

Research Article

Architectural approach for analysing and managing innovation in complex system design projects

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Abstract

Deep changes are taking place in business, brought about by increasing design innovations for enabling organisations to stay competitive in the era of Industry 4.0. Strategic methods for developing and managing innovation need to address multiple sources of technology advancement across a diverse range of disciplines. Organisations must have the flexibility to embrace new partnerships and form alliances that bring benefit to technology advancement, control the inherent risk introduced by development and ensure the agility to compete. Without strategically addressing these factors, organisations have struggled to overcome the inherent risks that innovations and introducing new technology and/or processes can carry. Consequently, organisations take a conservative approach, only committing to very small incremental change or attempting to offload risk to partners. As a result many innovations are stifled and fail to achieve their full success potential. This paper proposes that a systematic architectural approach is required to holistically manage and control innovation both within an organisation and an alliance environment to achieve success. The foundation of this architecture is the cyclic application of a system model known as 3PE, that ameliorates the identification of risks in innovations and an algorithmic process that crucially defines the priority of mitigation throughout the life cycle. The evaluation/assessment of innovation(s) concurrently, provides the flexibility to constantly manage residual and emergent risks. Furthermore, by understanding the correlation/interactions among the risks, both within an organisation environment and across alliance partners, promotes smart quantitative prognosis of potential risk impact and mitigation strategies across the project life cycle, which can be developed to minimise risks dynamically.

Keywords: risk, innovation, alliance, management, systematic, design process.

1. Introduction

In a technologically advancing world that has seen extreme acceleration of progress with the advent of Industry 4.0, an interesting question becomes apparent: how successfully are these technology innovations actually being developed and implemented? And additionally, how can improvements be made to enhance the management and control of innovation not only within an organisation, but also involving a multiple partnership environment?

Clearly these questions are applicable across all industries and fields with innovative advancements and the introduction of digital technology being ubiquitous. As an example, the automotive industry is seeing a watershed moment with the move from traditional petrol and diesel vehicles to hybrid and on to fully electric powertrains. Electric cars have been a consideration for many decades and previous attempts at development have seen little success. The domination of hydrocarbon fuels and automotive manufacturers' reluctance to innovate in new areas of powertrain design and technology is a large factor. Innovation introduces risks to sales, R&D costs, supply chain, reputation, to name but a few. Manufacturers have therefore, preferred the slower incremental development route. While this is perceived as the less risky strategy short term, it creates exposure to unexpected technology development and environmental changes. At a more extreme level, famed 'black swan' events can have catastrophic outcomes for organisations (Taleb, 2010). The recent advancements and the speed of changes in automotive technology has been, in many ways forced by both changes in legislation (e.g. strict Government requirements for emission reductions by 2030 in the UK) and several small companies innovating and seizing on advancing technology to develop competitive and attractive electric cars. This has left the larger automotive manufactures struggling to catch up as consumer preference changes.

This paper proposes an architectural approach that assesses and models the risk that developing innovation poses to an organisation. Crucially, the model is expanded to analyse systematically the impact of developing an innovation within an alliance. Furthermore, a case study is provided which models a historical project to demonstrate the value and effectiveness of the model.

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2. Literature review

Striving to survive in an ever-changing world as well as maintaining the ability to innovate has become increasingly crucial (Zhuang et al., 2018). Understanding the link between project complexity and innovation is highly pertinent. Strategic options to control and minimise risk through systematic modelling offers some benefits, if implemented and managed comprehensively from the outset (Cook & Mo, 2015). However, many challenging projects are further complicated by the introduction of partners, with the formation of alliances traditionally viewed as decisive for success (Young et al., 2016).

2.1. The nature of innovation in engineering projects

In their research into the challenge of innovation in highly complex projects, Shenhar et al. (2016) developed a model that suggests high-tech projects must include at least three cycles of design, build, and test. It also suggests that such projects need to allocate about 30% of the time and budget, as contingent resources, beyond a typical traditional plan. This was supported by a study into financial service firms by Das et al. (2018), the research highlighted if an innovation strategy, active management support, and a separate governance structure for innovation are in place, projects get stimulated at the exploration phase and do not experience a lack of appropriate resources or competition with traditional projects.

Similarly, Shenhar & Dvir's (2007) model suggested that complex projects should be seen as an "array", which they defined as a large collection of systems or organisations, working together for a common mission. The array project must prepare clear guidelines and co-ordinating mechanisms to ensure participating companies are aligned with terminology and standards, are similarly trained, and effectively communicating.

Yakovleva (2018) concluded that there was no systematised approach to the planning/implementation of innovation projects. As a result, a theoretically substantiated algorithm of innovation project management toolset selection to facilitate the task of innovation project management is required. This was supported by Marsh (1997) who highlighted that the lack of research and development could have significant consequences not just for organisations but countries. For example, between 1986 and 1994, Britain's share of world trade in mechanical engineering products dropped from 7.2 per cent to 5.9 per cent.

2.2. Innovation risks in long term projects, i.e. risks of lagging in competition

It is well established that the development of new innovation is a balance between risk and reward (Day, 2007). Therefore, suitable managerial practices to support these projects vary substantially from those supporting incremental innovation projects. From a project risk viewpoint, significant or radical innovation are characterised by higher uncertainty, high absorption of new knowledge by the organisation, as well as exploration of new markets, technologies and/or business models.

Kristiansen & Ritala (2018) established companies across industries have developed comprehensive toolsets for managing innovation projects and portfolios. Most of these tools and approaches are suitable for incremental innovation, but not for radical innovation. Highly uncertain radical innovation projects demand toolsets that are unlike those that perform well in the realm of incremental innovation.

Van Wezel et al. (2018) defined that Risk Analysis and Technology Assessment, referred to as "RATA," can provide a basis to assess human, environmental, and societal risks of new technological developments during the various stages of technological development. A study by García-Granero et al. (2015) concluded that an organisation's risk-taking climate for its employees is a determinant mediating the relationship between manager's risk-taking and innovation performance, i.e. empirically the risk-taking climate significantly affects innovation performance. To this end, Styhre (2006) detailed a case study suggesting senior management are not fully aware of the risks in science-based innovation; inherent risk in all scientific and engineering undertaking needs to be recognised.

Koulinas et al. (2021) highlighted that project risk management is one of the most challenging processes impacting the project's expense, time, and complexity. Risk identification plays a critical role in the first stage of the risk management process since it imposes the analysis framework. According to Ren & Yeo (2014), an integral part of the Systems Engineering Methodology is risk management. This means all risks must be assessed and checked at any time and during every phase of the project.

Cook & Mo (2018a) detailed how organisations favour forming an alliance when undertaking large and complex projects. Their research highlighted how risk pathways increase with the introduction of partners and thus needs to be carefully managed. Therefore, projects incorporating innovation had more challenges and complexity if undertaken by an alliance.

2.3. The Effectiveness of an Alliance

Deniaud et al. (2015) stated that the formation of an Alliance could be thought of as a risk reduction strategy that can share technical challenges, tap into appropriate resources, ensure competitive edge, share the financial burden and schedule pressure of large complex projects. From their research, Young et al. (2016) described the win-win culture created by the combination of alliance elements, which enabled the alliance to handle complex or high-risk projects and projects with great uncertainty. Benitez (2016) pointed out that there are examples of such alliances, and their value was mostly in areas such as aerospace and defence. These industries tend to undertake extremely technically complex projects that require massive financial investment and commitment for long periods.

