Innovation Dynamics of Large, Complex, Technological Products in a Monopsony: The Case of ESA Science Missions

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Abstract—The roles of actors in a particular class of complex technological system – the ESA Science Mission – are mapped onto a competitive functional framework in order to identify key differences imposed by the market structure. Three general results are observed: there is no clear separation between “buyers” and “sellers,” the governing driver is an explicitly defined need-based “pull” and a high level of technological maturity is required before a new capability can be incorporated into the product development process. They are explained in terms of the incremental impacts of the complexity of the system, in a monopsony market structure with the government as monopsonist. A preliminary model is proposed and policy implications discussed.

Index Terms—ESA, Innovation, Monopsony, Space Systems

I. INTRODUCTION

The engineering systems required for space and defense applications are typically sophisticated, technologically complex, and expensive, with long development times and short production runs. They are designed to the specifications of a particular customer, whose needs often exceed the current technological state-of-the-art. However, despite this implicit requirement to innovate, it is debatable whether traditional government acquisition practices are achieving this goal. While impressive technological feats are unquestionably being achieved, the question remains whether the exorbitant price tags that have become commonplace are truly required to achieve the rapid advances in system functionality. Or, whether there exist more efficient approaches to encouraging innovation in the monopsony market structure characteristic of government acquisition.

Although innovation dynamics have been studied extensively in the last 50 years, little work has been done to understand the fundamental dynamics underlying complex product innovation in a government monopsony, the typical scenario in government acquisition. This poor understanding can lead to an inappropriate choice of mechanisms and approaches for encouraging innovation and, ultimately, to an environment that does not foster successful innovation. This research work aims to fill that gap by addressing the key differences imposed by the space and defense acquisition context; specifically, the incremental impacts on innovation of the complexity of the system, in a monopsony market structure with the government as monopsonist.

This task is accomplished in five phases. First, the functional elements and key transfers of information that result in innovation in a competitive market are abstracted from the literature (section II). Next, an interview-based case study of a European Space Agency (ESA) science spacecraft development is conducted in order to identify the roles of actors in a monopsony structure (section III). These monopsony roles are then mapped onto the competitive functional framework to highlight key differences (section IV). The observations made in section III are then linked to structural elements of the market and inherent complexity of defense systems. This analysis leads to a preliminary model of innovation dynamics in a government monopsony (section V). Finally, the implications of these findings from the point of view of agency policy are discussed (section VI). Although examples from the space science case study are used to concretize the discussion throughout, the findings are applicable to government acquisition in general.

II. CONSTRUCTING A FRAMEWORK: THE FUNCTIONAL ELEMENTS OF INNOVATION

Although innovation dynamics have been studied extensively in the last 50 years, little work has been done to understand the fundamental dynamics underlying product innovation in a government monopsony. The focus has been pre-dominantly in the context of competitive, or nearly-competitive, markets; specifically cases where either supply or demand-side market forces can be identified as driving innovation. While the scope of factors considered to affect innovation has expanded to include national policies and
priorities in recent years, the concepts cannot be applied directly to government acquisition because a “normal” market is still assumed.

While the market structures of competition and monopsony are fundamentally different, and these differences significantly impact the mechanism by which innovations occur, it does not directly affect the structure of the innovation process; a new idea must be developed and manufactured before it can be brought to market, regardless of what forces drove its creation and realization. Therefore, if the models of innovation under competition can be expressed in terms of their functional elements, and the roles of actors in a monopsony market can be mapped onto this framework, insight can be gained into how, and to what extent, competitive market forces are replicated in the monopsony structure. This section builds the first element of that process, abstracting from the literature, the functional elements and key transfers of information that result in innovation in a competitive market.

Rothwell[1] identifies four generations of innovation theories and proposes an evolution to a fifth: 1) Technology Push; 2) Market Pull; 3) Coupled Process; 4) Integrated Process; and 5) Systems of Innovation. The first two represent essential building blocks for any discussion of innovation dynamics while the third develops ideas for their combination. The later theories incorporate a national and international perspective that cannot be applied directly to sector-specific government acquisition. As a result, this section will focus on push and pull dynamics and their combination.

A. Technology Push

The Technology Push theory of innovation asserts that the process by which new products enter the market, is a linear progression that begins with a fundamental discovery. As shown in Figure 1, in this paradigm, more basic research leads to more discoveries, which are developed into new products and subsequently brought to market. The emphasis is clearly on the supply side and implicitly assumes that any new product will be desired by the market.

Figure 1. Technology Push model of innovation

This relatively simplistic dynamic was popular in the post-war 50s and early 60s, when industrial expansion and economic growth seemed unbounded, making the expectation that the market would adopt any new development reasonable[2]. Although a supply-focused view is not appropriate for government acquisition, the underlying notion that new ideas can “push” the bounds of what is possible in future systems, is certainly relevant.

B. Market Pull

The Market Pull theory of innovation takes the opposite view. Where push describes a linear progression beginning with a new idea, pull proposes a regression starting from a need. Figure 2 illustrates how a recognized market need drives business strategy, which targets research that creates new capabilities, which are then developed into a new product which fills the original niche. This view was a reaction to the market saturation created by the “push” philosophy. In the late 60s and early 70s, when the supply-demand imbalance finally equilibrated as a result of increased manufacturing productivity, emphasis shifted to demand-side drivers. With increased competition, innovation strategies became targeted[3]; a response to the market rather than encouraged serendipity.

