20th ISPE International Conference on Concurrent Engineering
C. Bil et al. (Eds.)
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doi:10.3233/978-1-61499-302-5-30

Learning and Concurrent Engineering in the Development of a High Technology Product/Service System

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Abstract This paper explores project management techniques that can support the development of novel product-service systems. Some observations from the development of an airborne earth properties measurement system are provided. The intellectual property and the data this system could potentially deliver was more important than the potential commercial value of the product itself. What was sought was a complete business service solution. A concurrent engineering approach was implemented linking both product development and survey data/analysis services. The blend of product and service was integrated using a function modeling technique. It was observed that the implementation of some functions required radical innovation whilst others could be implemented through incremental improvements to current practice. It is suggested in the paper that adapting production learning curve concepts that reflect the relative degrees of uncertainty involved in individual subsystems can enhance project management forecasting practice

Keywords. Concurrent engineering, radical innovation, product/service systems

1. Introduction

Tatsunori et al [13][14] considered the design of product-service systems in response to market trends towards service-based solutions rather than products. They noted that this requires a particular kind of value proposition that may combine tangible products with intangible services, and that new kinds of design tools may be required. Potential problems were seen as a gap between customer analysis and product/service activity design, and the separation of product and service design activities. Menora et al [10] explored ways in which new service development might be different from product development, starting with consideration of what constitutes a new service. A radical innovation may be a new kind of service for undefined markets delivered via ICT; a new entry into an existing market or a new offering to existing market. Incremental innovation may be a service line extension, a service improvement or a style change. They suggested three research challenges:

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- Specifying a priori the type(s) of new service to be studied in order to design a study around that new service and frame the implications of research findings.
- Integrating understanding of relevant facets of new product development (process and performance) that are most applicable to furthering the study and understanding of new systems development.
- Choosing the appropriate unit of analysis that facilitates the research design, analysis and answering of the specific new system design research question(s) investigated.

This paper presents observations from a case study of radical product innovation (that could support a new service offering to an existing market) where both the product and the service aspects were developed in parallel. The unit of analysis was an individual project sponsored by a firm that was primarily interested in the data provided by the total system. This differs from most product-service cases reported in the literature where adding a service to a firm's product is seen as a way of capturing additional value. In the case study, ownership of the associated intellectual property and the data delivered was more important than the potential commercial value of the product itself. What was sought was a complete business service solution. The radical nature of the product and the concurrent engineering development of quite different kinds of subsystems involved: different professional communities, in some cases close collaboration with key technology providers, a high rate of learning, and the evolution of a form of agile project management approach.

The paper begins with some observation from the literature on concurrent engineering practice in these circumstances, followed by a brief case study description, and reflections on the case related to project management aspects.

2. Some Observations from the Literature

Valle & Vázquez-Bustelo [16] analyzed 134 responses from Spanish firms utilizing concurrent engineering techniques which suggested reduced development time and superior product were outcomes in an incremental innovation environment, whilst lower cost was the dominant outcome associated with radical innovation. Ellram et al [6] considered the interaction of product process and supply chains in a concurrent engineering environment to more effectively deliver a new product (see Figure 1). They saw that potential barriers were a lack of top-level commitment, a failure to integrate historical and new practices, and a lack of alignment between the professional communities involved

In the context of the increasing economic influences of the services industry sector, Tien & Berg [15] suggest a systems engineering approach drawing on emerging information, communication and decision technology tools to develop new services. Yang [19] proposed a systems approach to service development in a concurrent engineering environment, noting that service quality was the measure of success. Yang suggested a number of number of design activities had to be integrated: (i) process design; (ii) quality design; (iii) production-management design; (iv) capacity design; (v) management design; and (vi) physical and technical design.

The points taken from this brief overview is that what makes sense in the parallel development of a product/service system is context-sensitive, but that adopting a systems engineering approach may support integrated development. These points are illustrated in the following case study.