Walker (2015) provided evidence alliancing has been effectively used under conditions of uncertainty, ambiguity and high risk on complex projects. Walker attributed this success to alliances having specific standards and expectations. However, Cook & Mo (2019) provided evidence that all is not well with the alliance strategy as a method for mitigating risk. Their research detailed how introducing partners to a project increases risk pathways and chances of success are limited without a systematic holistic approach to risk management. This was further supported by Goa & Zhang (2008), who found the failure rate of alliance projects as high as 50%. Many factors contributed to these figures including the complexity of controlling partnership risks, the process of how individual partners will work, emerging behaviours of alliance partners, etc. Cui et al. (2018) went as far as to suggest there is some evidence of skulduggery, alleging some organisations used an alliance to facilitate the identification of partners' vulnerabilities and launch competitive strategies to undermine partners' weaknesses, secure technology and get the jump on innovations.

2.4. Innovation risks in alliances

In recent times, co-innovation has emerged as a popular concept for how organisations may create partnerships to develop innovations. Bugshan (2015) defined the term 'co-innovation' as innovation deriving from the collaboration of two or more parties. Of course, the reasons driving companies to co-innovate are manifold, spanning from accessing and co-producing new knowledge, to designing new products and services and decreasing time to market. Through co-innovation, partners increase their competitiveness by sharing knowledge, resources, improve production, exports, profits and/or the environment. Ombrosi et al. (2019) specifically highlighted two major sets of drivers that can be recognized for co-innovation: relationship-based reasons on the one side and technology-based reasons on the other side.

In their study on co-innovation risk, Abhari et al. (2018) found co-innovation actors (external co-innovators) perceived four different individual risks: time, social, intellectual property rights, and financial. The empirical results demonstrate a high degree of confidence in both translation validity and criterion-related validity. Negative effects of perceived co-innovation risk on actors' continuous intention to ideate, collaborate, and communicate in co-innovation were evident, but prior experience moderated these relationships. Chesbrough (2003) defines a new model of 'Open Innovation', where a company commercialises both its own ideas as well as innovations from other firms.

From their research, Zhu et al. (2019) found that in an alliance it is essential that the lead firm, as the initiator of the project, should understand the exploratory nature of the project as well as foster innovation-related capabilities and network-related capabilities as pre-conditions. Furthermore, Trappey et al. (2017) reviewed research in collaborative systems and concluded that the concept of collaborative systems is not just a collection of enabling technologies but also a fundamental business philosophy requiring strategic thinking for a variety of applications at different stages of collaboration, including management, dissemination, use of data, information, and knowledge throughout the entire life cycle of product development. The current research conducted into strategies and system architecture related to alliance formation is clearly immature.

2.5. Summary

It is well established that innovation is laden with risk and presents extreme challenges for any organisation. Forming a partnership or alliance is seen as a strategic method for spreading the risk of innovation and development. While on the surface this appears to be a sound strategy, from the literature it is clear all is not well with alliancing and the challenge of innovative complex projects has received limited research attention and theory development. A new system architecture approach that can expose the origin of innovation risks in complex (alliance) projects and provide an investigative direction of identifying these risks is required.

3. Alliance Innovation Life Cycle Assessment Methodology (AILAM)

Complex projects in areas such as defence and aerospace are usually co-ordinated by a technical process built on a backbone of Systems Engineering (SE) methodology (INCOSE, 2007). This methodology has been well

established for many decades and is structured around the SE V lifecycle model (Figure 1). Broadly speaking, the SE methodology encourages innovative ideas to be proposed according to a set of requirements that are determined at the infancy of the project, followed by specific phases of the design and realisation process (verification and validation). An integral part of this process is risk management. Innovative ideas are often application of immature technologies and developments. SE methodology includes several strategic mandatory gates at which the proposed advances in technology need to be sufficiently demonstrated before the project can progress to next phase.

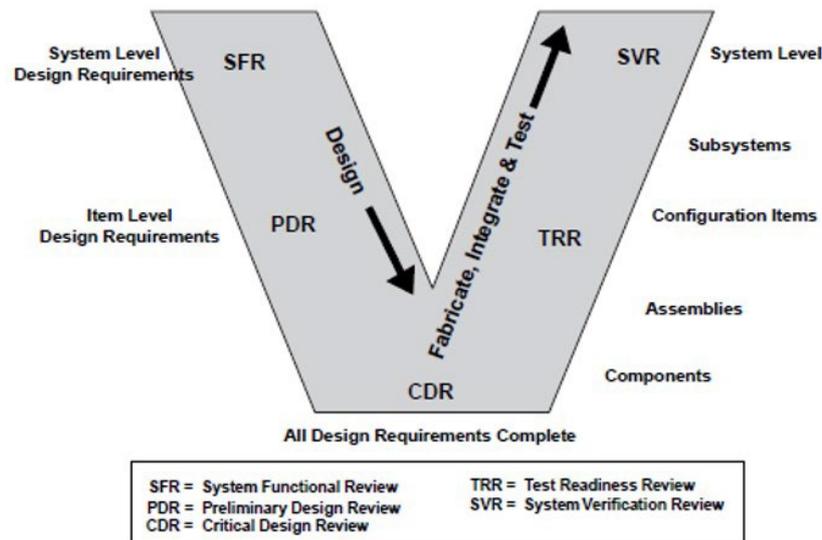


Figure 1. Typical Systems Engineering V Lifecycle.

Although successful application of innovative ideas can be highly rewarding, it is inherently risky. How can the project team decide that a certain innovative idea (at the SFR phase), has a good chance of success and will produce great benefit(s) later in the project? The SE V lifecycle has a good theoretical foundation that has been applied with varying degrees of success. This problem of making ‘the right choice’ for an innovation, becomes increasing apparent when significant complexity is introduced, such as the formation of partnerships and alliances. Cook & Mo (2018a) have written previously regarding the challenges that organisations face when forming partnerships and the questionable success alliances have achieved historically. They illustrated, by applying a system modelling method known as 3PE (Product, Process, People and Environment) that as more partners join the alliance, there is a significant jump in possible risk pathways and as a result, without very robust and comprehensive risk analysis and mitigation strategy, the project can become overwhelmed.

To address these challenges, Cook & Mo (2019) incorporated Analytic Hierarchy Process (AHP) into their 3PE analysis for assessing alliance risks. In this context, AHP is used to determine both the significance and priority that risks need to be addressed as a snapshot assessment at a certain point in the SE V lifecycle. The 3PE modelling methodology provides a structure where all risks (including anticipated innovation) can be located within the topology. The combined analysis methodology, e.g. SE+3PE+AHP, offers the ability to analyse where risks are potentially clustering and mitigated during the entire duration of project development (Cook & Mo, 2020).

It is well established that innovation needs to be a significant part of any organisation’s fundamental function. Without innovation, companies will quickly find they battle to compete and ultimately survive. However, innovation presents significant uncertainty that most organisations will struggle to justify and manage. As a result, companies will look to spread the risk by partnering up, which clearly adds further complexity to the alliance model. To cater for ‘uncertain time of success’ in innovation, the snapshot assessment described earlier should be applied several times over the SE V Lifecycle. However, this assessment should be done at the project infancy to ensure a better chance of preventing downstream problems from occurring.

Using 3PE methodology, the organisation can be modelled within its environment as shown in Figure 2, with the innovation being modelled as part of the product element. This modelling construct clarifies that each organisation can have its own innovation reflected in its product offering. If there is co-innovation in an alliance, the relevant part of the co-innovation in each organisation will need to be separately represented in each of the 3PE models.

It is worth noting that if innovation is in the process of using an existing product, or new procedure to manage the project team, innovation can also be identified in process element of the leading organisation. This paper focuses on product innovation as per Figure 2. Process innovation will be explored in future research.