Figure 2. Market Pull model of innovation

The concept of “specified innovation” proposed by Kirtley as a dominant driver of innovation in a government monopsony, can be considered a special case of Market Pull, where the market need is made explicit. Like Market Push, while many important complexities are ignored, the notion that market needs “pull” solutions is an important element of any theory of innovation.

C. Coupled Push and Pull

The Coupled Push and Pull theory of innovation recognizes that both dynamics contribute to the process by which innovation occurs.

Figure 3. Coupling Push and Pull

Although each driver is still seen as fundamentally linear, the interaction between the push and pull, reveal the cyclical nature of the overall process. This more subtle view of innovation emerged in the 70s and 80s, when tight competition and the so called “stagflation” caused companies to examine the innovation process in detail. A number of comprehensive surveys were conducted (see for example [5-9]) leading to the conclusion that: “innovation represents the confluence of technological capabilities and market-needs within the framework of the innovating firm.” In addition to highlighting the point that a new idea has little market value if it won’t be used, the surveys identified that while any new product will go through all the traditional phases of development illustrated in Figure 3, the process need not be sequential within the confines of one firm. Specifically, the innovating firm can capitalize on external research, development or market action to incorporate a new
understanding of technological capabilities and market-needs, at any point in the process.

D. Functional Elements of the Innovation Process

The functional map illustrated in Figure 4 represents a direct abstraction from the force-based innovation model expressed in Figure 3.

![Functional Map of Innovation Process](image)

The market is explicitly divided into a buy(demand)-side and a sell(supply)-side. Functionally, the buyers include a representation of their own need, the funds with which to acquire assets, the power to choose between the selection of available goods and the ability to benefit from whatever choice is made. While a single buyer often incorporates all these functions, they are broken out in order to maintain generality.

On the sell-side, the buyer’s need is interpreted and expressed as one of a focus, goal, requirement or order, depending on the maturity of the product. It can be seen that each functional element of the innovation process is carried out based on a combined expression of the need and a level of technical maturity (be it a concept, capability or plan).

In this framework, both the buy- and sell-side are expressed in the aggregate. Specifically, the cyclical nature of the process does not necessarily occur over one product life cycle and not all functions need to be carried out by the same firm. For example, the research loop may be carried out in academia on a completely different time scale than the production loop. Fundamentally new approaches may only be incorporated every few years, but that doesn’t mean that each instantiation of the product didn’t, at some point, go through each phase of the innovation process. The functional map, expressed in Figure 4, will be used in the remainder of this paper, to explore the extent to which innovation in a monopsony can be described by analogy to competitive markets.

III. OBSERVING THE PROCESS: THE CASE OF ESA SCIENCE MISSIONS

Now that a framework expressing the innovation process in a competitive market, in terms of its functional elements and basic information flows, has been created, the roles of actors in a monopsony structure must be identified. To accomplish this, an interview-based case study of a European Space Agency (ESA) corner-stone science mission was conducted. This case represents a suitable forum through which to study the dynamics of complex product innovation in a government monopsony because the projects are extremely technically ambitious and ESA is both an international government agency and the sole\(^1\) customer for major science spacecraft in Europe.

Initially, approximately ten experienced members of the core project team – spanning scientists, engineers, operational specialists and managers, representing both ESA and their industrial contractors – were selected for interview. However, when it became apparent that relevant supporting roles were being overlooked, the interview process was expanded to include supporting technical functions and parallel technological development programs. Since the interview subjects spanned such disparate roles, it was impractical to ask a pre-defined set of consistent questions. However, to insure a certain level of comparability across responses, subjects were chosen that had been involved in the same major project; and, although the interviews were loosely structured by design, the same four themes were covered across the board. They were: 1) perception of role within project as a whole; 2) opportunities to incorporate emerging technologies, motivations, incentives or disincentives; 3) type and quantity of communication across organizational boundaries; and 4) time-scale of planning horizon, both in terms of success metrics and future missions.

Since the focus of this paper is on structural implications of a government monopsony market on innovation, the presentation of results will be heavily weighted towards the first two interview themes, with the third and fourth entering, in a limited way through the discussion. A more complete analysis of the results will be presented in a future paper. In developing the process map described below, the interviews were supplemented with a review of ESA procedural documents\(^{11}\). Before discussing the process by which innovation occurs, it is worth clarifying the authors’ interpretation of the term. Conceptually, innovation combines the notion of invention and implementation; the key idea being that the creation of a new tool does not constitute an innovation until it either becomes useful itself, or increases the utility of the system of which it is part. In the context of technological innovation, this can be interpreted as the extent to which the cost of achieving a particular function is reduced over time\(^{12}\). Precisely defining the basic function of interest, for a class of systems, is extremely important if the goal is to measure innovation. In this paper, however, the focus remains on how innovation happens rather than whether it occurs. For this reason, any avenue for incorporating new functionality, into a flight system, is considered an opportunity for innovation.

A. A Top Level View

ESA is an international organization, born out of a desire to

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\(^1\) National Space Agencies in Europe do conduct work in this area; however these activities are coordinated and do not compete directly with any particular ESA project.
consolidate European resources in pursuit of advanced space science and exploration. In the words of the ESA convention: “By coordinating the financial and intellectual resources of its members, it can undertake programmes and activities far beyond the scope of any single European country.” ESA receives funding from its 17 member states, which each also maintain their own National agencies. Not surprisingly, in an effort to balance the desires of its multiple contributors equitably, ESA’s operations are quite complex and a significant amount of background is required to fully understand, even just the structure of the Science directorate. Since the goal of this section is quite specific, to identify how the various project roles interact to achieve ambitious mission goals, only limited background will be interspersed with the description, as deemed necessary. For a complete explanation of the workings of ESA, the reader is referred to [13, 14].

