



FRUGAL INNOVATION IN COMPLEX SYSTEMS: EVIDENCE FROM NUCLEAR REACTOR DESIGN AND DEVELOPMENT IN INDIA

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Abstract

Frugal innovation has typically been observed in the design of relatively simple artifacts and systems. This work finds evidence of it in a 'complex' setting: the design and development of nuclear reactors in India. Drawing on more than 40 interviews with reactor designers and equipment manufacturers, this paper describes the improvisational design practices that led to a localization of reactor technology in India. These findings are significant because they suggest the possibility of an alternate home-grown technology development paradigm for resource-constrained designers in developing countries.

Keywords: frugal innovation, complex systems, innovation management, design process

1. Introduction

Scholars of design and management have observed frugal innovation taking place in the design of relatively small and simple artefacts and systems. This work finds evidence of it in a 'complex' setting: the design and development of nuclear reactors in India starting in the mid 1970s.

The context which instigated the 'frugal innovation' in reactor design and development in India is unusual. The Indian nuclear program, while in the midst of building the second reactor of a two-unit pressurized heavy water reactor (PHWR) plant of Canadian design, found itself excluded from global nuclear supply chains and confronted with the task of completing a half-finished reactor following a nuclear test in 1974. Indian nuclear reactor designers and engineers, having been cut off from global supply chains, reinvented or reverse engineered reactor designs, initially doing so while the design knowledge and manufacturing ability for the equipment being designed did not exist. Simultaneously these designers also repurposed 'conventional' equipment, finding novel ways to test and qualify them for use in radiation environments. Starting in the late 2000s, following an Indo-American agreement, the Indian nuclear reactor market became open to designers and manufacturers and vice versa, and at over \$50 billion is one of the largest markets for nuclear technologies in the world. International suppliers expect to build at least 12 large reactors of over 1000 MWe each in India. Despite this reintegration into global supply chains, the home-grown technology development paradigm created in the 1970s remains dominant.

The findings presented in this paper are significant because they suggest that improvisational innovation that made reactor development possible in India is not unlike *Jugaad* or frugal innovation observed in design and development of smaller and simpler artefacts, but in this case for the design and development of systems of a much larger scale and complexity. The broader, intellectually interesting and also practically significant question to be asked here is whether this 'frugal' way of designing and developing new technologies suggests an alternate home-grown paradigm that developing countries can adopt rather than imitating the West, as they have done thus far (Gerschenkron, 1962; Kim, 1997).

2. What is ‘frugal innovation’?

What makes frugal innovations unique is that they are not easily be derived from western products. They are the result of “unique value architecture grounded in the desire to meet requirements at lowest possible cost”. Their development requires the use of local organizational structures and resources to understand the needs of the local consumers. Further essential conditions are “low cost manufacturing; simple, low-cost materials and design; and a basic focus on functionality and minimal feature sets” (Zeschky et al., 2011). Because products arising from frugal innovation are generally very basic, “core value identification” is critical (Christensen and Raynor, 2013). The management and design literatures on frugal innovation have developed relatively independently of each other. Management researchers have focussed on the approaches that can be taken to encourage frugal innovation. Suggested approaches include redesigning products (Zeschky et al., 2011), rebuilding innovation eco systems (Bound and Thornton, 2012) and reconfiguring value chains (Sharma and Iyer, 2012; Bhatti and Ventresca, 2013). Design scholars have chiefly focussed on the particular strategies that entrepreneurs in resource constrained settings can adopt as part of their process of product development (Austin-Breneman and Yang, 2013; Sonalkar et al., 2016).

Scholars writing about frugal innovation typically make a distinction between frugal innovation and a related topic – reverse innovation. Frugal innovations are those that lead to products that are affordable, just ‘good enough’ and meet the needs of resource constrained consumers. They are meant for consumption typically in the low-income segments of home markets, not globally (Nunes and Breene, 2011; Downes and Nunes, 2013). Practices describing the development of these products have also alternately been described as designing for the ‘base of the pyramid’ (Jagtap et al., 2014; Aranda et al., 2016). Reverse innovations are those that although developed in emerging contexts are developed by global innovation teams and are meant from the outset for worldwide consumption. A prominently cited example of a company engaged in reverse innovation is product developed at General Electric which has adapted products developed for emerging market into products for more affluent consumers (Immelt et al., 2009). This work regards ‘reverse innovations’ as arising from frugal innovations and constituting the next stage of product development.