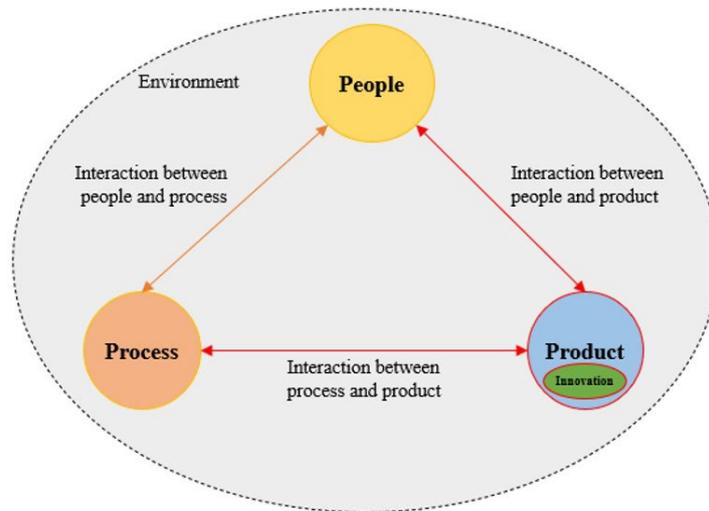


Figure 2. 3PE model that includes significant product innovation.

Having defined the architectural model of an organisation, this paper proposes an iterative approach to assessing the effect of innovation risks on long term projects under alliance arrangement, known as Alliance Innovation Lifecycle Assessment Methodology (AILAM). The iterative approach is a significant enhancement to the combined methodology, to enable a thorough assessment of risks at the infancy of the project. The AILAM can be illustrated in Figure 3.

After the initial set of risks has been established, the output requires evaluation by the project team. Post this evaluation, a new 3PE system model can then be launched, and the initial set of risks can then be refreshed and expanded as updated scenarios materialise with the new 3PE model and re-considered innovative ideas.

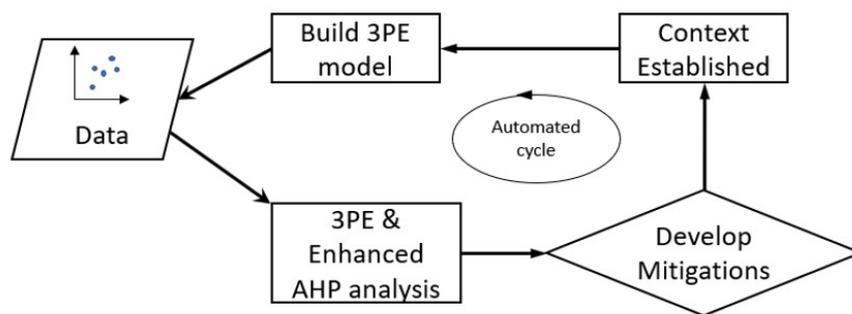


Figure 3. New 3PE+AHP System for AILAM.

With the new 3PE risks, a AHP matrix can be created and prioritisation process can be done to refine the mitigation plan. Theoretically, this cyclic process can continue until there is an acceptable set of risks for all innovative ideas being proposed. Research into past innovative projects, showed that each round of assessment can be more effective by setting improvement goals. This systematic approach is very likely to ensure completing risk assessment of innovation projects in circa three rounds. The initial round of assessment (or first iteration), will focus on a single organisation and the risk of innovation within that organisation’s own environment, see Figure 2.

A second-round iteration will be focused on interactions among partners within the alliance environment. It is important to highlight here that the elements of the 3PE model (People, Product and Process), are established within each of the organisation’s own environment, during the first iteration. The second iteration models interactions between the elements of all the partners, within the alliance environment, see Figure 4.

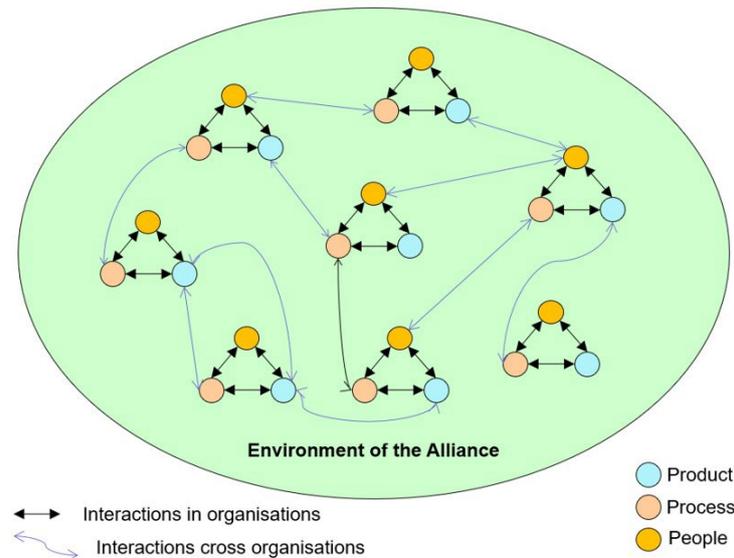


Figure 4. 3PE expanded into System of Systems modelling.

A third and final iteration of the 3PE model is now run where risks that are located within the individual organisation environments and the overall alliance environment and re-evaluated for the final time, and it is at this point that a definitive list of all project risks is captured.

4. Applicability of AILAM for Managing Innovation across alliance partners

When an organisation takes on a large complex project, there are many risks that need to be addressed/mitigated to achieve a successful outcome. The number and severity of the risks will increase drastically, when trying to develop and introduce complicated and cutting-edge innovations on top of the extant challenges of executing the project. As part of their risk analysis and modelling process, it is essential that organisations plan for uncertainty and problems. This is the key value of AILAM, its methodology will help establish what actions and mitigations can/should be applied to burn risk down through the project life cycle.

4.1. Added complexity of alliance

As an added complexity, many innovations and advancements in technology can come from a wide array of sources and industries. There are many examples of such alliances, and their value has been much publicised in areas like aerospace and defence (Keller, 2016). These industries tend to undertake extremely technically complex projects that require large financial investment and commitment over long periods of time. This invariably results in several companies, organisations or individuals attempting to create partnerships. In many cases, partners form an alliance where they attempt to work together to develop and deliver new innovations and technology. In large industry projects, this usually takes the form of a prime organisation leading with several partners contributing their expertise through the said prime. The formation of an Alliance is generally thought of as a risk reduction strategy for sharing the technical challenges, tapping into appropriate resources, ensuring competitive edge and sharing the financial and schedule burden of large challenging projects. This in turn means risks are essentially spread across two or more organisations. The theory being each organisation should have the attributes essential to meet key project requirements and thus mitigate risks.

AILAM can deal with this situation because of the structure that the 3PE model offers. As each partner is introduced into the alliance environment, interactions between the 3Ps are established which represent risk pathways that require assessment, refer to Figure 4. AILAM clearly defines each interaction and as the number of partners increases within the alliance environment, these interactions also increase and thus the number of potential risks.

4.2. Identifying risk adverse partners and customer

Innovation can bring the ultimate reward to any organisation, business, or project but it goes hand in hand with high uncertainty. In an alliance situation, this will drive certain behaviours with risk adverse partners and the customer, who will all look to avoid and/or offload risks (Parkhe, 1993). Consequently, significant project risks fail to be truly mitigated, due to partner's lack of commitment. This results in a failure to burn down the risk profile, increases in emergent risks and schedule/cost blowouts. As the project begins to fail, relationships break down, partners blame each other, some partners cut their losses and leave, all resulting in an unsatisfied customer.

