Evolving a Value Chain to an Open Innovation Ecosystem: The Cognitive Influence of Stakeholders in Customizing Medical Implants

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Abstract: While ecosystems can be used to create competitive advantage, how does this apply to firms with long-established business models, particularly when it requires a shift from closed, vertically integrated value creation to an open innovation (OI) model of co-created value? In particular, how do firms shift their conception of value creation when a potential ecosystem has multiple categories of stakeholders with multiple possible configurations? Using interviews, observations and archival data from three continents, we examine an example of how such a transformation has been approached for orthopaedic medical implants, and how one firm implements a shift from mass production to mass customization. Our findings show how firms, in the face of internal and external cognitive inertia, can transform an ecosystem to reflect the new value creating activities of a radical innovation. In particular, we reveal how a firm's linear conception of value creation can be evolved to a new bi-directional, network model of co-created value, and how the cognitive shift required for creating and evolving an OI ecosystem can be enabled through use of explicit shared cognitive artefacts. Thus, this paper contributes to the very limited research on the effect of managerial and organizational cognition in open innovation, particularly for adoption of OI and creation of an OI ecosystem. We also contribute to OI research on the importance of external ecosystems and non-economic incentives in promoting an OI strategy. Finally, we demonstrate how technology sourcing and commercialization strategies can be linked by a firm using OI to deploy a radical innovation.

Introduction

Managers have been advised for years to leverage the power of ecosystems to create competitive advantage and grow their business (Moore, 1993; Kandiah & Gosain, 1998; Iansiti & Levien, 2004; Iyer et al, 2006; Adner, 2012). The centrality of such ecosystems for joint value creation has risen in our increasingly platform-centric economy (Parker et al, 2017). In parallel, researchers have examined how firms manage the structure and interdependencies to jointly create value (Adner, 2017; Jacobides et al, 2018). As a result, academic interest in ecosystems has exploded, with nearly 90% of the ecosystem research published in the last decade (Bogers et al, 2019).

Following such normative ecosystem research is easier for some firms than others. Certain types of business models fit into standard patterns of ecosystem management, whether computing platforms (West & Wood, 2013), complex software systems (Ceccagnoli et al, 2012) or retail supply chains (Lusch, 2011). While many Silicon Valley firms thrive by extending and optimizing proven ecosystem models— such as by transforming two-sided advertising markets into surveillance capitalism (Zuboff, 2019) — nonetheless, most such firms are created to exploit some variant of one of these existing ecosystem models (Kenney & Zysman, 2016; Adner, 2017).

Even if ecosystem thinking offers broadly applicable insights into value creation, how do such insights apply to existing firms with long-established business models? In particular, how do firms, in the face of external and internal sources of inertia, transform existing closed, vertically integrated value creation to an OI model of co-created value? And how can these firms overcome both internal and external cognitive inertia to cooperatively develop such a new value-creating model with external partners (Prahalad, 2004).

Here we examine an example of how such a cognitive transformation has been approached by Medimplant, a pseudonym for one of the world's largest makers of orthopaedic medical implants. Since 2017, the company has been investigating a possible shift from mass-produced bone implants to customized prosthetic implants. The company is using inbound OI with hospital and university research partners to develop the needed technologies for designing, custom manufacturing and implanting these prostheses.

Based on action research performed for the company, this paper examines how a firm can implement a shift from mass production to mass customization. This requires the complex orchestration of transformation from a linear value chain into a networked ecosystem, simultaneously changing the roles and interactions among stakeholders while remaining in compliance with government regulation and payer expectations. This shift also requires understanding the dual motivations of key stakeholders in healthcare, both an intrinsic desire for improved patient outcomes as well as their own personal self-interest. This stakeholder understanding created a cognitive model of how the firm's new ecosystem would be implemented; however, before implementing this new model, a deliberate process of cognitive reframing identified a second, more radically different ecosystem configuration, which the firm ultimately decided to adopt.