The ESA organization is divided into nine directorates, including Technical and Quality Management (D/TEC), Launchers (D/LAU), Resources (D/RES), Earth Observation (D/EOP), External Relations (D/LEX), Human Spaceflight, Microgravity and Exploration (D/HME), Science (D/SCI), European Union and Industrial Programs (D/TEN) and Operations and Infrastructure (D/OPS). Each directorate is further subdivided into discipline specialties. Projects, while housed in a particular directorate, can draw staff from multiple specialties across more than one directorate. In the case of science projects, core team members will be drawn from several D/TEC specialties as well as operations and science. However, not all D/TEC staff involved in a particular project will be assigned to full-time project support; many will support a number of projects simultaneously as consultants, or continue non-project specific technology research and development work.

Figure 5 illustrates how a typical science project evolves, with particular focus on opportunities to incorporate new technology. The top half of the diagram captures the project flow, with the bottom half demonstrating how parallel technology development activities (outside of a particular project framework) get incorporated into the spacecraft design and development. Each block in the diagram will be explained sequentially in the sections that follow. However, project and non-project developments will be kept separate for clarity, with the interactions between the two sections and the extent of feedback discussed at the end. In Figure 5 and other diagrams in this paper, the color scheme is consistent with the legend. Any acronyms are explained in the text.

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2 ESA Convention abstract, see [16]
2) Mission Selection and Definition

By the time a mission is actually handed over to the project team, it will already have been studied by several technical groups. Major mission parameters will have been set; areas where new technology needs to be developed will have been identified and the development process will have been initiated. Moreover, possible solutions will have been found for any major technology gaps, as they represent an important cost driver. The Principle Investigator (PI) will also be selected in this phase, through a competitive bidding process. Clearly, the mission concept phase represents an opportunity for emergent technologies to be infused into an ambitious design proposal. However, due to the extensive qualification process required for all new-flight hardware, only relatively mature “new” developments will even be considered.

During the mission requirements process, the ESA team, in close collaboration with the Principle Investigator(s) (PI) through the intermediary of the Project Scientist (PS), translate the scientific needs into a set of mission requirements. The ESA European Space Operations Centre (ESOC) is involved at this point to ensure that any operational implications of the scientific requirements are accounted for. From a scientific point of view, this phase is critical, because from ITT forward, the spacecraft will be designed to the technical requirements and not explicitly to the scientists’ needs. The conceptual studies are used to a certain extent to inform the requirements definition. However, in the words of a senior discipline systems engineer: “phase A is about dreaming. In phase B, we figure out how the thing might actually work.” Although requirements are intended to define what the spacecraft must do, and not how the tasks should be accomplished, they will typically reduce the “envelope” of technically feasible solutions significantly.

Another important aspect of this phase is the more detailed definition of required Technology Development Activity (TDA) contracts. Since prime contractors will be unlikely to sign up to the risk associated with un-flight-proven technology, if there is a need to develop new technology to support a particular mission requirement, ESA will typically manage the contract until it is taken over by the prime in later stages. The TDA also represent the most well-defined mechanism though which D/TEC development activities are brought into Science projects. Where possible, TDA contracts are let on a competitive basis; however, for the most part, a specific, relatively mature technology is sought that has limited (or a single) potential suppliers.

The proposal phase allows at least two potential prime contractors, to develop a preliminary design solution independently (of ESA and each other). Typically, the same organization would have been involved in the mission concept study phase; however, the prime contractor’s study and project teams don’t tend to overlap. Nonetheless, this represents an avenue through which lessons learned, and technology developed on other projects, can be infused into the requirements definition. In addition, while the requirements definition, and mission studies establish a relatively tight envelope for system level design parameters, the adage “the devil is in the details” certainly applies to spacecraft. Even though entirely new technology-based solutions are rarely defined in the proposal response, there is ample opportunity to present innovative approaches to implementation using existing technology.

3) Spacecraft Design and Implementation

Once a prime contractor has been selected, major design elements are set through the process of contract negotiation. The so-called, project team then expands to include both the ESA project team and the prime project team. Members of the ESA technical directorate with specialties in each of the relevant fields are appointed and subcontractors and equipment suppliers are sought. Although contractually, subcontractors report to the prime-contractor, ESA is intimately involved in their selection and eventual management. In fact, as long as the constraints of contractual obligations are respected, the interactions are seen much more as collaboration within a fixed hierarchy, rather than a customer-supplier relationship. As a result, the ESA project team becomes an integrated part of the design and implementation team, offering not only management and oversight, but also detailed technical input. During this phase, although the types of innovations that arise are more subtle than in the earlier project phases, they are no less important in the long term. Many of the process-type product improvements that are realized during the design implementation phase get incorporated into future standards and can have significant cost and feasibility implications on future projects.

