for their to-do list. Similarly, the customer has to ensure to get the envisaged best value for money even when not everything is feasible as planned initially. To keep good relations when working together, spheres of responsibility and means of interaction need to be defined and adhered to appropriately. Technically competences to assess risks and opportunities are needed on both sides, and not exclusively with industry.

4 STANDARDISATION

Standardisation has a rather long history. For ensuring fair competition in market places, common scales for physical units were needed. Initially, basic physical units were defined locally. In the Napoleonic era, universal physical units were established. To calibrate physical units, the reference to the original artefacts of the basic physical units meter and kilogram in Paris needed to be traceable. In the twentieth century, the original physical units were re-defined on an atomic basis to make them better reproducible everywhere and with higher accuracy.

During the industrial revolution, the application of standards was extended from basic physical units to whole parts that may be used in larger physical assemblies. The ability to reproduce parts to certain dimensions within acceptable tolerances was a great achievement by itself. The pioneering example of rifle production in the United States has already mentioned above [5]. Standardisation of parts simplified the business of purchasers, traders and producers remarkably. A purchaser did not have to define every part needed for own purposes in full detail. They did not need anymore to be aware of all the intricacies to be considered by producers. For them, the agreement on certain standards by particular disciplines provided sufficient evidence for adequate quality and fitness for purpose by itself. Producers profited from the economies of scale. Larger production lots and less fluctuation of demands made the fortunes of their enterprises more plannable and calculable. Without standardisation it would have been nearly impossible for traders to develop and maintain effective markets in the light of an increasing variety of industrial goods.

Today, it is justified to talk about a standardisation industry with many national and international standardisation bodies that act as often in competition as they join their efforts for concerted action. From physical units over physical and immaterial products, standardisation reaches out into the process domain. For this reason, it is time not only to praise standardisation further, but to consider also limitations and some questionable aspects. One of the most frequent misconceptions of standards is overconfidence into the quality of the content of any standards. As with all human endeavours executed on a large scale, there are excellent and important standards, but also weak and rather immature ones that may never mature to an acceptable quality level.

All standards are the results of community efforts. The quality of a standard is primarily dependent on the range of expertise of the involved people and the group dynamic processes between them. At its best, the results represent a consistent and coherent common denominator acceptable to a majority of the standardisation community. Most standards reflect past experience in a condensed and harmonised way. If the context for applying a standard is changing, the standard may become outdated and finally obsolete. Practices demanding regular revisions may not provide full compensation, especially when a standard's scope itself loses its relevance. Overall, standards rarely promote technologies and methods at the edge of innovation and technical progress.

Standards are sometimes also used as weapons in market competition. Standards emphasising specific capabilities of a few enterprises or even the intellectual property rights of a single enterprise may influence market shares and future business and technological opportunities. Standards may have a discriminating impact too. A bulk of certain standards to be applied from the outset is usually a big challenge for newcomers who want to enter the market in a particular domain. For example, embedded systems are not anymore the exclusive domain of the aerospace and defence sector. Even when many environmental conditions are identical or close to each other, the standards to be applied for achieving certification may demand quite different means to demonstrate compliance. Some possible synergies may not be exploited.

At the end of this section, some conclusions are memorable. First, standards are important enablers to facilitate workshare for smooth cooperation between market players in a supply chain. Second, they should not be followed blindly, especially when they tend to adversely impact innovation. Third, all allowances for alternative and equivalent ways of conduct contained in certain standards should be taken into account to exploit effectiveness and efficiency gains. Applying a standard verbally word by word instead of searching for the meaning behind may not always be the best way to cope with a standard's content.

5 THE SYSTEM-OF-SYSTEM CONTEXT

In the flow of thoughts of this paper, we now narrow the scope to systems-of-systems. Doing this it is unavoidable to talk about definitions. Afterwards, the specific aspects of the NATO systems-of-systems will be summarised.

To the question what a SoS might be there is a clear and simple answer. When the term system-of-systems was coined initially, NATO followed naming practices in their terminology to define a fixed system architecture of their assets with each level of the system architecture identified by a specific term. The procured weapon systems were called systems. Consequently, the next upper level in the system architecture was designated as SoS. For good reasons, this terminology usage has not many followers anymore. From the relevant systems engineering standards only IEEE 1220 has conserved such practices, see Figure 2 [11].