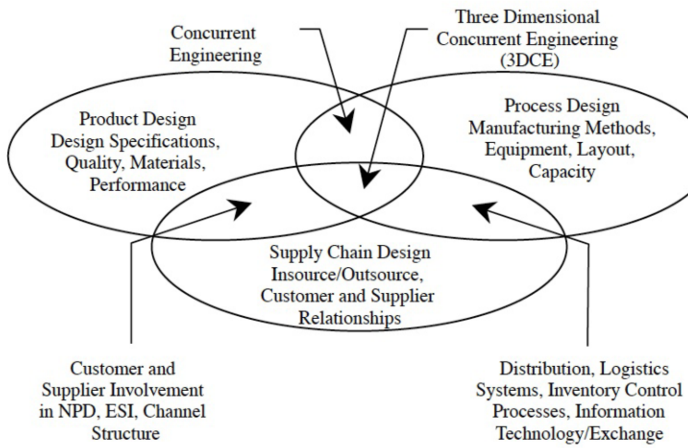

Figure 1. (from Ellram et al [6])

3. The VK1 Case

The case describes a product/service in transition from concept to an operational tool. The concept of an advanced type of gravity gradiometer sensor emerged from basic research at an Australian university in the 1990's [8]. The technology offered promise as a superior form of earth property aerial survey mapping tool that would supplement other kinds of data to help geophysicists identify significant mineral deposits. The aerial survey instrument must discriminate weak signals from substantial background noise, with high volume data processing arrangements to incorporate some transformations and corrections to yield usable data. This led to modeling, simulation and system tuning requirements and an iterative approach to system development [3].

The researchers had developed a prototype to demonstrate what they called “proof of concept” in that the soundness of the underlying theory was demonstrated. On this basis, engineering development of the instrument was funded. An iterative approach to project management became the norm. At this point, it was again declared that “proof of concept” had been demonstrated, in that it had been shown that a suitable instrument could be made. This did not necessarily impress the geologists who wanted to utilize data collected using the instrument. To them, what had been provided at this point was the equivalent of a medical CAT scan instrument without any imaging software. In their view, “proof of concept” would occur once the instrument had collected data from a region with well-understood earth properties, and this data was presented in a form of map that could be interpreted in geological terms.

A development program was initiated in the 2000's following a scientific expert panel review of possibilities. Scientists from a university, engineers recruited by an industry sponsor, and university technicians and tradesmen were organized as a project team. The university hosted the team, and a project manager employed by the industry client managed it. A number of complex technologies had to be combined in a unique way to achieve the desired outcome, but the project sponsor was experienced in the use of sophisticated sensors and complex data processing of aerial survey data. A pre-project review of the underlying science suggested that whilst all of the advanced technologies to be integrated had been used somewhere else before, their integration may prove problematic, and this was indeed the case. The iterative nature of the development process raised a number of issues. Whilst the researchers were quite comfortable with the process, and had formal procedures for capturing test data, etc., when it came to clearly defining what had to be made and how it could be consistently produced, there was an apparent lack of system, leading to misunderstandings and mistakes in manufacture. The client, who was familiar with stage-gate management, found it difficult to understand where and how progress was being made and how client requirements were being met in this iterative environment. Subsequently some systems thinking project lifecycle tools were introduced.

The systems thinking practices focused on the end-game of providing an aerial survey service also facilitated:

- The development of hierarchical functional specifications using an IDEF(0) modeling tool [1] without presuming the system configuration (people/hardware/ software mix) - see Figure 2.
- The declaration and specification of interfaces at a early stage to support the parallel development of different components of the whole system
- A life-cycle reference architecture that was re-used at multiple hierarchical levels as an evolutionary pattern within development phases as well as across phases [7]
- Adoption of the Plan-Do-Check-Act ISO 9000 philosophy [rcb]. The objective was to assure the quality of the underlying science, the quality of the system engineering, the reliability of production processes, the quality and reliability of the product, and the quality and reliability of the field data collection service and data processing operations. A dedicated Wiki-based system was used to both satisfy ISO 9000 data management requirements and support project knowledge capture [4]

Even at the high level representation shown in figure 2, the significant number of influence factors and the fact that a preceding function may provide both inputs to the next function and conditions governing its operation are evident. There were five major sub-tier functions associated with the survey logistics service system, and three associated with the survey data processing and interpretation subsystem. Functional descriptions were taken down to sub-sub-tier elements and proved relatively stable even though design details continued to change. An example of change in the descriptions was the addition of system trouble-shooting capability. Some subsystems were regarded as associated with incremental innovation, some with radical innovation, and all required some form of collaboration with a technology or service provider (see figure 1). In one way or another there was a degree of uniqueness about the management requirements of each subsystem, and each had a designated development team, which generally included a member from one of the other teams.