There appears to be some disagreement about the extent of exportability of the products and business models arising from frugal innovation. Some scholars believe that frugal approaches to innovation can be transplanted from developing to developed countries (George et al., 2012). Others disagree and point to a need to transform frugal innovations into ‘reverse innovations’.

While attempts to understand and theorize frugal innovation are relatively recent, the phenomenon itself is not. One set of authors point to product development in pre-world war Britain, US and Canada when rationing and other austerity measures forced designers to ‘do more with less’ as being examples of frugal innovation (Bhatti et al., 2012). However, even studies of design and development in developed countries point to the development of relatively simple artefacts and systems. This work shows that frugal innovation, or rather a more intricate variant of the process as it is now understood, is possible for the design and development of significantly more complex systems.

Although studies of design have largely transitioned from a theoretical to experimental phase (Blessing et al., 1995), there has been a rich tradition of exploring the structure of the design process (Simon, 1973; Schön, 1984; Cross and Roozenburg, 1992) and designers’ approaches to structuring problems and creating design solutions -- sometimes simultaneously (Dorst and Cross, 2001a; Cross, 2006). This paper draws on this earlier tradition of exploring the structure of the design process to develop a mechanistic understanding of frugal innovation in a complex and large technical system. Specifically, I use semi-structured interviews with reactor manufacturers and oral histories of reactor designers to reconstruct design and development approaches that made it possible to design and build nuclear reactors in India at a time of economic and industrial backwardness (Gerschenkron, 1962).

Over a period of three decades both the original Canadian and the indigenous Indian reactor technologies were scaled to larger sizes. Thus, the Canadian “control” and the Indian “experiment” are a unique opportunity to study and understand the technology development paradigm that was used to design and develop these reactor designs. As we will see the Indian reactors were not the inferior or “just good enough” designs that scholars have come to regard as frugal innovations. Instead these designs were not only functionally equivalent to the Canadian ones (developed in a context that was not resource

constrained) but in many cases the design choices made by the Indian designers were more elegant and led to superior performance.

These empirical findings are surprising because comparative studies of product development in developed and emerging contexts have found that the superior or more sophisticated versions of a product, often being more expensive to manufacture in the developing country context, are discarded in favour of more technologically backward variants (Fuchs, 2014). These design and development choices have long term consequences for innovation and trajectories of technological innovation, particularly when the design and manufacturing of products is moved overseas. Thus, these are two opposed paradigms of technological development – the development of sophisticated, high quality technologies at home, or their inferior (but less expensive) counterparts in emerging contexts. However, the case of reactor development in India suggests the possibility of a third paradigm for technological development – one in which home-grown design and development of sophisticated products and systems in developing countries can be expected to give rise to technological designs equivalent to those found in any developed country. Frugal innovation (as it is defined here) is the critical ingredient for this third paradigm.

This paper is organized as follows: In the following section I discuss the context in which reactor design and development was undertaken in India started in the mid 1970s. I describe what technology had already been mastered, how and what remained to be reinvented and reengineered. The next section is a description of the methods. The next section presents the results of this work in two parts – a first part how frugal innovation occurred (through four different processes) and a second part describes why this was possible. The subsequent section concludes this paper.

3. Context: The state of the Indian nuclear industry before 1974

3.1. The technology: Pressurized heavy water reactors (PHWRs)

The Indian nuclear energy program initiated in the 1950s at the time of Indian independence, had self-reliance as its primary goal. The first two power reactors built in India were two GE Boiling Water Reactors. The reactor contracts for these reactors were partially ‘turnkey’, and some equipment for this reactor project was manufactured in India. For subsequent power reactors, Canada and India agreed to work jointly on the development and construction of PHWR designs. In PHWRs, the nuclear fuel (typically in the form of unenriched uranium oxide) is contained in fuel bundles which pass through horizontal pressurized tubes sealed at both ends. The tubes are submerged in a vessel of heavy water which moderates the neutrons. Neutrons on colliding with heavy water molecules lose energy such that their probability of collision and fission with uranium nuclei increases. Important systems surrounding the reactor include the primary core cooling system as well as the shutdown and emergency core cooling systems and the steam generator. All these along with the reactor core are encased in a containment, with the turbine generator typically located in a separate but connected building. Altogether the reactor systems are both physically large and complex – made up of several hierarchical layers of sub-systems, some of which are tightly coupled (Simon, 1991; Suh, 2005).