AILAM can deal with this because it uses an AHP ranking system to establish a prioritisation on the migration of risks at the birth of the project. This can then be monitored as the project moves through the life cycle to ensure the expected risk burn down is being achieved to baseline.

4.3. Managing lack of commitment of partners in alliance

The purpose of many partners joining an alliance is to “share” the risk, i.e. if there is a problem, they are the first to run away (Kang & Zaheer, 2018). These potential behaviours need to be accounted for and managed from the outset. Consideration by the alliance holistically to partners selection, viability of seeing the project through, their history/track record, etc. are all areas of risk to a project’s success. For example, an organisation may have developed a solid technical solution thanks to an innovation by some core staff, but what if said staff leave or the business has weak leadership or financial backing? Is it possible the business will flounder and/or expose itself to takeover?

AILAM can deal with this because it has multiple iterative cycle assessment which can make critical adjustments and rebuild the risk profile based on the dynamic situation of partners and their impact/interaction within the alliance environment.

4.4. Mitigating lack of agreement between partners

In many alliances, competitive organisations may be forced to work together, with little account being taken of the risks and the strategies to deal with the selection of the collaborators and the repercussions (Deniaud et al., 2015). Unless the customer or the group managing the alliance takes firm control, partners can actually work against each other, unable to form a pragmatic working relationship and failing to develop basic agreements. This lack of co-operation introduces additional project risks and increases the severity of extant risks.

AILAM can deal with this because it can re-iterate the context over several rounds to clear all disagreement and identify areas of contention that require mitigation. Furthermore, emergent risks can also be identified as the project transitions through the life cycle.

4.5. Accommodate innovation into system engineering life cycle

There is now a global push for new products and services to address environmental and sustainability requirements. The social conscience of consumers, organisations and government legislation has changed, this pressure means that any innovation or new technology needs to offer environmental and sustainable benefits to achieve success (Baldassarre et al., 2020).

AILAM is able to manage these issues as it deals with risk mitigation over the project life cycle. This includes risks relating to the environmental and sustainable use of the product. These risks require quantification during risk assessment and appropriate mitigations defined.

4.6. Summary

It needs to be clarified here that the authors are not trying to imply that organisations and alliance should not innovate, but instead offer such projects a realistic and increased possibility of success by promoting a novel and robust system architecture risk model to dynamically manage risk through the life cycle. Only the 3PE+AHP model can assess complex enterprise (alliance) risks, existing risk assessment methodology does not take into account the nature of innovation risks, i.e. high failure rate, uncertain time of success, etc.

5. Case Study of AILAM for a long-term defence project

To illustrate how AILAM could be used to assess innovative work in complex engineering projects, a case study is provided, that highlights the challenges and disturbance forming an alliance and managing innovation can introduce to a project. A historical summary of the case study is provided and analysis of how the 3PE system model could have improved the outcome is presented. For reference, this is the first step in the 3PE+AHP System for AILAM defined in Figure 3.

5.1. Context Established

In the late 1990’s the UK began development of a new surface destroyer known as Type-45 or Daring class, with the first ship, HMS Daring, planned to enter service in 2007. Among a whole array of advanced and cutting-edge systems that were integrated into Type-45, the platform benefited from the introduction of a new state of the art innovative engine package known as WR-21 to meet fuel efficiency and endurance requirements.

The engine package was developed by partners in an alliance including Rolls-Royce, Westinghouse (Northrop Grumman), BAE Systems and the UK Ministry of Defence (MoD). However, midway through the design phase, Westinghouse was purchased by Northrop Grumman and upon assessment of the WR-21 project, Northrop Grumman made the decision to leave the project. Consequently, Rolls-Royce inherited the unfinished design and

development work but significantly, was offered little relief on schedule and cost. To achieve critical delivery milestones, the engine package underwent minimal analysis and testing, before being hastily finalised and built, in order to be ready for the first of class integration deadline. The results of WR-21/Type-45 project are well documented in the media (Weiler & Chiprich, 1997), with the consequences still being felt to this day.

Many classes of naval ship use a gas turbine(s) as their prime mover, as these engines offer incredible power to weight attributes. However, improvements in fuel efficiency have been desired for some time in both aviation and maritime sectors. The WR-21 engine package mainly offered two innovative technologies:

- An intercooler at the compression stage
- A recuperator at the exhaust stage

These developments ensured the WR-21 engine package would be unique in the world, with the major advantage being significantly increased fuel efficiency and thus increased endurance for the ship. Overall, the technical theory behind the WR-21 engine package remains sound, albeit an extremely difficult and challenging technology to develop. However, the subsequent issues and problems surrounding the project can arguably be traced back to poor management when introducing such an innovation via an alliance business model.

Some news feed documents have been consulted to construct the major events of the Type 45 ships systems engineering life cycle and are listed chronologically in Figure 5 (Writer, 2016; Trevithick, 2018; Allison, 2021).

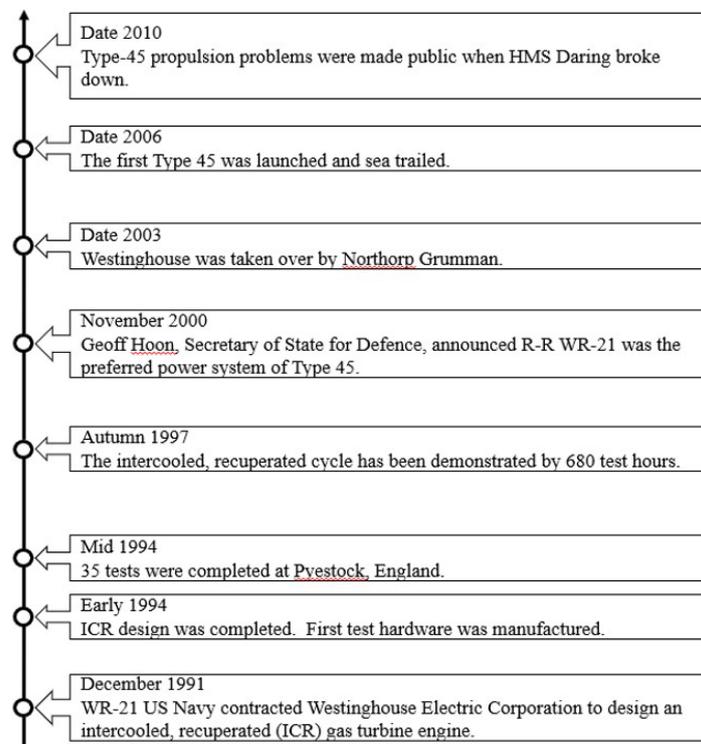


Figure 5. Major events in the systems engineering lifecycle of WR-21.

5.2. AILAM for WR-21 Project

Using the 3PE methodology, each of the companies within the WR-21 project alliance can be modelled with a set of risks according to the system elements (People, Product & Process). For reference, this is the “Build 3PE Model” step in Figure 3 of the 3PE+AHP System for AILAM. Risks within the individual companies can be identified and suitable mitigations can be planned. Figure 6 shows some entries of the 3PE modelled risks for Westinghouse. In practice, there can be hundreds or even thousands of risks in the actual 3PE modelled table. This is the “data” step in Figure 3. The data is then analysed, with AHP applied to determine the priority that the risks need to be addressed, this is the ‘3PE & Enhanced AHP analysis’ step in Figure 3. Finally, for each risk an appropriate mitigation is developed and modelled, as the final step of the 3PE+AHP System for AILAM. This model cycle should be run three times to generate three iterations as follows:

- Iteration 1 – Solve for an initial risk profile
- Iteration 2 – Include additional scope like innovation, alliance, etc.
- Iteration 3 – Final pass to including everything in the final risk profile

The 3PE+AHP System for AILAM model will now be applied using the historical case study of the Type-45 destroyer propulsion system WR-21, with details of each iteration provided.