This study utilizes interviews, observations and archival data from three continents to understand the challenges and opportunities of such a transformation effort. We use these data to show how a firm's linear conception of value creation can be transformed to a new bi-directional, network model of co-created value. It also contributes to OI research, by examining how the cognitive shift required for creating and evolving an OI ecosystem can be enabled through use of an explicit shared cognitive artefact. The insights add to our knowledge on the importance of external ecosystems and non-economic incentives in promoting an OI strategy. Finally, it demonstrates how technology sourcing and commercialization strategies can be linked by a firm using OI to deploy a radical innovation.

The paper begins with a review of prior literature on value-creating networks and open innovation, and how such concepts have been considered in healthcare. It then describes the data that were gathered from this study, and presents a summary of transformation to an open innovation ecosystem, along with the analysis of the role of stakeholder motives, constraints and cognition. From this, it offers broader implications for the practice of and research on open innovation.

Theoretical background

Systems, Value Networks and Ecosystems

While models of innovation often emphasize the contribution of individual firms, research over the past two decades has identified many examples of when firms (or other actors) must work cooperatively to jointly deliver a product or service (Bogers et al, 2019). In some cases, the inherent complexity of a systemic offering requires cooperative systems integration to achieve such value, whether in aerospace systems (Miller et al, 1995; Hobday et al, 2005) or IT systems (Bresnahan & Greenstein, 1999; Eisenmann et al, 2009). The common thread is that these firms jointly create value in a way that no single firm is able to do (Adner, 2006).

There have been two (overlapping) theoretical approaches for considering such joint value creation. One is the concept of the value network, which extended Porter's (1985) "value chain" concept by adding lateral and complementary value-creating relationships. This has been various called a value network (Rosenbloom & Christensen, 1994), value constellation (Vanhaverbeke &

Cloodt, 2006) or value web (Chesbrough, 2011). In general, these approaches focus on the cooperation and the value creation by network members.

The other is the ecosystem metaphor (Moore, 1993; Bahrami & Evans, 1995). Beyond the network structure, this literature (unlike most value network research) emphasizes the interdependence and shared goals of ecosystem health and ecosystem survival. Various forms of ecosystems that have been studied include platform ecosystems (Ceccagnoli et al, 2012), other forms of innovation ecosystems (Adner & Kapoor, 2010), and regional entrepreneurial ecosystems (Acs et al, 2017). Beyond the joint value creation, other common elements are the network, the self-interest of the actors in the network, and the interdependence of their efforts to create and capture value (Bogers et al, 2019).

Network Value Creation in Healthcare

The complex interdependencies needed to deliver healthcare have previously been considered as a form of value creating network (Acharya et al, 2017) or an ecosystem (Groves et al, 2013). However, such networks differ from other technology product ecosystems in four important ways.

First, the development and sale of biomedical products — such as pharmaceutical therapies or implantable medical devices — are part of a complex offering of products and services delivered by a diffuse network of medical providers. A range of expertise among doctors, nurses, technicians and other providers are required to diagnose and treat a single medical event for a single patient. Products can substitute for other products and services for products, or they can be combined — as when a surgeon implants a patented medical device into patient.

Second, this brings with it a complex web of stakeholders and stakeholder concerns. In some countries such as the U.S. with third party payment and independent healthcare providers, there are actually three customers that must be convinced to adopt any new product: the patient, the provider, and the payer (Shimasaki, 2014). In other countries, the latter two categories are subsumed under the central authority of a national health service.

Third, the questions of value creation and value capture are very different in healthcare. The definition of ultimate value creation — efficiently providing long term patient welfare (Porter, 2009, 2010) — is largely uncontroversial, but the absence (or distortion) of markets across the value-creating network makes it difficult to measure value creation by individual stakeholders. In terms of value capture, when making healthcare decisions many providers value improving patient welfare over their own self-interest (Godager & Wiesen, 2013). Even for individuals or organizations pursuing private interests, medical ethics constrain these goals to be pursued differently than in other industries (Werhane, 2000).