3.2. Industrial capacity

The first PHWR built in India at the Rajasthan Atomic Power Station (RAPS) was modelled on the first Canadian PHWR at Douglas Point, a 220 MWe reactor. Having signed the reactor contracts, Indian and Canadian designers agreed to work jointly to develop the PHWR designs. A Joint India Canada Study identified Indian companies that could eventually manufacture equipment for the pressurized heavy water reactors. Simultaneously teams of Indian engineers, financed by the Colombo plan (Blackton, 1951), were sent to Canada for on-the-job training. RAPS-1, the first PHWR built in India, was connected to the grid in 1972. Although most of the large equipment for this reactor had been manufactured in Canada, half of the first charge of fuel was manufactured in India.

When India carried out a nuclear test on May 18, 1974, the Indian nuclear program had learned how to manufacture fuel and electronic control equipment, how to perform the civil and construction work for a reactor project, and how to commission, operate and maintain a reactor.

But the knowledge and expertise needed to design an entire reactor system, manufacture both small and large pieces of equipment such as valves, pipes, reactor pumps, the moderator tank or the calandria, end shields, and fuelling machines as well as the manufacturing of special alloys and castings and forgings needed to make this equipment was missing.

4. Methods

This paper, which seeks to document and understand how Indian scientists and engineers reverse engineered or re-invented reactor technology is based on over 40 interviews, which were carried out in three stages: (1) interviews with international nuclear reactor companies intending to sell reactors and equipment to India, (2) Indian companies manufacturing equipment for nuclear plants and current and (3) Indian reactor designers many of whom were also officials of the Department of Atomic Energy (DAE).

The first set of interviews were with international reactor companies. These interviews focused on their views on India as a buyer of nuclear reactor technology and the status of their partnerships with Indian companies and governmental organizations for building nuclear reactors in India and manufacturing equipment for them. The interviews with Indian manufacturing companies focused on how these companies had become part of the nuclear reactor supply chain, and how they had acquired the skills and capabilities to become suppliers of nuclear equipment. The first two sets of interviews were conducted as semi-structured interviews which were not recorded. I took handwritten notes during the interviews and compiled my notes into detailed memos soon after the interview, describing both the conversation and my observations on it (Birks et al., 2008; Maxwell, 2012).

A third and final set of interviews were with Indian reactor designers who worked for the DAE and its daughter organizations. These designers are now retired and were initially difficult to identify. To solve this problem, a snowball sampling approach was used to identify interviewees. This strategy is particularly effective for reaching ‘hidden’ or hard to find populations (Atkinson and Flint, 2001; Noy, 2008).

The interviews with the retired officials were conducted as oral histories (Thompson, 2017) in which the interviewees described how they had joined the DAE and the contributions they made to the design and development of nuclear reactors in India. These interviews were taped and transcribed. Whereas the interviews with the private companies focused on how the companies had become suppliers of nuclear reactor equipment, the interviews with the current and retired scientists and engineers of the DAE were used to elicit detail on how public-private partnerships were forged, how companies were identified as potential suppliers of nuclear reactor equipment and how, by drawing on in-house expertise within the DAE organizations and the capabilities of the companies, the Indian nuclear program indigenized nuclear reactor technology.

A grounded theory approach was used to analyse the interview data (Glaser, 1992; Charmaz and Belgrave, 2007). The transcripts were analysed with specific attention to the mechanisms or processes that enabled frugal innovation. Here the development of an identical reactor technology in Canada and descriptions of the process of development as reported by Canadian nuclear engineers (Brooks, 2002) served as a ‘control’ representing the conventional (or non-frugal) approach to design. I paid specific attention to departures from the Canadian as well as American approaches (Verma, 2017) because these departures signalled the presence of an alternate design and technology development paradigm. The results although broken into sub-sections describing specific aspects of this Indian design paradigm, are also meant to be read and understood as a narrative of the roughly 20-year period over which the reactors were designed.