5.3. First iteration of 3PE+AHP

Within the WR-21 alliance, both Westinghouse and Rolls-Royce needed to develop new technology as their part of the WR-21 engine package project. Any organisation attempting to bring a new innovative product to market, will see a significant increase in the risks relating to the product within their organisation’s own environment regardless of whether the project is part of an alliance or not.

By applying the first iteration of the 3PE methodology solely to Westinghouse as a single organisation, it can be seen in Figure 2 that an emphasis on the Product element has been highlighted by the inclusion of such a challenging innovation i.e. designing and building an intercooler and recuperator. It should be noted that organisations rarely bring a completely new product to market, this is due mainly to the severity of risk it carries. In the majority of cases, organisations will generally only make small incremental changes/updates to minimise their risk exposure. However, in the case of the WR-21 project, both Westinghouse and Rolls-Rolls need to develop significant innovative technical engineering product solutions themselves, these will be brought together to form the final engine package.

The first iteration of the 3PE model was used to identify risks that Westinghouse would face developing the intercooler and recuperator for the WR-21 engine package. By defining a topology framework, the 3PE model drives a robust and accurate risk capture process, see Figure 6.

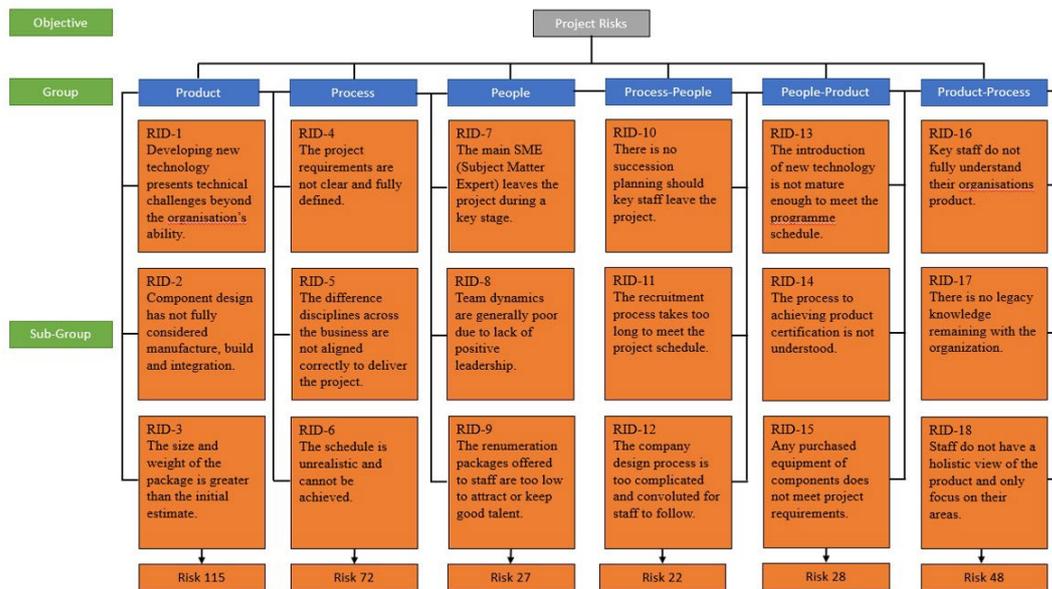


Figure 6. 3PE Framework of risk for Westinghouse.

Post the risk identification process, it was found that significant numbers of risks were clustering around the Product/Process elements and their interactions, this can be seen in Figure 6. This is clearly not unexpected considering the type of project and its technical nature. In order to give an example of the identified risks, but also maintain this paper to a manageable length, three risks for each of the 3PE elements and interactions has been provided in Figure 6.

With a comprehensive set of risks now identified and associated with either an element or interaction within the 3PE model topology, the next challenge for Westinghouse is to establish the priority for managing risks through the life cycle. It is important to note that this first iteration is taken at the start of the project, so it is this priority modelling that will establish the initial baseline risk profile.

This phase of the modelling primarily incorporates Analytic Hierarchy Process (AHP), a detailed explanation of the model has been previously presented by the Authors (Cook & Mo, 2018b, 2020). In short, each risk is essentially assessed with consideration of the likelihood and consequence of the risk in three values of Optimistic, Normal and Pessimistic situations.

A graphical representation of the results for WR-21 project and how the risks are spread across the 3PE elements and interactions can be seen in Figure 7. This level of capture and fidelity of risks has only been possible with the use of the 3PE model, as the structure of the 3PE framework provides a systemic methodology that ensures consideration is given to all areas within the project where risks could be present.

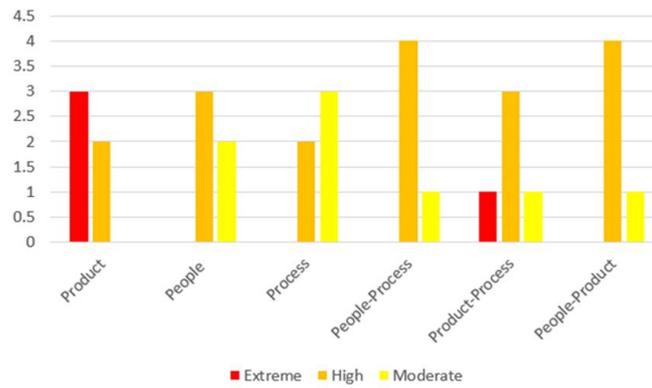


Figure 7. Distribution of Westinghouse risk levels for WR-21 project across the 3PE framework.

The integration of AHP with the 3PE model is a novel approach and has established a method to assess risks for the priority of mitigation and management across different strands in the project. This is only possible because the framework of the 3PE model has provided a structure that would have allowed Westinghouse to really understand where the extreme, high and medium risks are located or clustering within their development of the WR-21 technology. As a result, Westinghouse should have been able to direct its efforts in mitigating or at minimum control the right risks initially and on throughout the project life cycle.

For the WR-21 project, the most significant risks reside around requirements, performance, testing and the design process. These are all fundamental to an engine development project and as this risk analysis has shown, essential to be managed and controlled from the outset. Further complications were to befall the project (which are detailed in the following section), which would bring increased challenges and further emphasize the need to robustly control and manage project risks.

5.4. Second iteration of 3PE+AHP

Due to the complexity of the WR-21 engine package, Westinghouse, Rolls-Royce and BAE Systems formed an alliance to develop this technology. This three-way partnership was formed to ensure organisations with specific skills, such as gas turbine technology, were engaged and responsible (it should be noted that BAE Systems was the prime contractor to the Ministry of Defence for the overall Type-45 destroyer). However, when this alliance is examined more closely by applying the 3PE model, it becomes apparent that the potential risk pathways have increased dramatically, this can be seen visually in Figure 8.