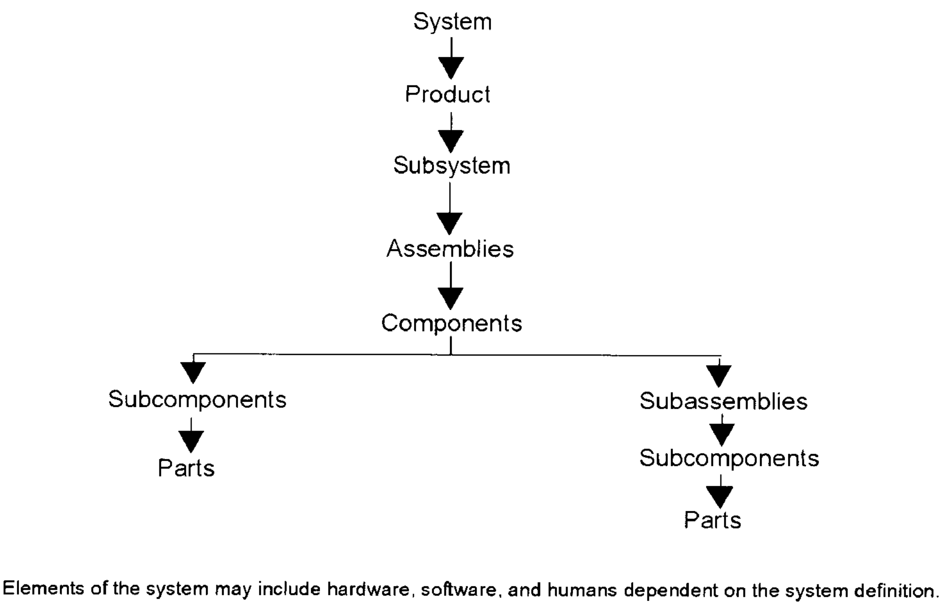

Figure 2: Hierarchy of Elements Within a System [11].

The other systems engineering standards have abandoned those practices, most prominently ISO 15288 [12]. They apply a recursive terminology pattern instead. Far less terms than before are necessary in order to describe the basic relations in a system architecture completely. In this paper, the terms system, system element, lower level system, upper level system, higher level system and neighbouring system fit the purpose, see Figure 3. The definition of these terms follow the definitions of ISO 15288. However, the ISO definitions are sometimes too scarce to precisely designate all important relations in a system architecture uniquely. For this reason, some amendments are introduced here.

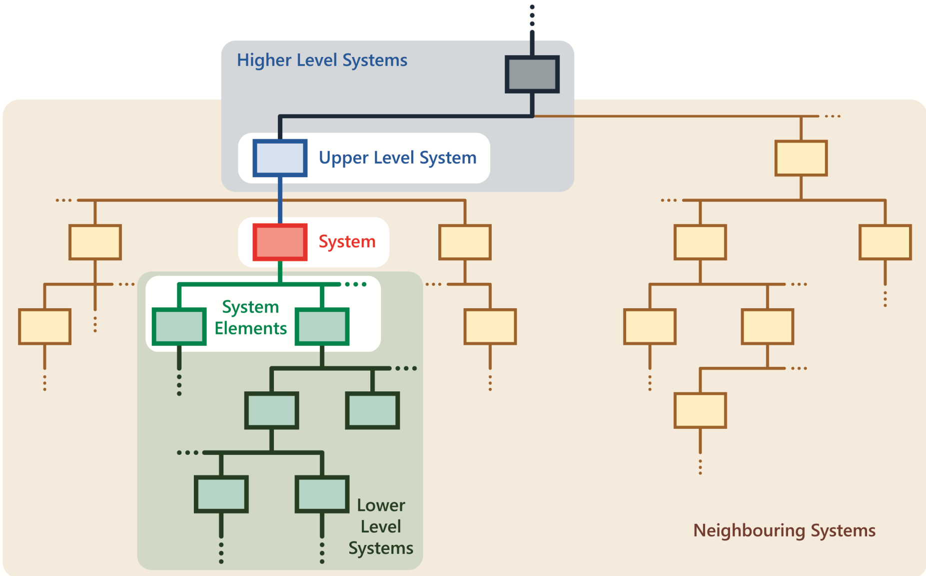

Figure 3: Relationships in a System Architecture Using a Recursive Terminological Pattern.

The term system is pivotal for all the other terms to identify the relations in a system architecture. A system is decomposed into system elements on the next lower level of the system architecture. In order to refer to all nodes in the branch below the system on all levels of the system architecture the term lower level systems is used here. Moving upwards the system architecture, the system on the next higher level is commonly addressed as upper level system. All others are referred to as higher level systems. Systems in other branches of the system architecture are called neighbouring system in this paper.