Finally, healthcare is an essential good alongside food and shelter. While a local healthcare ecosystem can fail temporarily due to natural disaster or war (Franco et al, 2006; Stone-Brown, 2013), a healthcare provider network is not going to disappear due to mismanagement or a lack of demand — unlike a proprietary IT ecosystem (West & Wood, 2013). At the same time, the total magnitude of total healthcare expenditures creates tremendous cost pressures that mean that medically desirable treatments will be denied solely due to cost (Relman, 1990; Mechanic, 1995).

Thus, a biomedical products company promoting adoption of a radical innovation must do so while meeting the constraints of government regulation and addressing on-going cost pressures. Most of all, it must navigate this complex web of stakeholders, both addressing their self-interest that influences their willingness to adopt (e.g., making their job easier, reducing organizational cost), as well as identifying and addressing their unique perspectives on how such an innovation can improve patient outcomes (Cain & Mittman, 2002; Ludwick & Doucette, 2009).

Open Innovation

Network perspective. The network and ecosystem perspectives are directly aligned to two core ideas of open innovation. The first is that OI assumes that the creation and commercialization of innovations requires cooperation across organizational boundaries between multiple organizations (Chesbrough, 2006). The second is the centrality of the business model in OI, with its emphasis on participants creating and capturing value, as well as the role of a value network in supporting such business models (Chesbrough & Rosenbloom, 2002; Vanhaverbeke and Chesbrough, 2014).

The importance of the network approach has long been identified in OI research, whether in value networks (Vanhaverbeke & Cloodt, 2006), systems integration (West et al, 2006), communities (West & Lakhani, 2008) or platforms (Gawer & Cusumano, 2014). Beyond the centrality of the business model and interorganizational collaboration, a common thread for network forms of OI are the ongoing patterns of interaction — rather than the transactional, often "one-off" nature of more commonly studied forms of OI such as crowdsourcing (West, 2014).

At the same time, there are aspects of such networks – particularly salient to the delivery of medical products and services — that are only rarely studied in open innovation. The first is the participation of not-for-profit (or government) organizations with nonpecuniary goals rather than strictly maximizing financial success (Dahlander & Gann, 2010; Chesbrough & Di Minin, 2014). The second is the possibility that rather than sending or receiving valuable knowledge from outside partners, firms co-create new knowledge with partner organizations (or even individuals) outside the boundaries of any organization (Piller & West, 2014).

Cognitive Barriers. A key issue facing firms in shifting to an OI perspective are cognitive barriers to adoption. At its core, OI is "both a set of practices … and also a cognitive model for creating, interpreting, and researching those practices" (West et al, 2006: 286). Prior OI research has examined how cognitive distance makes it easier or harder to access external knowledge (e.g. Enkel & Gassmann, 2010; Cassiman & Valentini, 2016).

However, little research has examined the role of cognitive factors in limiting (or shaping) the choice of a firm's OI strategy, or value creation more generally. We know cognitive barriers slow (or prevent) the adoption of any new business model (Chesbrough, 2006, 2010). We also know that technological disruption often forces firms to find a new business model, which becomes more difficult the longer and more successful the previous business model is (Tripsas & Gavetti, 2000).

When using open innovation, new value creation approaches require cooperation across firm boundaries between partners. Christensen (2006) showed how, in the case of a radical technological innovation, codification of knowledge made it possible for potential OI partners to build a shared cognition both for new opportunities and the collaborative business relationships they might establish. But the challenges of establishing shared cognition in a new OI ecosystem are even more daunting, because of the inherently multilateral coordination required across a network of partners (West, 2014). Prior research assumes that the ecosystem sponsor has an accurate cognitive model that will allow it create a successful ecosystem (e.g. Maula et al, 2006). However, if this cognitive model addresses the needs of some stakeholders better than others, such a cognitive blind spot can lead to the collapse of the entire ecosystem (West & Wood, 2013).

Methods

Research Setting: 3D printing orthopaedic implants

Medimplant is a US-based Fortune 500 company in the medical products sector. Founded more than 50 years ago, its main products are implantable orthopaedic devices, as well as tools and instruments that facilitate orthopaedic and other forms of surgery. Its prosthetic implants are used to replace or reinforce a damaged spine or bone, or to replace an entire joint in the hip, knee or elbow. In its current business model, Medimplant uses a linear value chain to supply off-the-shelf implants to hospitals on inventory consignment order: these implants are produced and sold in various sizes, scaled to fit a particular anatomy that might range from a small child to a tall adult.