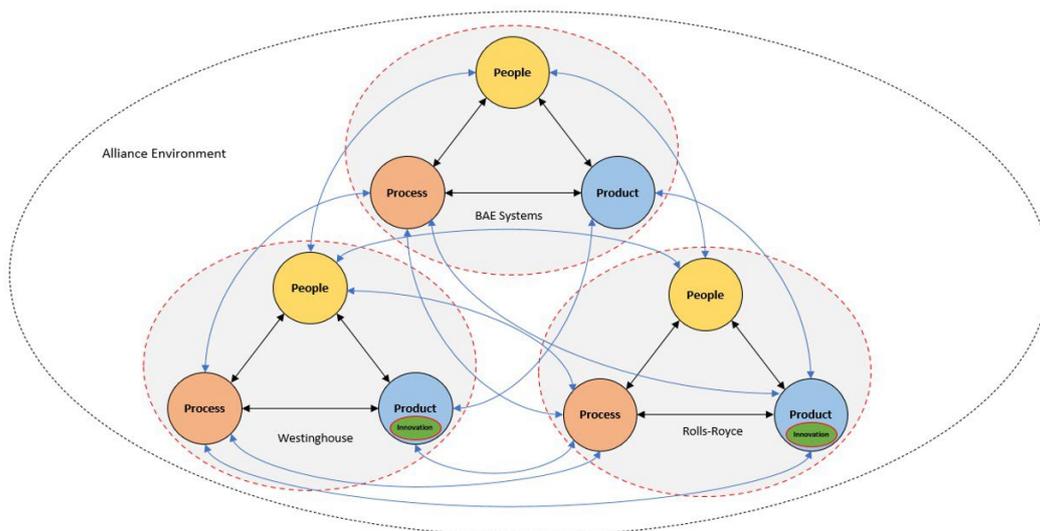


Figure 8. Alliance 3PE model that includes significant product innovation.

According to the 3PE model, by introducing two or more partners into an alliance environment, it is the interactions between the 3PE elements that will expand significantly within the alliance environment. Whereas the risks associated with the elements themselves remain static within each of the organisation’s environments. This is defined in Table 1.

Table 1. Identification of alliance risks by pairwise 3PE models of Westinghouse and Rolls-Royce.

	Westinghouse			Rolls-Royce			BAE Systems			
	People	Product	Process	People	Product	Process	People	Product	Process	
Westinghouse	People	Internal interactions			1	2	3	7	8	9
	Product					4	5		10	11
	Process						6			12
Rolls-Royce	People	Replicated			Internal interactions			13	14	15
	Product								16	17
	Process									18
BAE Systems	People	Replicated			Replicated			Internal interactions		
	Product									
	Process									

As before, the 3PE model framework was applied to identify a set of project risks. However, this time the risk analysis included potential risks that forming an alliance have introduced to the WR-21 engine project. The unique 3PE structure defines interactions between elements or risk pathways across the alliance partners and ensures consideration is given to all possible risks. Figure 9 presents a comparison between the distribution of risk for a single organisation, in this case Westinghouse, and the formation of an alliance by Westinghouse, Rolls-Royce and BAE systems.

As described earlier, the main motivation to form an alliance is to reduce and spread risk across several organisations. From Figure 9, it can be seen that both the elements of Product and Process have seen some reduction in the identified risks. However, by using the novel 3PE model, the analysis highlights an actual increase in risks located in the interactions between the elements due to the number of risk pathways introduced by the formation of an alliance (Figure 8). There are now circa 459 risks identified against the WR-21 alliance identified at the beginning of the project, while the sole organisation of Westinghouse had a total of 312 risks.

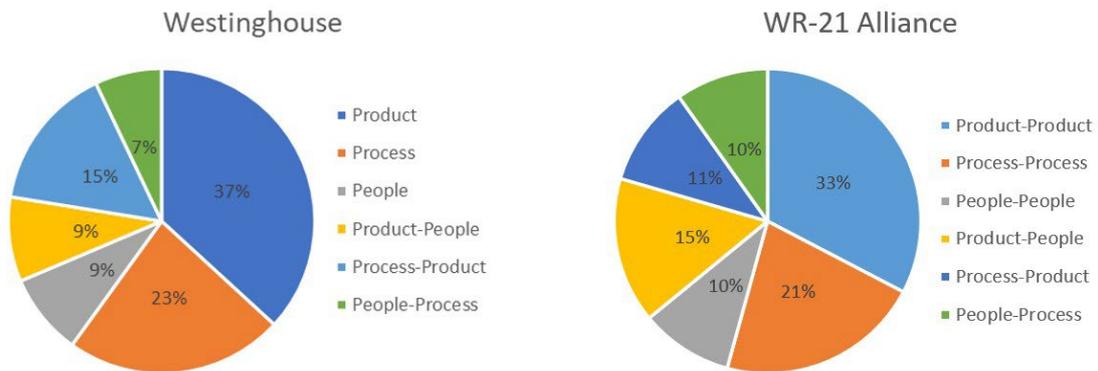


Figure 9. Distribution of risk, single organisation versus an alliance.

The results of the 3PE modelling for the WR-21 engine project as an alliance throws up a set of initial risks that are somewhat different to a sole organisation attempting to complete the project. While clearly the challenges of the product and the introduction of a new technology remains dominant, the difficulties of working with partners has become significant with the elements of Process, People and their interactions being more pronounced.

The next stage of the 3PE+AHP model was then applied to the risk set to again determine the priority for tackling the project risks. As before, the novel topology of the 3PE model highlights where risks are tending to cluster, and thus allows more precise mitigations to be developed. Once the model has been run and PERT has been initiated to define the severity of the risks, AHP is then deployed to determine the priority. The AHP output is shown in Table 2.

Table 2. AHP for the WR-21 Alliance.

		Product-Product			Process-Process			People-People			Process-People			People-Product			Product-Process		
		RID1	RID2	RID3	RID4	RID5	RID6	RID7	RID8	RID9	RID10	RID11	RID12	RID13	RID14	RID15	RID16	RID17	RID18
Product-Product	RID 1	1.000	5.000	3.000	5.000	5.000	1.000	1.000	0.333	0.333	0.333	0.333	0.333	3.000	0.333	0.200	0.200	5.000	1.000
	RID 2	0.200	1.000	0.200	0.200	1.000	0.143	0.111	0.143	0.143	0.143	0.143	0.200	0.333	0.333	0.200	0.333	0.333	0.333
	RID 3	0.333	5.000	1.000	0.333	5.000	0.333	0.200	0.333	0.333	0.200	0.200	0.200	0.333	0.333	0.333	0.333	0.333	1.000
Process-Process	RID 4	0.200	5.000	3.000	1.000	3.000	0.200	0.143	0.143	0.333	0.200	0.200	0.200	0.333	0.333	0.333	0.333	1.000	0.333
	RID 5	0.200	1.000	0.200	0.333	1.000	0.200	0.143	0.143	0.200	0.143	0.143	0.143	0.333	1.000	0.200	0.333	0.333	0.200
	RID 6	1.000	7.000	3.000	5.000	5.000	1.000	0.200	3.000	5.000	3.000	1.000	1.000	1.000	3.000	3.000	1.000	3.000	1.000
People-People	RID 7	1.000	9.000	5.000	7.000	7.000	5.000	1.000	1.000	1.000	1.000	3.000	3.000	5.000	1.000	5.000	3.000	1.000	0.143
	RID 8	3.000	7.000	3.000	7.000	7.000	0.333	1.000	1.000	5.000	1.000	1.000	1.000	-3.000	1.000	3.000	0.333	3.000	5.000
	RID 9	3.000	7.000	3.000	3.000	5.000	0.200	1.000	0.200	1.000	0.333	0.333	0.333	1.000	1.000	0.333	0.333	3.000	1.000
Process-People	RID 10	3.000	7.000	5.000	5.000	7.000	0.333	1.000	1.000	3.000	1.000	0.333	0.333	3.000	3.000	3.000	0.333	5.000	5.000
	RID 11	3.000	7.000	5.000	5.000	7.000	1.000	0.333	1.000	3.000	3.000	1.000	1.000	3.000	3.000	3.000	1.000	5.000	5.000
	RID 12	3.000	7.000	5.000	5.000	7.000	1.000	0.333	1.000	3.000	3.000	1.000	1.000	3.000	3.000	3.000	1.000	5.000	1.000
People-Product	RID 13	0.333	5.000	3.000	3.000	3.000	1.000	0.200	-0.333	1.000	0.333	0.333	0.333	1.000	1.000	1.000	0.333	5.000	1.000
	RID 14	3.000	3.000	3.000	3.000	1.000	0.333	1.000	1.000	1.000	0.333	0.333	0.333	1.000	1.000	1.000	0.333	3.000	1.000
	RID 15	5.000	3.000	3.000	3.000	5.000	0.333	0.200	0.333	3.000	0.333	0.333	0.333	1.000	1.000	1.000	0.333	5.000	3.000
Product-Process	RID 16	5.000	5.000	3.000	3.000	3.000	1.000	0.333	3.000	3.000	3.000	1.000	1.000	3.000	3.000	3.000	1.000	5.000	5.000
	RID 17	0.200	3.000	3.000	1.000	3.000	0.333	1.000	0.333	0.333	0.200	0.200	0.200	0.200	0.333	0.200	0.200	1.000	0.200
	RID 18	1.000	3.000	1.000	3.000	5.000	1.000	7.000	0.200	1.000	0.200	0.200	1.000	1.000	1.000	0.333	0.200	5.000	1.000
Sum		33.467	90.000	52.400	59.867	80.000	14.743	16.197	13.829	31.676	17.752	11.086	11.886	24.400	24.667	28.267	10.800	56.000	32.210