5. Results: Reactor design and development in India

The results are presented in two parts. The first part describes the process of frugal innovation as it was observed in the design of nuclear reactors. The second part describes the motivations of the designers as they went about doing the design work. Understanding both of these aspects of frugal innovation in the context of complex systems is important as a first step towards replicating this approach to technological design and development in other contexts.

5.1. Frugal innovation in action

Canadian cooperation in the area of reactor design and development was terminated overnight following the nuclear test. At this time, the first reactor of the two-unit plant was complete (RAPS-1) and the second reactor (RAPS-2) was under construction. Without access to Canadian design expertise and manufacturing and supported only by companies that had not yet learned how to manufacture nuclear equipment to high tolerances and precision, completing the second reactor (RAPS-2) was unlikely to be an easy task. A grounded theory analysis of the interview data reveals three processes or approaches that Indian nuclear reactor designers used to reverse engineer and reinvent and ultimately redesign the reactors. These processes were not pre-determined or known but emerged on-the-fly.

5.1.1. *Improvisational product development and testing*

The first reactor (RAPS-1) that had already been built had to be kept operational to produce power, and for another function that would soon become important: to serve as a sort of test facility for equipment that would become a part of that reactor and future reactors. Although reactors are designed to have lives of several decades, not all reactor equipment is long-lived. Valves, pipes, pumps, wires, and instruments for measuring fluid flow rate, temperature and pressure have to be replaced periodically. Moreover, the reactor built at Rajasthan was a copy of the reactor at Douglas Point, the first PHWR in Canada. The Canadian and Indian reactors were thus each the first of a kind. In a complex system such as a reactor that is made up of many hundreds of pieces of equipment, a great deal of learning takes place over time (Arrow, 1962; von Hippel and Tyre, 1995). This learning-by-doing is especially critical for novel technologies for which codified engineering knowledge about system behaviour and performance does not yet exist (Pisano, 1996). This learning, when absorbed tacitly or explicitly, leads to improvement in the performance of the system (lower operating and maintenance costs, fewer mishaps, higher capacity factors) as operators begin to see patterns of faults or to read signals that cannot easily be recorded or measured. The learning also leads to the design of better sub-systems of the larger system and eventually to improved versions of the whole original design. The first PHWR had by then only been operational for less than two years and little of this tacit knowledge had had time to accumulate or be codified. Further, the inventory of spare parts at the first reactor had started to run out and the maintenance crew at RAPS-1 needed to source spares to prevent the reactor from shutting down. An Indigenization Cell was created to source and develop these spare parts. The Cell was made up of three engineers - two electrical engineers, a mechanical engineer and an instrumentation specialist. These engineers started exploring the Indian market to understand what the Indian companies could make, whether locally made variants could be used as substitutes and whether they would work as well as the original parts.

For much of the equipment that was rapidly nearing end of life, the Indigenization Cell did not have detailed technical drawings or even specifications to give to potential suppliers. Bulk orders for the equipment that was needed could not be placed—because this equipment did not exist in India. Nor could the Cell's engineers provide drawings and specifications to potential suppliers, and request small trial orders of equipment. Instead, a two-pronged approach was taken. Functionally equivalent parts that were already on the market were brought to the reactors and tested on auxiliary systems, as far as possible from the core, and identical copies were gradually moved inwards towards safety-significant systems after the reliability of the copies had been tested in the non-nuclear areas of the reactor.

The use of these parts necessitated the development of new techniques for installation and inspection. As one of the engineers described, “you have to be ready to replace the equipment and you have to be ready to put it in such a way that you can replace it quickly once it fails. So that you can take it out without exposing it to radiation. So, these are the tricks that we had to adopt ... to be able to replace imported equipment with Indian equipment. But we had to tell our suppliers to be ready to supply spares every month in case something failed. We had to encourage the suppliers to take on the challenge and develop the equipment”. The equipment that was initially tested on the reactor was placed in locations that would be easy to reach and replace with a frequency higher than nuclear grade equipment would otherwise have required. When equipment failed the Cell's engineers returned to the suppliers with instructions for improvements. This improvisational development and testing made it possible to

replicate or reverse engineer most of the smaller pieces of reactor equipment – particularly for reactor instrumentation.