While traditional implants are mass produced, the advent of additive manufacturing technologies (3D printing) have offered the possibility of producing customized products for each patient — whether through direct printing, or by printing a mould for a plastic or metal product that is produced using that mould. Early success for 3D printed medical products came in the 1990s with dental prosthetics such as crowns and bridges (Liu, 2002). In response to more recent research identifying the potential application of 3D printing for producing orthopaedic implants (e.g., Mok et al, 2016), medical implant companies have been researching the technical and market feasibility of using such an approach to manufacture patient-specific orthopaedic implants. Whether mass produced or custom produced, the process for making and controlling the quality of medical implants is tightly regulated by national agencies such as the US Food and Drug Administration (Morrison et al, 2015).

At the same time, the production and distribution of such products requires a transformation of how value is created and delivered, also calling for a shift in the firms' conception and strategic choice of value creation and delivery. Whilst a mass-produced medical implant fits the classic strategy of a linear value chain (Porter, 1985), the mass customization of a medical device or implant requires a transformation of that approach (Dalgarno, 2006). Our empirical data showed both structural changes — from a linear chain to a more complex ecosystem — and also a transition from unidirectional to multilateral flows of information and value. Furthermore, we charted the process of strategic change associated with the transformation of existing linear supply chain into networked ecosystem, and also show how Medimplant managed the cognitive shift towards such an OI strategy.

Data Collection

The authors are part of a team that was commissioned by Medimplant to examine the business feasibility related to 3D printing patient-specific implants for one particular application treating bone sarcoma by creating an orthopaedic implant to replace cancerous bone removed by surgery. Given differences in demand, regulation and production capabilities between national markets, the study included research on three continents: Australia, Europe and North America.

To develop technology for its intended product offerings, Medimplant created an OI research partnership (as defined by Perkmann and West, 2015) to collaboratively develop new technology with three external partners: a manufacturing research laboratory at a leading engineering university, the advanced research lab of a private not-for-profit hospital, and a centre of innovation within a university business school. These partners were contracted to develop and assess the benefits of prototypes for innovations in two areas. The first combined existing technology for 3D printing titanium components with advanced imaging technology that customizes the shape and size of the implant for each specific patient. The second technology provides robotic surgery to more precisely and reliably excise the tumour and implant the prosthetic replacement into the patient.

This technology development was part of a broader project to understand the scope of producing 3D printed bone tumour implants based on "just-in-time" (JIT) principles, where parts and materials are delivered when they are needed, rather than before, to the hospital. This project also included a strategic analysis, where two of the authors from the centre of innovation were involved in collecting and analysing data on the various stakeholders involved in the existing treatment pathway, and to evaluate their interests and concerns for implementing this potential new treatment through such an OI strategy.

Given the managerial and theoretical questions, we opted for an inductive case-study design (Eisenhardt, 1989; Eisenhardt and Graebner, 2007). Consistent with accepted models for inductive theorizing from management (Edmondson & McManus, 2007), the study used iterative process of data gathering, reflection and analysis. We collected and analyzed rich data in four phases. Our dataset includes 86 semi-structured interviews, as well as insights from a design-led stakeholder workshop, informal conversations, archival and secondary data.

The first step in our research was to understand the process of design and manufacturing of implants at Medimplant, and the role of internal stakeholders in this process. Because Australia was identified by Medimplant as a potential test market, one author interviewed six company executives in the operations, design, sales, logistics, regulatory and R&D functions in Australia. These interviews also gave an initial appreciation of how stakeholders external to Medimplant play a key role in the bone tumour implant ecosystem within the wider healthcare system.