The specialists from the ESA technical directorate serve a dual purpose. Firstly, they provide technical advice and support at the request of the ESA project team. Since they are only involved with any one project on a part time basis, they can bring in the perspective of multiple parallel developments, while at the same time, remaining au courrant of the leading edge technical developments in their field; something that is impossible for the integrated support staff who become entrenched in the specifics of their current spacecraft. Secondly, the technical directorate fulfills the role of peer review. At each major milestone, the project is asked to demonstrate its progress and justify many of its technical decisions. Although, the technical staff can’t possibly remain abreast of all the details of the numerous projects in which they are involved, this mechanism provides another opportunity to make the project aware of relevant aspects of other projects, while at the same time serving as a “sanity check” for the project. In fact, the ESA project reviews are considered sufficiently rigorous that prime contractors reportedly don’t feel it necessary to conduct their own parallel internal technical reviews.
The science instruments are developed in parallel, under the oversight of their respective PIs. Although PIs retain complete responsibility for the scientific performance of their instruments and any corresponding requirements, in the end, the instrument is a passenger on the ESA project manager’s spacecraft. As a result, despite being the end customer, the PI fits into the project as a virtual second prime, subordinate to the project from the point of view of technical mission success (even though there is no formal contractual obligation; the PI is funded by their national space agency). In order to ensure that the instrument is developed to meet their, sometimes loosely defined, needs, PIs will typically assemble a research staff analogous to ESA’s project team. Depending on the complexity of the instrument, portions of the development and much of the manufacturing will be contracted out to industry. There is a significant overlap between equipment suppliers on the spacecraft and instruments.

The phases of system assembly integration and validation, while extremely important to mission success, do not tend to result in product innovation - the subject of this paper. As a result, they are omitted from this discussion. The main responsibility of the project team, including both industry and ESA project members, ends with on-orbit commissioning. Once all spacecraft systems are shown to meet the requirements, the project is deemed a technical success. Thus engineering success might be established as much as a decade before any scientific data is collected and returned.

4) Mission Operations and Results

After commissioning, the spacecraft is passed to ESOC and the focus shifts back from feasibility to scientific return. Since the physical system cannot be changed after launch, product innovation no longer occurs. The operations phase is, however, extremely important in terms of fulfilling the user’s need. If unanticipated scientific opportunities arise at the target – after all, the target is unknown – it is the role of ESOC to determine the realm of feasible accommodation. This is when the operability requirements are truly tested and a more detailed understanding of what will be required for future missions is gained. If all goes well, the desired science data is collected and returned to the PI.

In addition to the obvious benefits to a particular scientific community, the second major material output of a mission is the media coverage. Public opinion is extremely important to a sustained space program because the funding comes from public money. Press is a significant avenue for public accountability in the space sector. The last benefactor, explicitly called-out in the cosmic vision, although not formally incorporated into the mission selection process, is European industry. This benefit is realized in terms of firm competitiveness, both in terms of the infusion of capital into a quiet market and the experience gained by working on advanced science missions.

C. The non-Project Space Technology Development Process

Technology development outside the context of a particular project happens in one of two ways. Either future needs are recognized and developed by an advanced studies group, or development occurs within the technical directorate. Since the advanced studies group tends to focus on payload capabilities, which are not the focus of this paper, this discussion will emphasize technology development in the technical directorate (D/TEC).

One of the core functions of ESA’s (D/TEC) is to retain in-house expert technical knowledge in fields relevant to space science and exploration. In addition to their role as technical consultants and reviewers in the project context, as described above, they also directly support the fourth aspect of ESA’s mandate: to foster a globally competitive European space industry[16]. This is accomplished through technology development contracts.

D/TEC staffs are continuously on the look-out for the emergence of a new capability in a related, ground-based field that might be relevant to a future space-based need. Because of the long development and qualification times in the space sector, development must start many years before the technology will be sufficiently mature to incorporate into a project design phase. After the D/TEC staff member has convinced themselves of the relevance of the innovation to space, he simultaneously approaches the ESA funding board responsible for study-stage development and the firm or academic institution responsible for the innovation. Once funding from the former, and interest from the latter have been secured, a series of paper studies are initiated; the goal being to establish the feasibility of applying the new capability to space. This process might take as many as five years.

Next, the D/TEC approaches the equipment (or subsystem) supplier that could eventually use the new component. Introductions will be made between the capability originator and the space sector developer. A development plan is agreed to, which typically allows each company to keep its portion of the intellectual property rights. In addition, the specification is written in a way that will not preclude future industrial applications. These efforts will be funded primarily through a second ESA development funding source, on the initiative of the D/TEC. As the technology matures, ESA’s role tends to become increasingly hands-off, acting more as facilitator than co-investigator.

Acquiring development funding for the first two phases, while difficult, is feasible for a good idea. However, once the new capability has been proven in the ground-test environment[3] it is nearly impossible to secure the remaining funding, unless the capability is required by a project. Although there are cases where a technology development contract has supported a new capability from inception to first flight, or a project has initiated a development from a very early stage, these cases are rare. Separate funding sources, albeit minimal in comparison to project budgets, exist within ESA for both concept development and capability development. However, despite significant lobbying efforts on

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[3] In the language of NASA technology readiness levels, a TRL of about 7.
the part of TEC staff, there is almost no funding available to space-qualify newly developed technologies or have them launched as piggy-back payloads for on-orbit testing. Yet, projects are extremely hesitant to assume the risk and costs associated with qualifying “un-space-proven” technology, creating a veritable “catch-22.”

This is because, despite the multiple years required for the design, development and implementation of an advanced science spacecraft, the schedule is extremely tight, and the design is frozen quite early in the process. As a result, in-project, technology development will not be supported unless the mission cannot be achieved without it. Fortunately, from the point of view of innovation, missions often require technology development in at least some area. Thus, the initiating D/TEC will spend time advertising the results of his latest development projects to his colleagues on the project side, while at the same time listening carefully to design problems that arise in the projects for future ideas.

In the end, whether and which particular new capabilities get incorporated into a project is often a matter of timing. This process is driven by the confluence of a project need and the sufficient maturity of the requisite capability, catalyzed by the legwork of a number of key individuals.