5.1.2. Building formal written-down component and system specifications from tacit knowledge

For the larger pieces of reactor equipment like pumps, steam generators, pressure vessels, the designers needed to develop not only the functional requirements for the equipment but also understand how changes to the design parameters of these larger parts impact the performance of other reactor systems. The absence of written down specifications of materials and equipment was made up for by the consolidation of tacit knowledge in single individuals assigned to specific pieces of equipment which they were tasked with developing. These individuals, having built deep reserves of knowledge, were then able to transform them into heuristics for product design. The task of reinventing and reengineering the large equipment fell to the Quality Surveillance Group of the Power Projects Engineering Division (PPED). The PPED engineers divided their time between labs and research centres and shop floors. Prototype equipment designed conceptually in the labs was fabricated by the private suppliers and brought back to the labs for trial runs on test loops.

A consolidation of design knowledge in single individuals instead of dispersing it across large teams was critical because complex tightly coupled systems such as reactor systems can be prone to emergent modes of failure. Successful anticipation of these failure modes, which is critical for developing formal risk models of these systems, requires drawing on expert knowledge and intuition acquired from years of operational experience. The Indian reactor designers cultivated this intuition by deeply implicating themselves in the design and manufacturing process. Having developed this intuition about the performance of the systems and the capabilities of the manufacturers, the designers were able to take calculated technological risks.

Prospective suppliers for the large equipment were brought to the reactor to study equipment while the reactor was running and during outages. Broken parts and pieces whose material composition was tricky to ascertain were sent for multiple rounds of destructive and non-destructive testing. Some of the alloys needed to make these parts were not made in India. In many cases, even after extensive materials testing, the exact composition of some materials could not be determined. When this occurred, the suppliers were asked to codify what they had and had not been able to glean about the material composition of a part and the Cell's engineers took calculated risks.

“The people in charge were told that we had to take risks. The manufacturers were specifically told not to cut any corners and to make everything as best as they could so that we could take the risk so that the manufacturers did not get blamed in case anything went wrong.” [interview 04082014].

In the process of learning how to make equipment for the reactor, the difference between ‘technology transfer’ and ‘technology absorption’ became clear. “Technology transfer is different from technology absorption. The transfer of technology is at a very macro level, it involves the transfer of design documents but god is in the details. There are many trade-offs involved in a technology transfer decision. Should the technology be transferred to the buyer country or should the buyer country rely on the host country? An example is the pump casing. Manufacturing it requires a foundry, a linear accelerator is needed for radiography. The manufacturer must be ASME qualified. The equipment must be subject to inspections. A particular kind of steel may be needed. So although the documents that are part of the technology transfer agreement have the technical specifications, this is not the full story, this alone is not sufficient and a lot of learning is involved in understanding and perfecting the processes involved in manufacturing.” [interview 05082013].

5.1.3. Identifying and designing systems with functional equivalencies

The Canadian ‘control’ is important to this history as a way of comparing resource-constrained Indian reactor design and development with reactor design and development in a setting that was not resource-constrained. There is no single comprehensive indicator that can be used to evaluate the performance of a nuclear reactor – improvements in capacity factors, the ability to learn from operational experiences, redesigning sub-systems to improve reactor safety, and increasing the electrical output of an initial design are all indicators of performance. Because the first Douglas Point reactor and RAPS -1 were the first full scale pressurized heavy water reactors built in each country, the evolution of the designs in

each country provides a way not only to understand how the Indian nuclear engineers were thinking about the design and manufacture of individual equipment but more broadly, it is a way to gauge their mastery of reactor systems.

In Canada, the initial 220 MWe reactor at Douglas Point was immediately scaled to 515 MWe. The first 515 MWe reactor (Pickering-1) was connected to the grid in 1971. In 1976, a 734 MWe reactor (Bruce-2) came online. The reactors were scaled further upwards to an 817 MWe design which was first connected to the grid in 1984. Canada had designed three new generations of reactors and nearly completed the scale-up effort by the time the Indian nuclear program started to scale up its own reactors. While RAPS-1 was under construction, the Canadian designers had considered the possibility of transferring the design of the 500MW reactor to India but the nuclear test had eliminated this possible pathway of development.