We used this initial data gathering to map out Medimplant's existing value chain (Figure 1), and identify the relevant external stakeholders involved in the patient journey through diagnosis, treatment and rehabilitation. The first stakeholder — both theoretically and ethically — is the *patient* being treated, as well as the related concerns of friends or family members involved in the care decisions. Next comes healthcare employees — in this instance, professional in a specialist oncology hospital — involved in diagnosis and treatment: a *nurse* that specializes in treating sarcoma patients, a *radiologist* who performs diagnostic imaging to detect the tumour prior to removal, and the *surgeon* who both removes the tumour and implants the prosthetic replacement. After treatment, the nurse and physicians will evaluate the success of the treatment pathway and plan recovery stages, while *rehabilitation* specialists (such as an occupational therapist and physiotherapist) will work with the patient to restore as normal function as possible. Outside the health system are the government *regulators* as well as *insurance* reimbursement (whether private or government). Finally, the *manufacturer* itself has its own interests.

In the next round of interviews, we spoke to representatives of all the identified external stakeholder groups, both medical professionals in the hospital system as well as representatives of health insurance, government and regulatory bodies. In all, we conducted 29 semi-structured interviews in Australia with multiple stakeholders comprising the bone tumour implant ecosystem. We analysed these interviews to identify their value creation role in the ecosystem and in the journey of the sarcoma patient, their current experience and pain-points in delivering their role, and opportunities to enhance value creation. In parallel, we collected and analysed archival data from the Medimplant website and internal documents, but also from various industry reports on the global healthcare, additive manufacturing and orthopaedic oncology market. This gave us a detailed understanding of the scope of 3D printing in medical technologies, the relevant stakeholders and regulatory pathways that form part of this space.

During the third phase of data collection and analysis, researchers facilitated a workshop that adopted a design-led approach (cf. Brown and Katz, 2009; Liedtka and Ogilvie, 2011) to enable all interviewed stakeholders to fully validate and enrich our research findings regarding pain points of the current patient and stakeholder experience, and also the gain points and opportunities for value creation. To do so, we use the "patient and stakeholder journey map" model an accepted approach for research on improving healthcare outcomes; for surgery, such a journey includes diagnosis, pre-operative care, the actual surgery and recovery (Trebble et al, 2010; Ljungqvist et al, 2017).'Current' and 'future state' patient and stakeholder journey maps were created and used explicitly to stimulate reflection and discussions among participants in the workshop, which led to the development of the 'ideal state' patient and stakeholder journey map. Workshop participants (28 in total) included representatives from Medimplant (operations, design, sales, logistics, regulatory, R&D), hospital employees (surgeons, radiologists, rehabilitation, physiotherapy, occupational therapy, sarcoma nurses) and government/industry experts (prosthesis committees, reimbursement, cancer advocate groups and government health department). This approach was specifically adopted to help facilitate broad stakeholder engagement to comprehensively explore complexities and strategic considerations relating to implementing an efficient and effective healthcare value network corresponding to the 'ideal state' patient and stakeholder journey map. For Medimplant, this workshop started the strategy formulation process to achieve 3D printed patient-specific implants.

In the fourth phase, we conducted 39 interviews with relevant stakeholders in Europe and North America. Interviewees ranged from Medimplant representatives from multiple departments (Design, Regulatory, Marketing, Product development, Health economics, Operations, Logistics/Procurement and Customer Service) as well as external stakeholders across the bone tumour implant ecosystem (surgeons, nurses, rehabilitation therapists, radiologists and hospital administration). These allowed us to validate our models for the value chain and stakeholder network roles, and gain a deeper understanding of the value creation goals, motives and interactions of these diverse stakeholders across the value network.