By the end of the 2000's initial flight trials involving some subsystems had commenced [2]. A significant number of patents relating to ways of making this unique product had been filed. There were some interesting discussions about that time as to the readiness of the equipment to fly. Should more lab work be done first, or will things be learned that could not be learned in the lab? Subsequence experience suggested that lab and flight trial iterations informed each other – there was learning across sub-systems as well as learning within each one.

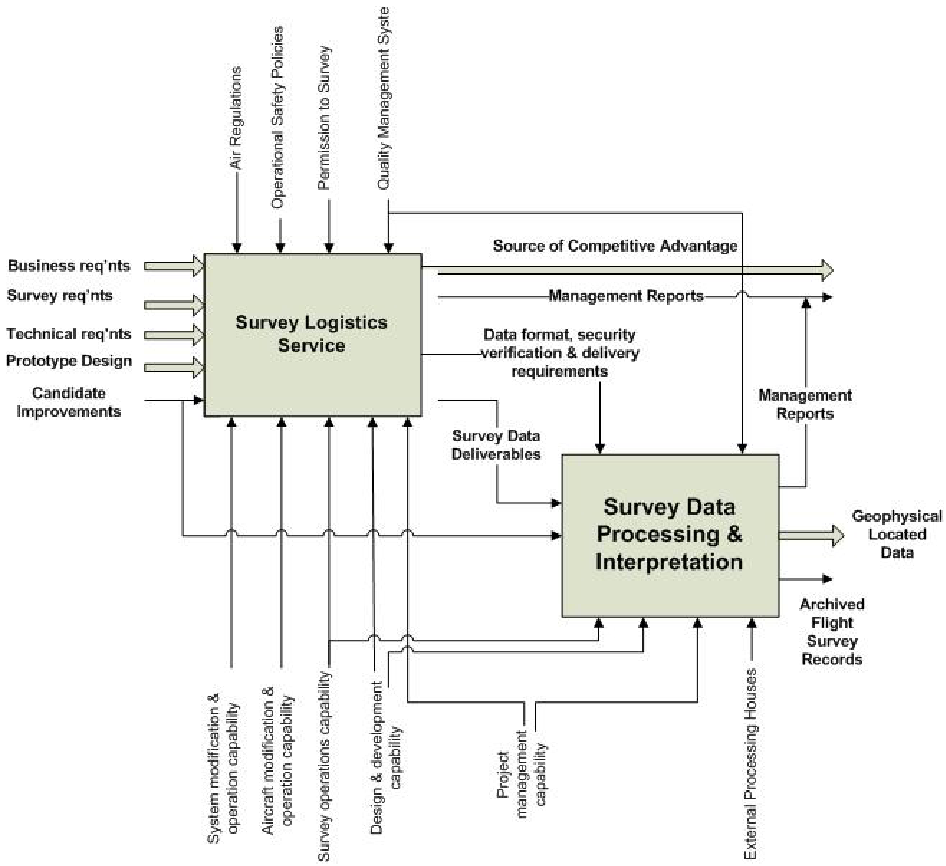

Figure 2. IDEF(0) Top Level Model

4. Some Observations from the Case

The project management arrangements that evolved blended a conventional mix of milestone/high level activity identification with less common iterative, agile management practices (see figure 3) within this broad framework. Although it was not seen in this context at the time – it simply made sense.