As the Indian designers began to scale up the 220 MWe initial CANDU design to larger sizes – initially a 500 MWe reactor -- they understood that they, “had to design the reactor in such a way that it would be easy to manufacture. I had to take the manufacturing industry into confidence even as I went ahead with the design. I showed them what I was going to design and asked them if they could build it. It is not easy to make a design and throw it at them and say “you do it!”. So, it was going on side by side in parallel. I used to talk to them. There were development orders to get something made...to see if they can make it that would give me confidence in whether I can make them go ahead.” [interview 07082014] The Indian designers also realized that the initial design was not robust. It was an untested design and much could be improved. The original Douglas Point and RAPS designs had a tank of water above the reactor core. The tank was effectively a suppression pool mechanism to lower pressures in the containment building and provide cooling in the event of an accident. One of the design team’s earliest innovations was to lower the elevation of the tank to eliminate the possibility of an accidental release of water in case of a rupture of the tank lining.

The Indian designers discovered that the safety of the design could be improved in many other ways as well. As one designer described, “it was not a very robust design in the sense everything was hanging from the rods! Even the calandria ... It was hanging from top. Of course, they had wires on which it could swing. The end shield was also hanging. So, it was not a very good design.” He continues: “the second thing about being untested – they used materials that were not radiation resistant.” The design team changed the material for the end-shields for the first Madras reactor (the second PHWR-based nuclear plant in India)- using stainless steel there. For the third PHWR plant built at Narora, the end-shields were redesigned as integral structures and the calandria and the end shields were welded together.

To further improve reactor safety, the Indian designers sought to emulate international safety practices. The decision to add a redundant shutdown system in the first reactor built at the Narora plant was influenced by IAEA safety standards. The second shut down system was made up of horizontal rods into which a liquid neutron poison could be injected to shut down the reactor. This was different from the Canadian system that relied on the injection of the poison directly into the moderator (thus contaminating it). On exchanging views on the designs of these safety systems at international conferences, the Indian designers were told by their Canadian counterparts that they did not expect the second shutdown system to work. The Indian design did prove to be effective and was used in the 220 MWe reactor designs.

Another change to the design was the removal of valves between the primary and secondary systems of the reactor. Leakages from the valves could cause a loss of coolant accident. The valves could not simply be eliminated. They had to be replaced with a structure that could isolate the primary and secondary systems of the reactor during an outage or isolate one of the coolant loops. The valves were replaced with an inflatable structure. “So, we used a ball type structure that goes to the inlet, inflates and seals it. So, this also we had to demonstrate to our [nuclear safety regulator], before we could get clearance.” [interview 08082014].

The designs of the containment structures also evolved as the pressurized heavy water reactor was scaled to larger sizes. A double-containment structure was designed to minimize ground releases of radioactivity during an accident. The first double containment was built at the Madras plant but not fully implemented because of the height of the steam generators. The containments of the Madras reactors

have double walled cylinders but a single walled dome. A complete double walled design was built at the Kaiga plant. The Canadian approach to containment design was different. Multiple units at plants had free-standing single containments, connected to a single vacuum building.

The largest Indian nuclear power reactor is a 700MWe reactor. Four units of this reactor are under construction at two sites. The core configuration of the 540MWe reactor was used for this design. Both reactors have an identical number of fuel channels (392) but the power level of the 700 MWe reactor was increased by extracting more heat from each fuel bundle in the fuel channel. Although the Indian engineers were aware of the Canadian design decisions, the Indian reactor designs diverged. “We did our work separately. What they are doing is different from what our approach is. When we were making the 500 MW reactor, Canada already had a 500 MW reactor and we had some basic knowledge of what they had done, but not the details. But whereas for the 700 MWe design we did completely different things.” [interview 08082014].

Indian and Canadian designers started meeting and discussing their work at conferences by the early 2000s. The Canadian designers were surprised to learn that the Indian designers had developed designs and techniques they did not think would work - chiefly among them a simpler and cheaper fuelling machine based on a rack and pinion design. All of this suggests that necessity and a lack of resources had led the Indian designers to invent simpler but functionally equivalent substitutes for the equipment had come with the original Canadian reactor.