In the final phase, more than a year after the first workshop, researchers ran a follow-up workshop with relevant stakeholders. During this time, building on the vision of 'ideal state' journey map developed during the previous workshop, Medimplant had evolved their strategy radically: the goal moved from developing a value network for 3D printed patient-specific implants to launching a full-fledged OI ecosystem in the form of an R&D hub. This Medimpant-led R&D hub would bring together a range of stakeholders focused on digital healthcare transformation including hospitals, industry (SMEs/Startups), government and universities, to collaboratively develop innovative treatment solutions that leverage 3D printing, robotics and other digital technologies also brought by the ecosystem stakeholders. The purpose of this workshop was to take stock of these strategic developments over the past months, and to facilitate the implementation of Medimplant's revised OI ecosystem strategy. We also had 4 follow-up interviews and several informal discussions with workshop participants from Medimplant (and those already interviewed in Phase 1) about the cognitive shift in OI strategy along the way. Overall, our research process allowed us to develop a framework of the transformation of linear, vertically-integrated supply chain into an OI ecosystem model of co-created value.

Orchestrating Stakeholder Cooperation in Ecosystem Transformation

During the first phase of the fieldwork, we confirmed that the potential benefits of adopting the new technology broadly fell into three categories of increased value:

- Quality: providing a better patient outcome; (Table 1)
- Speed: reducing the time required to deliver the treatment, or for the post-operative recovery to return to normal function after surgery; (Table 2)
- Cost: improvements in economic efficiency by speeding up the surgical and manufacturing process, reducing labour or material waste. (Table 3)

We then used the interviews to identify each stakeholder's perspective on several key questions. Under the existing treatment, we asked what role they play in treatment, how do they interact with other stakeholders, and what do they perceive as deficiencies ("pain points") with the existing approach. Regarding the proposed new treatment approach, we asked how their role and interactions would change, as well as what benefits (among the three categories) they thought would be realized from this new approach.

First, we structure and present our findings on the interactions among stakeholders along the stages of the "patient and stakeholder journey" model: diagnosis, pre-operative care, the actual surgery and recovery (Trebble et al, 2010; Ljungqvist et al, 2017). Here we start by presenting the existing linear value chain – in particular, the value creating roles and unmet needs among relevant stakeholders for each stage of the patient journey, that motivated Medimplant's efforts to deliver 3D printed patient-specific implants. Then we present how Medimplant's collaborative strategy formulation process enabled the co-design of Medimplants' value network strategy, with intended changes in stakeholder roles, responsibilities and outcomes for each stage of the patient journey. We particularly show how the use of an explicit shared artefact during this stage Following this, we show how this process led Medimplant to pivot its strategy to a multi-stakeholder, collaborative R&D hub, and discuss the process driving the implementation of this OI ecosystem model of co-created value.

1. Medimplant's Linear Value Chain and related stakeholder challenges

Diagnosis. As evident from Figure 1, Medimplant's value chain is vertically integrated. Medimplant's linear value creation logic translates into several pain-points in the sarcoma patient journey. The process starts with the patients presenting themselves to the specialist clinic with potential tumour identified in X-ray. The sarcoma nurse who is usually one of the first clinical staff to meet the patient and whose role it is to enter patients into the system and organise imaging, also sees that these patients and their families are often anxious due to lack of clarity on the treatment pathway, costs and process of sarcoma treatment. One sarcoma nurse elaborated:

> *"So you're very sensitive to where the patients are at, they're always very anxious, stressed [...] they do become more panicked and more concerned and waiting a week for a scan or a biopsy can sometimes just be harrowing".*

However, dealing with their anxiety imposes additional burden on the nursing staff that dedicate extra time that is not accounted for in their resourcing levels, often causing delays in diagnosis.

Patient diagnosis is sensitive and it could take up to three weeks, before a specialist can be seen and an initial treatment plan charted. This is exacerbated by the current imaging process which includes multiple radiology scans and consumes a lot of time and resources at the radiologists' end as it is "*a reasonably intensive process".* The resulting extra scanning can expose patients to increased levels of radiation and time, adding to their anxiety. Furthermore, limitations in image analysis technologies and radiology resources affect the accuracy of diagnosis, and also the surgeon's capacity to perform timely surgery.

Hospital Post-operative pathway. During this phase, the surgeon undertakes surgical planning to plan treatment. The limited treatment options and protocols pose challenges for surgeons in treating patients. For example, lack of consistent protocols for sarcoma patients means each surgeon may treat cases differently.