People who are not specialised on systems use the term system to describe a part of the world with specific characteristics that may be not easy to understand. A typical example is the following sentence: "It is so complex that we may call it a system." This one is from Cowan's book on the social history of American technology [5]. Unique for the term system is its linkage to complexity. The other aspects of recognising wholeness, or in other words emergent features and behaviours of a system leads us directly to basic linguistic concepts [3] and cognition psychology [1, 6, 7, 13]. To illustrate the connections an example from biology is used below.

For us humans, it is an easy task to determine a bird, a flock of birds, or the annual bird migration. All three phenomena have emergent features on their own. That means some of the specific characteristics are best described with respect to a particular entity. For example, the manoeuvring of a flock of birds is a result from a number of birds flying in formation, but the behaviour of the swarm as a whole is not easily comprehensible when observing the flight of the individual birds alone. Also the purpose to defend against attacks from falcons by irritating them with dynamic manoeuvring, or to optimise energy consumption during long-haul flights is not really easily recognisable with the focus on the individual birds. Similarly, the annual bird migration tells us little about flocks of birds although many species perform the long-haul flights in swarm formations.

We may conclude that the terms bird, flock of birds and the annual bird migration exist in the English language just in order to designate the distinctions of the three observed phenomena. It is easy to organise the three terms in a hierarchical manner: The annual bird migration consists of the flight of all flocks of birds (plus the flight of birds that do not practice flying in swarms), and a flock of birds consists of the flight of many individual birds. Following this cognitive pattern, a meaning of the term system overlaps with the meaning of such general terms like entity, category and class - to just identify a few. Furthermore, the recursive usage of the term system is supported by the fact that we may analyse birds, flocks of birds and the annual bird migration as systems on their own. Eventually, the inherent claim of systems theory and systems engineering for being universally applicable is backed by these fundamental ties.

So far there is no reference made to the term system-of-systems yet. In close analogy to the simple initial definition, the term system-of-systems could just be used as a synonym for upper level system, but that would devalue years of fruitful research on SoS. There must be a role of SoS beyond the basic hierarchical relations within a system architecture. In the literature, various definitions for the term system-of-systems are stated [10, 14]. Unfortunately, these definitions are not really convincing to justify the invention of a separate term because the term system fulfils already the same criteria.

One reasonable way out of this dilemma is to enrich the basic system architecture by considering the organisational independence of legal entities in accordance with the workshare considerations from above. It should be noted that some definitions of systems-of-systems refer to managerial independence as an important characteristic of SoS, but without clearly referring to legal entities only [14]. In a generalised view, a particular enterprise is responsible for a part of the system architecture representing their product and its recursive architectural decomposition down to system elements that are procured from other enterprises. The system representing their product is embedded in a system environment consisting of all higher level systems and all neighbouring systems of the system architecture. The term system-of-systems could then comprise the part of the system architecture under control of the enterprise that is in charge of the upper level system. When applied to the procurement of military weapon systems, this enterprise may be identified as the one providing military security, e.g. either the national governments, the ministries of defence, or NATO as a whole.

Of course, the basic facts were already valid before the term system-of-systems was coined in the last decade of the twentieth century. It was just not common before to emphasise the commonality of the governmental operations and the industrial producers providing weapon systems in a common system architecture. Industrial enterprises worked on technology and physical products while the governmental operations were merely based on people and paper. Changing the viewpoint was caused by two separate developments.

The first reason was the consideration of COTS products in military procurement. The combination of the traditional green-field style approach and management practices based on command and control. The responsibility for successful integration of new or updated weapon systems could be widely transferred to the producer of the weapon system. The role of military procurement was just the establishment of the appropriate requirements to ensure that the right weapon system was developed and manufactured. For COTS products this did not work anymore as they have to be taken as they are. In this case, successful system integration of particular COTS products into the SoS including all technical aspects becomes an issue of SoS engineering, e.g. becomes the responsibility of the governmental organisation itself.

This resembles existing practices regularly found further below in the system architecture. For example, a fighter aircraft is developed by a first-tier weapon system producer based on a particular demand. The enterprise defines the appropriate flight control system. For the development of the flight control actuators a specialised second-tier enterprise is contracted. Due to the specific characteristics of the aircraft and its flight control system, the flight control actuators are at least on demand customisations of existing designs, if not all new developments. The second-tier enterprise procures position transducers from a third-tier supplier. Under the assumption that appropriate position transducers are available from scratch, the responsibility that they satisfy their purpose as parts of the new flight control actuator design resides completely with the actuator manufacturer as long as changes to the COTS position transducer are not planned.