5.2. Institutional factors that enabled frugal innovation

5.2.1. Using trust and informal institutions to build supply chains

Over this period of reactor development, both the DAE as well as private companies that partnered with it became porous to the flow of information and people. As one designer describes, this openness was essential for designing and manufacturing complex reactor components that had never before been made in India: “[T]he nuclear components involved extremely high precision, much more than was the case for conventional equipment. There was an enormous amount of training of the industry people and a lot of the effort was in fact a joint development between the people who worked in the Atomic Energy department and the industry people so they would ... there would be regular and continuous dialog between our people ... going to the manufacturing shops there and jointly evolving methods and processes. It was quite a tough proposition.” [interview 04082014] Another retired official recalls that working with private companies to develop equipment “became part of the culture of the nuclear energy program.” The reactor designers I interviewed unanimously recalled this period of reactor design as a time when they were “doing something for our nation.” [interview 05082014] The interview data suggests that both the DAE designers as well as the companies that agreed to manufacture equipment for them, were not necessarily motivated-purely by economic self-interest.

In general, three kinds of contracts were used: developmental contracts, cost-plus contracts and fixed price contracts. Developmental contracts were utilized for equipment that was least well understood and thought to be hardest to manufacture. [interview 04082014] Nevertheless even these contracts could not encompass the full range of technical and financial risks associated with developing complex, new equipment for the first time. The manufacturing companies nevertheless agreed to work with the reactor designers. Some companies that were offered cost-plus contracts rejected them. The engineer who led the development of the moderator pumps, recalls one such instance. Unlike low pressure or low-head pumps that have a single volute, moderator pumps are double volute pumps. The company that was contracted to supply the pumps was unable to make the double volute pump casing at its foundry. A competitor company accepted the order to make the pump casing. The company’s CEO was aware that DAE, having made considerable investments in the development of the pumps, had failed thus far. He accepted the order, agreeing to supply the double volute to his competitor for fabricating the entire pump, and he refused a cost-plus contract saying, “business is a game of risk. When I make a profit, I don’t share it with you so when I make a loss how is it fair to share that?” A high degree of trust between the designers and manufacturers led to informal understandings on how financial and technological risks would be shared, with some companies agreeing to take on disproportionately large risks. In general the formal contracts coupled with the informal understandings between the designers and manufacturers

lowered transactional costs (Williamson, 1979), reduced asymmetries of information and ultimately made the improvisational approaches to design and development described above possible.

5.2.2. Working without a plan and end goal

Reactor design and construction projects are typically managed by detailed schedules. However, in this case not having previously designed and built reactors, the Indian reactor designers appear to have worked without a plan. One of my interviewees explained that the low level of industrial development in India at the time made it impossible to forecast end dates for projects. Instead the designers and manufacturers worked as quickly as they could. “And then you had cement and sugar equipment, they require some machine components. Even bicycles were not really being made. At that time, they had just started making bicycles in the country. And some textile and milk components were being made. So those were the conditions at the time. So, I don’t see how we could have done it faster. We did the best we could. If ten years was long, that was the best we could. If ten years was short, we worked very hard and achieved it.” [interview 04082014].

6. Towards a theory of frugal innovation in complex systems

This paper has described one instance of frugal innovation in a complex system. However, this is not an isolated example. The Indian space program, started in the 1960s had a similar trajectory of development: international assistance and technology transfer followed by a period of a near-complete localization of technology (Misty, 1998). Perhaps the most significant achievement was the 2013 successful launch of the Mars probe Mangalyaan developed on a budget of \$74 million – the cheapest interplanetary mission (which, the Indian Prime Minister Narendra Modi noted, was less than the budget of the film Gravity).

In order for frugal innovation to become an implementable technology development paradigm, it must be better understood. This study of reactor design and development in India is an initial step in direction. Table 1 below describes the differences between frugal innovation in simple systems (as described in Section 2 at the start of this paper) and in the reactor design and development adopted in India.

Table 1. A comparison of frugal innovation in simple vs complex systems

	Frugal innovation in simple systems	Frugal innovation in complex systems
Design team	Single designer or small design teams	Large, distributed design teams
Design project	Short-term design projects lasting at most a couple of years	Long term design and development projects lasting a decade or more
Design goals	Design goals derived from the consumer needs and preferences which are specific to the design settings	Design goals derived from overall system performance (cost, safety, reliability)
Resource constraints	Product design and development constrained strongly constrained by the consumer’s willingness to pay and weakly constrained by the materials, tools and techniques	System design and development strongly constrained by the availability of expertise, materials, tools and techniques
Production and use of knowledge	Little or no new knowledge generated as a result of product design and development	Generation and transformation of tacit knowledge into codified knowledge
Alternations to resource constraints	No significant alterations to resource constraints as a result of product design and development	Technological and skill upgrading for designers and manufacturers
Designed product	Simple and low cost, not functionally equivalent to products for affluent consumers	Less complex and low cost; functionally equivalent to systems developed in non-resource-constrained settings