D. Continuity from one Project to the Next

Three classes of output were identified from the project process: technical experience, scientific data, and publicity. Figure 5 illustrates how these outputs feed into future projects, in the form of a more capable industry, a set of next scientific questions and a willingness to commit funds to future missions, respectively. None of these connections are direct or formally controlled, perhaps to the detriment of progress.

The other aspect of experience, which is not explicitly captured in the diagram, is that of the project team. Much of the continuity and transfer of lessons learned, from one project to the next, remains with the team. No matter how much a design is documented, tacit knowledge is an important part of engineering.[17] While the prime contractor may change from project to project, ESA tends to keep project teams together from one project to the next. This is extremely important since the requirements definition and TDAs are largely the domain of the project team.

It is worth noting that while there is a certain amount of informal understanding of what is technically possible within the science community, there is no formal mechanism through which future scientific desires and potential technical capabilities are exchanged. Given that the expression of science needs is the main “pull” for technology development at ESA, this seems like a transfer worth facilitating.

IV. Creating a Mapping: Monopsony Roles on Competitive Functions

Having discussed roles and responsibilities of the monopsony actors in the Science project structure in some detail, they can now be mapped onto the functional framework constructed in section II. This mapping is shown in Figure 6. When viewed this way, three things become immediately apparent. First, there is no clear separation between “buyers” and “sellers,” at least not in the manner observed in the competitive scenario. In fact, the only group whose function remains exclusively on one side (in this case the buy-side) is the public. Given that most external observers would consider the government to be the customer, in what is explicitly a government acquisition, this is quite a surprising result.

Second, the cyclic interaction of seller-capabilities and buyer-needs that dominates the competitive dynamics is replaced by a relatively discrete, nearly linear and structured acquisition, where the marketing function (the main gatekeeper of product-push under competition) is more to determine which company will do the prescribed work, rather than what work needs doing. While there is some feedback, it is largely informal and not directly incorporated into any decision making.

![Figure 6. Mapping of Monopsony Project Roles onto Competitive Functional Framework](image)

Finally, note the extent to which competitive functions remain “unused” within the product structure of a monopsony market. It was argued earlier that the functional product evolution whereby research yields a concept that is developed into a proven capability that can be used in the implementation of a design, is independent of market structure; that market structure only impacts the extent and rate at which this evolution happens. Why then are there so many red “X”s in Figure 6? Since requisite new capabilities don’t just appear, ready to be implemented, extensive development work must occur outside the project structure. In fact, when the technology development roles, described above, are included, all the functional elements of innovation are accounted for. However, the distinction between project and non-project development is an important one. The level of funding and policy priority allotted to projects is significantly more substantial than for D/TEC development. Thus, despite the fact that technology development outside the project structure is critical, as seen through this mapping, the process is seen as peripheral to product innovation.

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4 One interviewee reported spending as much as 30% of his time securing funding for their development projects.
V. INNOVATION DYNAMICS OF COMPLEX PRODUCTS IN A GOVERNMENT MONOPSONY

In the preceding sections, the product development process for a particular class of complex technological system – the ESA Science Mission – was described in terms of opportunities for technology development. The roles of actors in this monopsony structure were then mapped onto a competitive functional framework in order to identify key differences imposed by the market structure. Three general results were observed: there is no clear separation between “buyers” and “sellers,” the governing driver is an explicitly defined need based “pull” and a high level of technological maturity is required before a new capability is incorporated into the product development process.

In this section, the connection is made between these observations and the nature of the product and market of interest; specifically, the incremental impacts of the complexity of the system, in a monopsony market structure, with the government as monopsonist. This discussion leads to the development of a preliminary model of innovation dynamics of complex systems in a government monopsony.

Although the analysis presented in this paper is based on a single case study, it is believed that the cross-section of interview subjects is sufficiently varied and experienced to be representative of ESA science projects. However, ESA is just one example of a government monopsonist engaged in the acquisition of complex technology products. The innovation dynamics in the NASA and the US Department of Defense (DoD) structure, for example, may be quite different. That being said, the particular generalizations made in this paper are believed to be relevant in general. Nonetheless, further case studies of different organizations are required before the proposed model can become more final.

A. Complexity of the System and Component Level Innovation

A complex system is, by definition, composed of multiple constituent parts; each of which is a system in its own right. Thus, innovation in a class of complex systems will occur at multiple levels; functional improvements will be observed to varying degrees in all of the components as well as the system as a whole. As a result, when quantifying the extent of innovation is of interest, it is appropriate to take a holistic view. By tracking the change of a user-centric functional cost over time, any relevant sub-component contributions are captured implicitly. However, when the goal is to understand how innovation is achieved, the parts are at least as important as the whole.

The Coupled Push-Pull Model of Innovation, presented in section II, asserted that innovation occurs at the intersection of market-need and technological capabilities. This is particularly pertinent in the realm of complex systems. A system level need can be broken-down into a set of requisite sub-functions. It follows that an incremental (or major) increase in functionality may not require equal improvements in every sub-function. Conversely, if an innovation is achieved in even one particular sub-function, the system level design may be able to capitalize on that improvement at the system level. As system complexity increases, the notion of “a natural functional progression” becomes less concrete; system design is dominated by defining and integrating a set of subsystems. As a result, system level improvements are often driven by the availability of component level innovations.

In addition, different component technologies evolve at different rates. While in the philosophy of product-push, increased research funding will result in increased performance and new capabilities, the extent of that improvement and the time-frame during which it occurs cannot be predicted precisely. Therefore, a system level need that implicitly requires a particular component-level functional improvement is contingent on the time (and ability) necessary to achieve and integrate each sub-innovation. It is for these reasons that innovation in complex systems represents the confluence of needs and capabilities.