The second reason was the progress in information processing. This allowed the transition to network centric warfare. Command and Control (C^2) was transformed over time into Command, Control, Communications, Computers, Intelligence, and Interoperability (C^4I^2). A system-oriented approach was necessary to cope with the new complexity of the SoS. Operations research on war theatres, air defence scenarios etc. needed to be tightly linked to the technical features and behaviours of the information processing networks.

6 SYSTEM INTEROPERABILITY

System interoperability is one important aspect of a complete description of a SoS. Literally, system interoperability is concerned with the interaction of the systems that are constituents of the SoS, i.e. the system elements of the SoS. However, NATO had a wider understanding of the NATO Interoperability Environment (NIE) from the outset [17]. In addition to the NATO C3 Technical Architecture (NC3TA), its scope also extends to the NATO C3 Systems Architecture Framework (NC3AF) with operational, system and technical views. Thus, the operational capabilities of the SoS as a whole become traceable to the implementation of the technical architecture. Regarding the relation between NC3AF and NC3TA, the NATO defined the NC3TA as the principle source of procedures, architectural concepts, data (standards and products) and their relationships from which the technical view according to the NC3AF may be constructed. The document titles give the impression that the scope of NATO system interoperability captures just command, control and communication. This restriction was not kept. Some years later, the NATO C3 Technical Architecture evolved to the NATO Interoperability Standards and Profiles (NISP) [18]. Equivalently, the NATO C3 Architecture Framework mutated to the Architecture Framework (NAF) [19].

The coverage of system interoperability by the NIE is limited in another dimension. It comprises all information system aspects, but there are other aspects of system interoperability as well. Overall, NATO manages system interoperability by standardisation agreements for which the acronym STANAG is used. Each STANAG is identifiable by a four-digit number. STANAGs are partly concerned with the NIE, but address other facets of system interoperability as well. A particular group of STANAGs is concerned with such mundane issues like cross-servicing. For example, cross-servicing capabilities ensure that a NATO aircraft may be refuelled almost at every NATO airbase. Other basic maintenance services are provided as well in order to avoid that the aircraft does become stranded when landing on another NATO airfield. Even those services may be tricky on their own. However, they do not reach the complexity and implications of information technology systems ensuring system interoperability within the SoS, of course.

For a number of reasons, the complexity is much higher for achieving the NATO Network-Enabled Capabilities (NNEC) envisaged. First, an increase of the number of nodes in a network increases the number of possible interfaces according to a quadratic function. That means, systems-of-systems do not scale with the number of systems involved. Intentionally, omitting a portion of the possible interfaces reduces the complexity of the whole SoS remarkably when the number of systems participating in the SoS is high. This is usually the case for the NATO warfare scenarios. On the other hand, cutting interfaces may affect the SoS capabilities adversely by not providing certain capabilities. In order to provide guidance, the NC3TA defines five interoperability degrees as follows [17]:

Degree 0 - Isolated Interoperability in a Manual Environment
The key feature of Level 0 is human intervention to provide interoperability where systems are isolated from each other.

Degree 1 - Connected Interoperability in a Peer-to-Peer Environment
The key feature of Degree 1 is physical connectivity providing direct interaction between systems.

Degree 2 - Functional Interoperability in a Distributed Environment

The key feature of Degree 2 is the ability of independent applications to exchange and use independent data components in a direct or distributed manner among systems.

Degree 3 - Domain Interoperability in an Integrated Environment
The key feature of Degree 3 is a domain perspective that includes domain data models and procedures where data is shared among the independent applications which may begin to work together in an integrated fashion.

Degree 4 - Enterprise Interoperability in a Universal Environment
The key feature of Degree 4 is a top-level perspective that includes enterprise data models and procedures, where data is seamlessly shared among the applications that work together across domains in a universal access environment.

Second, over time some systems may be removed, others added, and many updated. This brings a dimension of dynamic evolution to the SoS. The changes may lead to capability enhancements of the SoS, but may also just counteract wear-out and technology obsolescence. Maintaining the appropriate system interoperability capabilities is a constant challenge. Changes to individual systems participating in the SoS demand dedicated system integration. For the validation and verification of the system interoperability part, NATO provides the NATO Interoperability Environment Testing Infrastructure (NIETI). Changes to the technologies implementing system interoperability directly may have an especially far-reaching impact on the SoS. Not all systems affected may be updated immediately due to resource constraints.