With the AHP modelling complete, the priority for managing/mitigating risks within the WR-21 alliance can be determined. Again, this is a set of risks that have been defined at the infancy of the project, clearly the priority will evolve as the project moves through the life cycle. Some risks will be mitigated, some will be realised and there will also be emergent risks to account for, hence the model should be applied frequently. A list of the initial risks that have been determined as high importance for the WR-21 project, are listed in Table 3.

Table 3. Alliance risks for WR-21.

Element or Interaction (3PE)	Risk Description There is a risk that...
Product-Product	1. When all components (products) are brought together and built into one system, the propulsion package does not perform as expected.
	2. One of the partners produces a substandard product.
Process-Process	3. Partner internal processes do not align.
	4. The timescales the partners are working to, do not align.
People-People	5. There is a personality clash between partner senior managers (e.g. CEOs).
	6. Staff from alliance partners take no ownership or responsibility.
	7. Staff try to undermine reputation of alliance partners.
	8. Certain staff do not want to communicate with the alliance partners.
People - Process	9. Organisations have lack of control or direction over partner staff.
	10. Suitably qualified and experienced people (SQEP) cannot be resourced to work on the project.
	11. Partner staff are unable or unwilling to work across the alliance partners.
Process - Product	12. The lack of an integrated process leads to lack of holistic product understanding by partners in the alliance.
	13. One or more of the partners leaves the alliance and a replacement product is needed.
Product - People	14. Staff are unwilling to share information about their organisation's product.
	15. Staff from the alliance do not really understand their partner's product.

For the WR-21 engine package alliance, there was a watershed moment just over halfway through the project that would have significant consequences. In the early 2000s, Westinghouse was bought by the US defence giant Northrup Grumman. Upon reviewing all of Westinghouse’s live projects, Northrup Grumman concluded that the WR-21 project was unsatisfactory and therefore decided to cut their losses and pull out. This decision clearly had devastating consequences for the project.

From the results of the 3PE+AHP model presented in Table 3, it can be seen that ‘Risk 13’ identified the possibility of a partner leaving the alliance. There are also a number of other risks that will be realised, should a partner exit the alliance. For a project like WR-21, where new and innovative technology is being developed, this risk is increased as organisations face significant ongoing technical and development issues, slippage in schedule and challenges controlling costs. If the WR-21 alliance had used the AILAM model, these risks would have been identified at the infancy of the project and mitigations/conditions imposed on cost, schedule and technical shortfalls.

5.5. Third iteration of 3PE+AHP

The exit of a partner from the WR-21 alliance was identified by the 3PE model at the initial stage of the WR-21 project. Mitigations for this risk should have been established before the project commenced. Westinghouse (Northrup Grumman) was developing an innovative and complicated set of parts for the engine package that were essentially bespoke (i.e. the alliance could not simply reach out to industry for a similar COTs product). The alliance was now facing the technical challenge of being able to progress the intercooler and recuperator development, concurrently with huge pressure to complete the WR-21 engine package on time to meet the ship schedule and control costs.

This risk(s) had clearly not been addressed by the alliance to a satisfactory level and as a consequence Rolls-Royce inherited the partially complete design from Northrup Grumman and became solely responsible for the WR-21 package. This can be seen in Table 4, where the alliance has now reduced to two partners.

Table 4. Identification of alliance risks by pairwise 3PE models of Northrup Grumman and Rolls-Royce.

		Rolls-Royce			BAE-Systems		
		People	Product	Process	People	Product	Process
Rolls-Royce	People	Internal interactions			1	2	3
	Product					4	5
	Process						6
BAE Systems	People	Replicated			Internal interactions		
	Product						
	Process						

Whilst clearly the number of potential risk pathways within the alliance has reduced with the exit of Northrup Grumman, risks around technical challenges of the engine package, schedule and cost have all dramatically increased across all the interactions. The 3PE+AHP model has identified that without dramatic intervention to mitigate these risks, the WR-21 alliance is in significant danger of failure. This means if AILAM had been available for risk assessment prior to commencing the WR-21 project, the risk of dramatic change in the alliance could have been mitigated, possibly by one of the following plans:

- (1) A contractual agreement could have been setup such that any innovation developed as part of WR-21 should remain part of WR-21 project. This could include all IP including the part of Westinghouse was responsible for innovating.
- (2) BAE Systems and Rolls Royce could have defined a backup plan in case the innovation was considered a failure. This backup plan might have deterred innovation development, but it could have ensured the successful completion of the project.
- (3) If the above were missed, there was still opportunity to set up legal conditions such that the sale of Westinghouse to Northrup Grumman was allowed only if Northrup Grumman was forbidden from pulling out of the WR-21 project, otherwise heavy penalties would apply.

AILAM does not discourage innovation, instead it takes into account potential risks that might hinder innovation success and ensures the alliance is prepared and ready to take up the challenges.

6. Conclusion

This paper has highlighted the challenges and complexity that developing innovation brings to a project. The favoured mitigation by organisations is to attempt to spread the risk by entering into co-innovation partnerships. Whilst on the surface this seems reasonable, this research has detailed how this strategy actually introduces significant numbers of risk pathways the more partners that enter the alliance.

The Contribution of this research is the architectural analysis model of AILAM for assessing innovation risks in complex product (system) development, where risks in alliances are often ignored. The 3PE model has the ability to identify risks within a sole organisation's environment. In addition, and importantly, the analysis can identify where risks are clustering across the three main elements of the 3P model (People, Product & Process) and the associated interactions, to ensure effort and resources are applied to the right areas for targeted mitigation.

AILAM then goes further to assess projects that are developing challenging innovations under an alliance structure. As each partner enters the alliance, AILAM demonstrates an expansion in potential risk pathways. The integrated 3PE models in AILAM is unique in identifying these pathways and this crucially offers enhanced risk identification fidelity. By applying AHP capability to the model, each risk can be assessed and ranked for mitigation priority throughout the project lifecycle.