The ESA Science Spacecraft case study revealed that a high degree of technological maturity is required before a new capability will be incorporated into the spacecraft development process. It was also noted that once a component technology is “proven” for space use, it immediately gets incorporated into numerous projects under development. While these observations appear to contradict the notion that spacecraft innovation is driven by the need to meet ambitious requirements, it is certainly consistent with the above discussion of complexity. If spacecraft development relied on timely innovations in several of its constituent technologies, the resultant schedule risk would be enormous; thus technology must be developed so that it is almost ready when a project needs it. This cyclical dependency can be overcome through the mechanisms of advanced planning and technology development activities as described in section III.C. The particulars of the mechanisms are discussed in more detail, with regard to the monopsony nature of the market, below.

B. Monopsony Market Structure and Specified Innovation

In a competitive market, the mechanism of price elicits all relevant information regarding both technological capabilities and user tastes, through the self-interested behavior of all economic agents[18]. As a result, there is a continuous incentive to improve the capability baseline, in the direction of inferred customer needs. In a monopsony market, on the other hand, there is no aggregate from which customer interests can be inferred. Thus, tastes must be revealed explicitly, as each new need arises; in effect, the market is discreet, only existing when the buyer wants to buy. In addition, although the existence of a monopsony buy-side does not explicitly preclude competition on the sell-side, it will be limited by the extent to which the monopsonist has sufficient need to support multiple firms. Simply put, since anything developed outside the expressed needs of the sole customer will not be bought, there is little incentive for sellers to innovate outside the specifications of a particular acquisition. Although any “extra” innovation could theoretically be applied to the next project, there is no guarantee that it will be a) requested and b) that the particular firm will win the next bid. Thus, the governing
innovation dynamic in a monopsony market is not only discreet, but also specific.

In this way, the top-level “product push” that is so critical to the cyclical dynamic observed in competitive markets is effectively eliminated in the monopsony structure. This leaves the explicitly specified need-based “pull” to drive the overall dynamic. Yet, the above discussion revealed that innovation in complex systems cannot be driven exclusively by a system level pull; a high degree of technological maturity is required before a new capability can be incorporated into the product development process. This suggests that there is an element of technology push driving the process from the supply side, despite the lack of incentive for the seller.

However, a closer examination of the out-of-project technology development initiatives revealed that this is, in fact, not the case. There are two dominant mechanisms for technology development in the ESA context (described in more detail in section III.C). Either an innovation in a terrestrial-based technology piques the interest of an ESA D/TEC staff member, leading to an ESA-funded technology development program; or, an ESA advanced planning group recognizes a future agency need and initiates the requisite development, sufficiently in advance of the needs of any particular project. While in both cases the first implementation of the new technology on an actual mission requires the well-timed intersection of a project need (pull) and a sufficiently mature capability (push), the impetus for the initial developments came from a perceived future ESA need (governing pull). Even where the TEC’s interest in an emergent technology can certainly be construed as a product push, it is important to note that the development occurs outside the space industry. The act of adapting the capability and qualifying it for space, while typically carried out by a space firm, is funded and facilitated by ESA.

C. Government Buyers and Role Integration

The inherent complexity of space and defense products requires that component level developments be achieved before system level advances can be planned. The monopsony market structure forces the buyers to explicitly reveal their needs and to facilitate any requisite component development in advance of system level acquisition. However, neither the complexity of the system, nor the monopsony structure of the market, explain the extent of buyer-seller role integration observed in the ESA Science Mission case study. This is a function of the government as monopsonist.

Originally, it was believed that this role integration resulted from the unknown nature of the advanced projects (since the work had never been done before, the cost was difficult to predict) compounded by the limited price-competition supported by a monopsony market. Another argument stems from the necessity to keep an under-achieving industry “honest.” Since there are so few firms capable of serving as prime-contractor for a major government acquisition, effectively guaranteeing their future business, some believe they have no incentive to do any more than exactly what they are forced to. However, either of these issues could theoretically be addressed through more extensive benchmarking on the buy-side and more aggressive contracting; both of which have been pursued extensively in the literature and neither of which requires the extent of role integration observed in the mapping. A third particularity of the government-as-buyer was revealed through the interviews in this study: government acquisitions simultaneously serve multiple, sometimes intangible, often incompatible, needs.

Although the aim of an ESA Science missions is nominally to collect the data required to support the research of the Principle Investigators and their collaborators, the overall goal is actually more complex. Firstly, basic scientific research is supported by government grants because, despite a lack of direct market value, the pursuit of knowledge is considered to be worthwhile for all of humankind. Secondly, in addition to needing advanced technology, specifically to support this scientific research, a competitive high-technological industry has implications for national (or regional) security and international prestige. Thus, through the vehicle of an advanced science mission, ESA attempts to serve three communities: 1) All European research scientists; 2) the whole European technology industry; and, indirectly 3) the European public, both in terms of knowledge and pride.

It is an economic truism that when one transaction combines multiple products, each elemental exchange will be less efficient than if it had been conducted separately[19]. Government acquisition takes this principle to the extreme. The result, in the case of ESA science missions, is that scientific needs are used to drive technology innovation from the top down and profit-driven firms are expected to act in the interest of the whole industry. Clearly neither of these will realistically emerge without the intervention of ESA as government monopsonist.

This need to meet multiple objectives through the vehicle of science projects manifests itself in at least three ways, each of which are regulated through ESA involvement in every stage of the project. While scientific mission selection is based nominally on scientific return, mission scope is determined by technical feasibility at a prescribed budget class. The budget cap is determined in part by the total ESA purse, but the number of simultaneous projects derives from a desire to distribute funding over multiple communities. As a result, although there might be sufficient funding to tackle one important scientific question that requires a major technical development program, instead of several lesser questions, this trade cannot be considered because of the need to support all communities.