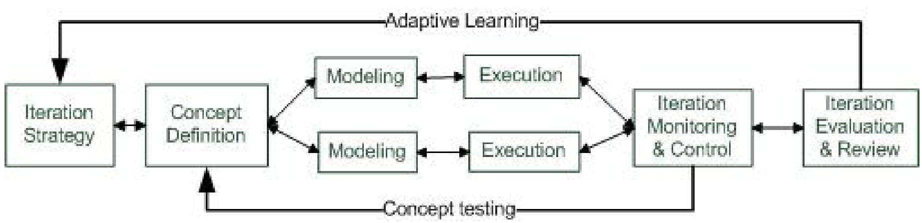

Figure 3. A representation of iterative development (adapted from Virine, [17])

An illustrative iteration strategy was a series of tests designed to help fine-tune simulation models used in optimizing subsystem configurations. A standard agenda was adopted for the weekly product development team meetings that addressed both administrative and development activities. Team members that generally worked independently reported on progress against a succession of short-term assigned tasks and were assigned new ones. Information about each task was placed on a board in the project room, and through the week, each team member updated information about their task. This practice has parallels with agile project management techniques used in software development (see e.g. planbox [11]) where an "initiative" may involve a number of projects, each of which has a backlog of items to be worked on progressively involving a number of tasks. Backlog items are scheduled into an iteration cycle having a preset duration (e.g. a week)).

In the context of this project management perspective the question of how to plan for iterations arose, recognizing this might only be evident in retrospect. Conventional planning identifies a linked series of requisite activities, with an estimate of time and resources required based on the assumption that all will go according to plan. Worst case scenarios may also be considered – but how can these be imagined? Savci & Kayis [12] suggested that concurrent engineering practice – running many activities in parallel may have its own risks. They suggested pooling experience from multiple projects to identify potential areas of risk and identifying management responses may help keep things on track. There is anecdotal evidence from the operation of other kinds of aerial survey platforms that system reliability improves over time as experience is gained. In other words, there is a kind of learning curve. Learning curves have been observed in other situations like the repetitive construction of complex objects such as aircraft, and empirical formulae are used in forecasting total cost over many years of production using these curves.

Records from VK1 monthly and quarterly project meetings over several years were available in the sponsor firm document repository, and these were analyzed to assess estimates to complete compared with actual as a particular activity progressed. For the more complex activities, the estimate tended to increase soon after work had started, based on what had been learned at that time. As an activity progressed, the residual time reduced, but not at the rate forecast. As might be expected, more iterations were required in the more complex systems, with higher rates of learning being indicated.

In the notion of a learning curve historically associated with aircraft production, there is a characteristic reduction in cost at every doubling of the production number. With an 85% learning curve, the second aircraft will be made in 85% of the time of the first one, and the fourth aircraft will be made in 85% of the time of the second one. The 400th aircraft will be made in 85% of the time of the 200th one and so on. Mapping actual numbers on a log-log plot often reveals such patterns.

The Table below provides an order-of-magnitude summary of the effect of different learning curves. A 95% factor is appropriate where there will be limited scope for learning, for example in a highly automated process or when the task is a very familiar one. 75% is appropriate where there is a high rate of learning, for example where the task is complex or there is uncertainty about what has to be done or how to do it. For conditions of substantial uncertainty a 50% curve may be appropriate. By way of example, in a high learning rate environment (75%) the level of effort to support the first flight may be 12.3 times that required after experience has been gained over 400 flights. Using another example, in making custom parts, experienced people may have made say ten parts broadly similar to the one now under consideration. If the part or the process is quite complex (75% curve) it may take 2.6 times that estimated based on the ten part experience, but if the part is simple or the process is automated (95% curve) it may only take 20% longer.

Number of Repetitions	Factor 95 on 400 base	Factor 95 on 10 base	Factor 85 on 400 base	Factor 85 on 10 base	Factor 75 on 400 base	Factor 75 on 10 base
1	1.56	1.19	4.16	1.73	12.3	2.6
10	1.31	1	2.4	1	4.7	1
100	1.11		1.38		1.79	
400	1		1		1	

Table 1. Worst case multipliers based on learning curve factors (base estimate 1 shown shaded for different scenarios)

The idea here is to identify some rationale for estimating the impact of learning in complex development projects, recognizing that different parts of a total system may have different levels of learning associated with them. By way of example, an existing gravity gradiometer system uses a sensor based on US military technology purchased as a "black box" from a military supplier. Due to the prior military application testing and experience, the sensor is very reliable (save for infant mortality problems often associated with complex systems), and it might be expected that the level of adaptation associated with its use might be low. A learning factor scenario of 95 % might describe that situation. The primary cause for concern with the total system has related to the correction and interpretation of data collected in terms of its geophysical implications. Anecdotal evidence suggests that software refinement took 4 – 5 years with an accumulated effort that might imply a learning factor of 75%.