Recent design work in this area has sought to develop best practices for designers in resource constrained settings (Austin-Breneman and Yang, 2013; Sonalkar et al., 2016). This study has taken a different approach of understanding the frugal innovation from the ground up by focussing on the production and

management of knowledge and the organizational and institutional arrangements developed during the innovation process.

A key distinction between the findings here and an experimental study of frugal innovation is worth noting. Unlike the information-driven resource-constrained designers in Jagtap et al. (2014), the Indian designers focus in equal parts on the constraints imposed by the design context and those imposed by the system being designed. This is likely a specificity of complex system design because changes in single design parameters can propagate through the whole system and affect system-wide stability and performance. Altogether the findings presented in this paper and summarized in the table above suggest that the design and development of large complex systems in resource-constrained settings differs significantly from frugal innovation as it has been described and understood thus far in smaller and simpler design contexts.

The design and development of reactors in India and a near total localization of technology and manufacturing was made possible by improvisational ways of designing and building systems and supply chains. This in turn was made possible by supplementing formal contracts between designers and manufacturers with informal understandings of how technical and financial risks would be shared. Key to this whole process were the reactor designers who moved freely from their offices to laboratories, factories and shop floors to design, develop and test large and small reactor components. The roles played by these designers have similarities to those played by DARPA program managers described by Fuchs (2010) and the heavyweight designers described by Clark and Wheelwright (1992). The DARPA program managers identify and seed technology development directions, bringing together researchers who might not otherwise have worked together. Heavyweight designers (unlike managers of design teams having a functional, lightweight or autonomous team structure) possess technical expertise and have access to and responsibility for the work of the entire project team.

The reactor designers were effectively played a hybrid role: leading the design process (like the heavyweight designers, though being significantly larger in number than the designers on a heavyweight team) and deeply embedded in the process of technological development (like the DARPA program officers). The design process for these designers was inherently more uncertain than even those typically observed for the design and development of other complex systems in environments that are not resource-constrained. Design problems rarely present themselves as well-defined problems to be solved consecutively, instead problem and solution often co-evolve (Dorst and Cross, 2001b). This problem and solution co-evolution was especially amplified for reactor design and development in India such that the designers of these reactors were in a constant practice of 'reflection-in-action' (Schön, 1984). Thus at least one implication of this work is that frugal innovation, especially for the development of complex products necessitates that designers rely a great deal more in their work on interpretive design practices (Lester and Piore, 2009). The critical role played by these reactor designers suggest that one approach for replicating frugal innovation in other contexts is to create a new kind of designer able to move freely across design and development settings, granted wide discretion and encouraged to improvise.

7. Conclusions

This case of reactor design and development in India starting in the 1970s was unexpected and exceptional because of the events that triggered it. Nevertheless, the technology development paradigm – a variant of frugal innovation but in a complex system persists to this day. While this particular case has been revealing, it also points to the general problem of studying frugal innovation in similarly complex contexts. Laboratory and experimental studies that design scholars have recently favoured, part of the experimental turn in design studies (Blessing et al., 1995; Blessing et al., 1998) are unlikely to be efficacious for the study of frugal innovation in complex systems. As we have seen, informal institutions were needed to mediate and indeed critical for the design and development of these complex systems did not emerge overnight. Additionally, the development of these systems spanned both a large time scale large design teams spread across many organizations. All of this points to a need to study frugal innovation in complex system contexts in situ through participant observation when its occurrence can be anticipated or through using approaches typically favoured by historians of technology.

Finally, if frugal innovation is to be used a replicable technology development paradigm to be used across a range of design domains and context, what is needed is a mechanistic understanding of the different processes by which frugal innovation occurs across a range of design contexts varying in the size and complexity of the design artefact. A subsequent paper drawing further on the Indian case as well as the published literature on frugal innovation will construct such a typology of frugal innovation across systems varying in size and complexity.

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