Secondly, technical work must be distributed based on the principle of geographical return. Essentially, contributing member states are guaranteed an equal percentage per project return in the form of development contracts. Arguably, this adds both unnecessary complexity in terms of project management and a non-meritorious criterion to the selection process. Finally, although ESA initiates and funds a large number of industry technology development activities, it rarely keeps the intellectual property rights. While this contributes to industrial competitiveness, it severely limits
ESA’s ability to “cross-pollinate” good ideas from one project to another; often creates monopolies in a particular technical specialty and reduces the ability for ESA’s technical staff to communicate technology developments to the scientific community.

D. Preliminary Model

Based on the above discussion, a preliminary model of the innovation dynamics of complex products in a government monopsony can be developed. It is illustrated in Figure 7 and described below.

In a government monopsony market for complex technological products, the system level innovation begins with an advanced user need. This is because, as described above, there is no market for products that have not been expressly requested. However, this does not mean that the innovation process can be represented by a simple “need-pull.” The act of representing user needs in terms of verifiable technical requirements, that are ambitious yet realizable, is quite complex. Innovation requires the confluence of user needs and component level technology maturity; users must know how much to ask for, and the developers must have predicted the right capability to bring to maturity. In the model, the “mission selection and definition” (MS&D) block is the interface between three domains of focus: User needs, technical feasibility and future requirements. It evaluates the compatibility of mission objectives with the constraints of technical capability (for a given budget) and translates them into an implementable set of requirements. While the MS&D block fulfills a critical interface and definition function, both the rate and extent of innovation are largely determined by the expressions of need and capability that feed into it.

Although users have a mechanism to formally express their needs, there is a perceived necessity to be strategic about which needs to express. Since so few projects get funded, and only feasible projects have a chance, the user community tends to ask for things that they believe to be realistic. However, this has the potential to limit innovation in two ways. First, users tend not to have the technical competence or information required to accurately gauge how much to ask for. Combined with their focus on their own utility (i.e., science as opposed to requisite technology) this mechanism for expressing a realistically advanced user need tends to err on the conservative side.

Second, since there is no formal mechanism for linking user needs with the direction of technology development, development engineers must plan based on perceived user needs. If users don’t express the ambitious objectives they actually desire, the required technology will never be developed. In the case of ESA, D/TEC staffs have a great deal of independence with respect to which development initiatives to pursue, and report a lack of coherent direction in terms of long term technology plans. The interface with MS&D is surprisingly informal as well. When a project has a specific need, technology developers will be approached directly; however, for the most part, the responsibility seems to fall to the developers to “advertise” new capabilities. This is accomplished through “informal conversations in the corridor” and requires significant initiative on the part of developers.

Contrary to popular belief, the interview responses suggest that technology spin-in is at least as prevalent as spin-off within the space and defense sector. This is in part attributable to the inherent complexity (as described in section V.A) but also to the extreme reliability required for “must-succeed” applications characteristic of space and defense. Since the qualification requirements are so stringent and time-consuming, most new space capabilities result from adapting a ground-based innovation to space. This statement is not intended to minimize the advanced nature of space applications. The process of adapting a ground-based capability to space often pushes its operating envelope and results in a “reflective” spin-off of more advanced group applications. As shown in the model, the act of spinning-in ground-based technology (and the concurrent infusion of funding into that market) benefits both industries.

There are three main sources of feedback shown in the model, namely, public interest, industry capabilities and next user needs. They were discussed in section III.D and that discussion will not be reiterated here. However, it is worth highlighting that the feedback is from one project to the next. While projects can represent an opportunity for new capabilities to be used for the first time, system level innovation only has meaning over several projects. As it stands, much of this “cross-pollination” was reported to occur informally, again through conversations in the corridor on the initiative of individual engineers (except in the case of certain
required new technologies). It was reported that as soon as a technology gets qualified, the time before it is widely used on other projects is extremely short. It seems that an insufficient budget for general technology development has created a culture of waiting until the capability is absolutely necessary before it is developed. This dynamic certainly has retarding effects on innovation.

VI. POLICY IMPLICATIONS

The preliminary innovation model presented in this paper does not purport to have predictive value with respect to selection of an appropriate mechanism for innovation. In fact, this study has revealed that there is only one dominant mechanism for innovation within this industry: timely, targeted development of a customer-identified, soon-to-be-needed capability. Rather, it provides a top level view of how the structure of a government monopsony translates into a particular set of avenues through which new capabilities are brought into the product development process. In this way, the areas in which institutional policy can have the most impact on innovation are revealed. This section describes how four of these areas could be explored further with a view to harnessing innovation potential.

A. Non-Project Specific Technology Development

There is a perception that an ambitious need coupled with adequate funding create a sufficiently strong pull to advance space and defense systems on a project-by-project basis. However, it was shown that system level innovations emerge from the well-timed intersection of user need and mature component level technical capabilities; an ambitious need alone is not enough, even if there is adequate funding. Further, as a result of the monopsony nature of space and defense markets, technology development must be initiated by the monopsonist. Finally, while individual projects are quite different, there is significant overlap in constituent technologies. Thus, for major technology advances to occur from one project to the next, targeted, component level, technology development must occur. This must be done outside the funding realm of any one project and sufficiently in advance of the formalized project need.