5. Discussion

Badham et al [5] noted from studies of CE implementation effectiveness gave mixed results . They saw influence factors as: (a) senior management commitment to new product introduction, (b) preparation for implementation as a political resource allocation process, (c) a focus on organizational issues to avoid cross-functional conflicts, and (d) a project leader as product champion, team member motivator and stakeholder manager. The case study sponsor organization was experienced in the management of complex projects, and factors (a), (b) and (c) were well attended to. The VK1 project leadership function involved multiple champions at different levels within the organization drawn from different professional communities, and a hierarchy of weekly, monthly and quarterly review meetings to facilitate project communication and integration. The development status of competing technologies was also discussed at the quarterly reviews, with the possible option of putting development effort behind another technology. But then IP access may become problematic. This grounded view helped revisit the value proposition promised by the project, even if development time was longer than hoped for.

Yan and Jiang [18] observed some issues associated with the use of concurrent engineering practice that they suggest might be accommodated by blending agile management and concurrent engineering concepts. They saw the potential benefits as giving resource sharing special consideration, providing organizational flexibility through the use of agile teams and fitting in with the firm's existing organizational structure with little change being required. In the VK1 case study, both the project sponsor and the university provided some kinds of resources to support a dedicated project team located within the University. , The University Head of School involved suggested the collaborative working arrangements that evolved provided more effective technology transfer than licencing or spinoff company strategies. Karlström and Runeson have suggested that [9:p49] "*Agile methods give the stage-gate model powerful tools for micro planning, day-to-day work control, and progress reporting. The functioning product and face-to-face meetings, for example, support much more powerful communications than written documents. The stage-gate model, in turn, gives agile methods a means to coordinate with other development teams and communicate with functions such as marketing and senior management*". This is also consistent with the practices that evolved in the VK1 project.

Chachere et al [6] studied a process for rapid concept development at NASA's Jet Propulsion Laboratory using a combination of expert designers, advanced modeling, visualization and analysis tools, social processes plus a specialized design facility. Planning involved a focus on average and worst case scenarios to clarify what had to be managed – an exception handling orientation rather than a best practice one. They discuss the impact of latency (a measure of time delay in a system) in information or decision flows. They suggest Just-In-Time knowledge flows with short lead times plus facilitation make the next step clear plus team autonomy and keeping it simple. These features were evident in the VK1 project, but rather than being designed-in, they were the result of several team members having worked together for a long time with minimal financial resources. This raises the interesting question of whether adding more resources would have significantly sped things up, as then the current experts would have to devote part of their time to bringing others up to speed. On the other hand, there is anecdotal evidence that collaborating with others through social networks has been beneficial.

6. Concluding remarks

There is increasing interest in the fast-track development of products/service systems and new services. Some academic literature suggests this may be achieved by a combination of concurrent engineering project practices and systems engineering methods. The literature also suggests the nature of and benefits derived from concurrent engineering practices is contingent on the nature of the innovation sought (incremental or radical) and the extent of collaboration involved (supply chain and joint development). This paper describes project management techniques that evolved to support the development of novel product-service system - an airborne earth properties measurement system for use in mining exploration. The intellectual property and the data this system could potentially deliver were more important than the potential commercial value of the product itself. What was sought was a complete business service solution. The blend of product and service was integrated using a function modeling technique. The high level functional descriptions and the management of interfaces between the subsystems provided a stable platform for relatively independent subsystem development. It was observed that the implementation of some functions required radical innovation, sometimes in conjunction with specialist technology providers, whilst others could be implemented through incremental improvements to current practice, sometimes in collaboration with established service providers. A point to be made here is that without getting into the subsystem level, just what has to be managed may not be evident.

The concurrent engineering approach that evolved included some attributes found in agile project management practices now often used in software development. This involves managing a series of iterations that facilitate fast learning about what works and what doesn't. But when developing a complex system, how many iterations are required and how is this influenced by the rate of learning needed? Some ideas based on learning curve concepts used in other settings is presented. There is some evidence from the literature that the project management practices that evolved in the case study project have been observed in other project settings, and thus may have more general application.

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