To demonstrate AILAM and the 3PE+AHP model, a case study of an historical naval ship propulsion project was presented. The project suffered technical failings that can be traced back to a badly managed alliance. The 3PE+AHP model identified and prioritised the mitigation of key risks for this project and would have increased the possibility of success should the alliance have had the benefit of this model.

7. References

- Abhari, K., Davidson, E. J. & Xiao, B. 2018. A risk worth taking? The effects of risk and prior experience on co-innovation participation. *Internet Research*, 28, 804-828.
- Allison, G. 2021. All Type 45s to have received engine repairs by mid-2020s. *UK Defence Journal*.
- Baldassarre, B., Keskin, D., Diehl, J. C., Bocken, N. & Calabretta, G. 2020. Implementing sustainable design theory in business practice: A call to action. *Journal of Cleaner Production*, 273.
- Benitez, J. 2016. Alliance at Risk: Strengthening European Defence in an Age of Turbulence and Competition. Brent Scowcroft Center on International Security.
- Bugshan, H. 2015. Co-innovation: the role of online communities. *Journal of Strategic Marketing*, 23, 175-186.
- Chesbrough, H. W. 2003. *Open innovation the new imperative for creating and profiting from technology*.
- Cook, M. & Mo, J. P. T. 2015. Strategic Risk Analysis of Complex Engineering System Upgrade. *European Scientific Journal*, 2, 64-80.
- Cook, M. & Mo, J. P. T. 2018a. Investigation into the Risks of Forming Alliance. *25th ISTE International Conference on Transdisciplinary Engineering*. Modena, Italy.
- Cook, M. & Mo, J. P. T. 2018b. Lifecycle Risk Modelling of Complex Projects. In: HESSAMI, A. (ed.) *Perspectives on Risk, Assessment and Management Paradigms*. London: IntechOpen.
- Cook, M. & Mo, J. P. T. 2019. Architectural Modelling for Managing Risks in Forming an Alliance. *Journal of Industrial Integration and Management*, 4, 1-17.
- Cook, M. & Mo, J. P. T. 2020. Determination of the severity of risks in engineering projects using a system architecture approach. *TMCE 2020: Thirteenth International Tools and Methods of Competitive Engineering Symposium*. Dublin, Ireland
- Cui, V., Yang, H. & Vertinsky, I. 2018. Attacking your partners: Strategic alliances and competition between partners in product markets. *Strategic Management Journal*, 39, 3116-3139.
- Das, P., Verburg, R., Verbraeck, A. & Bonebakker, L. 2018. Barriers to innovation within large financial services firms. *European Journal of Innovation Management*, 21, 96-112.
- Day, G. 2007. Is It Real? Can We Win? Is It Worth Doing?: Managing Risk and Reward in an Innovation Portfolio'. *Business Review magazine*.
- Deniaud, I. F., Marmier, F. & Gourc, D. 2015. Alliances decision-making in NPD: A risk point of view. *IFAC-PapersOnLine*, 48, 942-947.
- García-Granero, A., Llopis, Ó., Fernández-Mesa, A. & Alegre, J. 2015. Unraveling the link between managerial risk-taking and innovation: The mediating role of a risk-taking climate. *Journal of Business Research*, 68, 1194-1104.
- Goa, S. & Zhang, S. 2008. Opportunism and Alliance Risk Factors in Asymmetric Alliances. *IEEE Xplore Conference Series*, 1109, 680-685.
- INCOSE 2007. *Systems Engineering Handbook*. International Council on Systems Engineering, Vol.3.
- Kang, R. & Zaheer, A. 2018. Determinants of alliance partner choice: Network distance, managerial incentives, and board monitoring. *Strategic Management Journal*, 39, 2745-2769.
- Koulinas, G. K., Demesouka, O. E., Sidas, K. A. & Koulouriotis, D. E. 2021. A TOPSIS—Risk Matrix and Monte Carlo Expert System for Risk Assessment in Engineering Projects. *Sustainability*, 13.
- Kristiansen, J. N. & Ritala, P. 2018. Measuring radical innovation project success: typical metrics don't work. *Journal of Business Strategy*, 39, 34-41.

- Marsh, P. 1997. Foreign rivals inspire engineering innovation. *Financial Times (UK)*.
- Ombrosi, N., Casprini, E. & Piccaluga, A. 2019. Designing and managing co-innovation: the case of Loccioni and Pfizer. *European Journal of Innovation Management*, 22, 600-616.
- Parkhe, A. 1993. Strategic Alliance Structuring: A Game Theoretic and Transaction Cost Examination of Interfirm Cooperation *The Academy of Management Journal*, 36, 794-829.
- Ren, Y. & Yeo, K. T. 2014. Risk Management Capability Maturity and Performance of Complex Product and System (CoPS) Projects with an Asian Perspective. *Journal of Engineering, Project, and Production Management*, 4, 81-98.
- Shenhar, A. J. & Dvir, D. 2007. *Reinventing project management : the diamond approach to successful growth and innovation*, Boston, Mass. : Harvard Business School Press.
- Shenhar, A. J., Holzmann, V., Melamed, B. & Zhao, Y. 2016. The Challenge of Innovation in Highly Complex Projects: What Can We Learn from Boeing's Dreamliner Experience? *Project Management Journal*, 47, 62-78.
- Styhre, A. 2006. Science-based innovation as systematic risk-taking. *European Journal of Innovation Management*, 9, 300-311.
- Taleb, N. N. 2010. *The Black Swan: The Impact of the Highly Improbably*, Penguin Books. ISBN: 0141034599
- Trappey, A. J. C., Elgh, F., Hartmann, T., James, A., Stjepandic, J., Trappey, C. V. & Wognum, N. 2017. Advanced design, analysis, and implementation of pervasive and smart collaborative systems enabled with knowledge modelling and big data analytics. *Advanced Engineering Informatics*, 33, 206-207.
- Trevithick, J. 2018. Royal Navy Will Retrofit Type 45 Destroyers To Keep Them from Breaking Down. *The Drive*.
- Van Wezel, A. P., Van Lente, H., Van De Sandt, J. J., Bouwmeester, H., Vandeberg, R. L. & Sips, A. J. 2018. Risk analysis and technology assessment in support of technology development: Putting responsible innovation in practice in a case study for nanotechnology. *Integr Environ Assess Manag*, 14, 9-16.
- Walker, D. H. T. 2015. Risk Managing Complex Projects Through Alliancing. *Journal of Modern Project Management*, 02, 9-17.
- Weiler, C., Chiprich, 1997. WR-21 Intercooled Recuperated Gas Turbine System Overview & Update. *The ASME ASLA '97 Congress and Exhibition, Singapore*.
- Writer, T. 2016. Putting the Type 45 propulsion problems in perspective. *Navy Lookout – Independent Royal Navy news and analysis*.
- Yakovleva, A. Methodological Aspects of Project Techniques Selection for Innovation Project Management. *International Journal of Innovation 2014*, 2, 13-31.
- Young, B., Hosseini, A. & Lædre, O. 2016. The Characteristics of Australian Infrastructure Alliance Projects. *Energy Procedia*, 96, 833-844.
- Zhu, F., Jiang, M. & Yu, M. 2019. The role of the lead firm in exploratory projects. *International Journal of Managing Projects in Business*, 13, 312-339.
- Zhuang, L., Williamson, D. & Carter, M. 2018. Innovate or liquidate - are all organisations convinced? A two-phased study into the innovation process. *European Journal of Innovation*, 21, 96-112.