Third, the information technology means for implementing system interoperability are rather complex by itself. In the first place, the NIE is only concerned with the distribution and processing of information. However, due to the need for physical representation of information, system interoperability may have a deep impact on the participating systems at low levels of their system architecture. Appropriate modularisation and segregation concepts are needed to simplify the interfaces required for providing powerful system interoperability capabilities. Available means include application of the OSI network layer model in order to segregate the application information widely from the physical representation. Common patterns for defining the application interfaces as offered by Service Oriented Architectures (SOA) provide promising opportunity. And, reliable and standardised electronic circuitry contributes to the protection of the SoS application layers against many external threats.

However, we do not live in a perfect world. In practice, the isolation of network layers may be less than the theory would suggest. Physical implementations of electronic circuitry and data transmission protocols are not flawless. And of course, experienced people will not commit to claims that approved standards are fully compatible to each other by default. Even different standards from the same standardisation body may contain inconsistencies. In the next section, we investigate how system interfaces may be effectively managed.

7 SYSTEM INTERFACES

In general, system interfaces are a result of the architectural decomposition throughout the whole system architecture. In the scope of system interoperability in a SoS, the external interfaces of the systems participating in the SoS are the appropriate starting point for the considerations in this section. Over the external interfaces all the interaction between a system with the SoS as a whole and neighbouring systems are channelled.

As far as system interoperability is concerned, these interfaces are abstracted as information flows. Pieces of information flow from one source to one or multiple sinks. This feature in information theory makes information models a perfect means to express cause and effect relations. In this model, the effect has no direct impact on the cause. If there is a reverse impact to be considered, information theory provides the feature of feedback loops for adequate modelling without violating the underlying principle of directed information flow. With these provisions information theory has gained many merits.

However, it is not easy to transfer the directed-flow principle into practice. In communication situations between humans, the information content is only one part of the story. The motivation of the source, the intention of the source regarding the communication partner's reaction, and the way the communication partner interprets the situation of which the information content all contribute to successful communication. For the NATO interpretation of SoS this is an important aspect of course for their C3 systems, as the human element is to be found in many leadership roles. However, as in the previous section we will not further dive deeper into the domain of the operational view. But we have to keep in mind that the human communication aspects affect the human-machine interfaces. And, the human-machine interfaces impose essential requirements on system interfaces.

To implement information theory on a physical basis, similar issues occur. Like in human communication, natural laws define mutual impact only, for example Newton's laws and Kirchhoff's laws. However, engineers have been creative to overcome these restrictions to make electrical energy flow into one direction, and to generate controlled movement in any intended direction with the technologies and products they invented. This is achieved not by cheating nature, but by exploiting large differences in magnitude. Physical stress can be measured because the monitored structure is much stiffer than the strain gauge. Similarly, operational amplifiers nearly eliminate the impedance of the output load on the input by very high amplification rates.

The intricacies of physically implementing information interfaces, makes interface standardisation a field in which NATO has invested a lot of effort. A huge repository of STANAGs defining all aspects of data bus systems has built up in the past, now amended by considering standards established by other standardisation bodies. Producers of the systems participating in the SoS have to accept obligations to apply these standards and corresponding COTS components or GFE. These requirements may actually be implemented on quite low levels of the system architecture by enterprises involved somewhere deep in the supply chain.

Then implementation may become one of the most tedious and critical tasks when a system interface does not work as expected. The remarkable number of individual and organisational contributors involved and the long communication channels are challenges for successful corrective actions performed in due time. System interface management needs to become an integral part of all design activities on all levels of the system architecture. The second lecture on the system architecting of systems participating in SoS will pick up this issue.

8 CONCLUSIONS

This paper defines the term system-of-systems in an overall system architecture in relation to the organisational boundaries between legal entities taking responsibility for their part of the overall system architecture. This makes the specific characteristics of systems-of-systems comparable to the options how to organise workshare in industrial cultures. Thus, a wide range of alternatives for organising workshare, ranging from green-field approaches to market opportunistic approaches, becomes available for evaluating the NATO approach to system interoperability and system interface standardisation.

The evolution of procurement policies within NATO and NATO member countries is reviewed. The utilisation of former exclusive military technologies in other industries led to the consideration of COTS products in military acquisition. NATO member countries adapted their procurement policies, but in slightly different directions as they had different expectations of what could be achievable. A product taxonomy is proposed to allow the generation of guidelines for appropriate variations of procurement processes.

Then, the NATO approach to system interoperability is described briefly. The technical aspects of system interfaces and the implications for engineering the weapon systems is emphasised. A second paper will further dive into the intricacies that system interface engineering adds to the systems engineering process.

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