A qualitative approximation of how much technology development is enough was not explored in this study. However, the prevalent sentiment that technology can only get space-qualified through an expressed project need, and projects will only express that need when they are left with no other choice, is indicative of a funding deficit within ESA. A comparison of relative technology budgets across a number of industries would provide insight into appropriate action on this issue.

B. Valuing Function

In this paper, it was argued that although innovation measures the extent to which the cost of achieving a particular function is reduced over time, one can discuss the way in which innovations occurs without defining the function of interest. However, from a policy point of view, the ability to measure success, of which innovation is an important part, is critical and non-trivial. Thus, the function that is to be improved must be defined explicitly.

Government acquisitions attempt to serve multiple communities through the vehicle of a single advanced technological project. These communities, typically spanning users, an industry and the public, each have different levels of personal investment and varying expectations. For example, in the case of ESA, science needs are used to drive technology development from the top down and profit-driven firms are expected to act in the interest of the whole industry. Viewed this way, the spacecraft is only a part of the product being developed; thus, the cost of functionality should incorporate a measure of multiple factors. The key point being that an apparent unsatisfactory rate of improvement of the cost of spacecraft functionality may result from a poorly defined system boundary. ESA isn’t just buying a spacecraft; it’s buying scientific knowledge, a healthy high technology industry and European pride. All these factors need to be valued as part of “function.”

C. Contracting with Collaborators

Traditionally, contracts are written between a buyer and a seller; the buyer agrees to pay for a well-defined product or service and the seller agrees to provide it. In the case of space and defense acquisitions, the product can’t be fully defined in advance and there is an expectation that both buyers and sellers be involved in that resolution. While there has been significant research focused on optimal methods of contracting, under a wide range of market conditions, there is always a fundamental assumption of separation between buyer and seller roles. The mapping presented in this paper showed that this assumption may not be valid in the context of government monopsony acquisition of complex products. This reality was explained in terms of the government’s effort to balance complex needs, however the implications of this fact on contracting practices weren’t treated in this paper. That being said, they may be significant, and certainly merit further study.

D. Multi-project Planning Horizons and Informal Social Networks

There is a perception in the space sector that innovation happens within the context of each large-scale advanced project. This perception is reflected in the significant budgetary emphasis on project funding compared to technology development, as well as the lack of formal feedback between different project groups and from one project to the next. However, it was argued in this paper that not only does an important portion of technology development happen outside the project but also that new capabilities become innovations as they get used and improved across multiple products. This reality should be reflected in the agency’s budget, by providing sufficient funding for generic technology development as discussed in section VI.A. And, for the allocation to be efficient, a multi-project long-term planning focus with formal feedback between projects is
critical.

The notion of long term planning is not new. ESA, for example has both a “Cosmic Vision” plan for science and a number of technology roadmap documents. However, there appears to be a lack of formal interaction at the working level. As described above, scientists propose missions that they think are feasible, and technology developers fund initiatives that they predict will be asked for. This inexact planning is exacerbated by the fact that the group that establishes early feasibility of future missions has no formal contact with any of the scientists, the technology developers, or the project engineers. Yet, despite the lack of formal avenues, the necessary communications do tend to happen, through informal interactions at the individual level, both within the project and from one project to the next.

This raises the question of whether these informal avenues arise to compensate for a deficient organizational structure, or the structure is appropriately designed to leverage the social element of teamwork. Since this study revealed that a significant portion of the institutional learning, that is so critical to innovation, occurs through informal pathways, understanding how they work may be an important subject of further study.

E. Effect of External Constraints

The fact that government acquisitions are inherently political has been addressed in this paper in a number of different ways. Any complex project requires a certain amount of management overhead, controlling interactions of the many players through regulations, contractual obligations and hierarchical organizations. The structure of these non-technical oversight functions, which vary from one government monopsonist to the next, can have a very significant impact on how the engineering on a project is conducted, particularly with respect to the informal working culture. Further, the significant institutional inertia present in any complex government organization, make it easy for employees to come to take working methods for granted. As a result, there is a limit to what can be inferred, with respect to the effect of external constraints, from the study of a single organization. Future work will examine other examples of complex product development in government monopsonies.

VII. Conclusion

The value of understanding how innovation occurs in the space and defense sector is clear. In a field that exists on the cutting edge, funded to a high degree by public money, it is important to understand how to spend those funds efficiently. However, despite a significant body of literature on the subject of innovation in a competitive market, little work has been done to understand the fundamental dynamics underlying complex product innovation in a government monopsony, the typical scenario in government acquisition. This poor understanding can lead to an inappropriate choice of mechanisms and approaches for encouraging innovation and, ultimately, to an environment that does not foster successful innovation.

This paper has addressed that gap, at least in part, by identifying the impact of certain elements of market structure on innovation dynamics within ESA. This was accomplished by mapping the roles of actors in a particular class of complex technological system – the ESA Science Mission – onto a competitive functional framework. Three general results were observed: there is no clear separation between “buyers” and “sellers,” the governing driver is an explicitly defined need-based “pull” and a high level of technological maturity is required before a new capability can be incorporated into the product development process. These observations were explained in terms of the incremental impacts of the complexity of the system, the monopsony structure of the market, and the government as monopsonist.

Based on this analysis, a preliminary model was created which provides a top level view of how the structure of a government monopsony translates into a particular set of avenues through which new capabilities are brought into the product development process. In this way, the areas in which institutional policy can have the most impact on innovation were revealed. Through the discussion of the policy implications of a government monopsony market structure, that ensued, multiple areas worthy of future study were identified. As a next step, the authors intend to follow this work with an additional case study of a non-ESA project, with a focus on entrants from peripheral competitive markets.

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