While every case is different, due to Medimplant's limitation of not being able to customise implants efficiently and to meet the patient need, prostheses may not replace the patient's native anatomy. Such complications prolong surgical intervention, delay patient rehabilitation and hamper patient outcomes. Moreover, the ability of Medimplant to fulfil the need of the surgeon and patient is limited by current radiology and imaging capabilities which are not sufficiently advanced. Thus, technology-related challenges currently limit patient treatment and outcome options. Besides the sub-optimal performance of off-the-shelf implants, sometimes the regulatory or reimbursement roadblocks makes it all too hard to design/manufacture implant, so surgeon decides to remove whole joint or femur.

Another significant challenge prior to surgery and delaying patient treatment is communication between Medimplant and the surgeon when ordering the implant for a surgery. Mulitiple forms, emails and design sessions are often coordinated and guided by Medimplant with ultimate sign-off required by the surgeon, typically taking *"maybe 6-8-10 weeks maybe more for complex cases"* before the order is sent to the hospital, and the surgeon can implant. One surgeon explained his frustrations with the process:

> *"One of my problems is that I am extremely time poor. I want to offer my patient the best possible solution, but I know that is I want a custom product at the moment, I have to drive that process and take ultimate responsibility. I have to book it in, follow the paper trail…..so the problem you can solve me is to help me speed up this process"*

As a result of these technical, manufacturing and regulatory constraints, the "best" option is often not available to surgeons to deliver to patients. At the same time, patients see surgical options available elsewhere and desire same outcome, mounting pressure on surgeons to deliver on patients' expectation.

Medimplant's traditional value chain designed to manufacture and deliver off-the-shelf implants poses issues for not only surgeons and patients, but also the Medimplant itself. Tumour margins differ between surgeons, and inconsistencies in facts of tumour growth mean that implants often go a waste if the tumour has changed. Implants left on the shelf also become obsolete and expire, adding to costs.

Manufacturing and delivering patient-specific (instead of off-the-shelf) tumour implants can help overcome these issues. However, this comes with its own challenges. The ordering system for custom implants is not yet optimised and hence takes a long time, as one surgeon relates:

> *"If someone comes with a grade 6 [...] you don't want to wait 6 weeks before going in and operating on them. [...] Maybe, a couple of weeks you could wait, but I certainly wouldn't want to wait 6 weeks."*

Moreover, the one-off nature of custom design means costs are higher. Thus, supporters of the new approach face a challenge making a case to regulatory bodies and health insurance companies to approve custom implant manufacturing.

Surgery. During this stage, the patient presents for surgery, and the surgical team and instruments are coordinated. Here, the surgeon faces challenges that compromise patient outcome and recovery. The lack of consistent treatment protocols means that surgeons may handle cases quite differently. In non-bone preserving surgery, the surgeon may cut more bone and tissue than required, as this interviewee explained:

> *"At the moment we cut to the size that is available on the table. So if they've got three sizes available, what I'll do is I'll make my cut and then I'll say, "Right, I need size A and a size A is too small." So I turn to size B, size B might fit perfectly or it might be that I'll need size C. And C means after I've cut out the tumour I need to cut a little bit more. So that's how it works currently."*

The surgeon is also often not sure what will be found in surgery, and a tumour change or differing bone quality could mean that the implant ordered may not fit, and the patient treatment time is lengthened. Invasive and unnecessary cutting and prolonged surgical procedure, resulting in additional cost, time, resourcing for both the hospital and Medimplant. Hospital resource constraints such as limited amount of theatre time each week for patients has a negative impact on patient treatment time:

> *"At the moment there is not an alternative really. And so, we're doing our best as surgeons to get margins. But, you'd be telling lies to say that you think that you've always got the best margin possible for a patient. I think probably what we're doing now is very wide margins so that there's not a possibility of you actually entering the tumour. Whereas with this technology we can perhaps then do lesser margins because we know that it's still going to be a safe margin."*

Post-operative Care. The focus during this phase is on sarcoma nurses administering radiotherapy and chemotherapy based on pathology results, as well as on rehabilitation professionals taking care of patients' pain management, exercise regime and recuperation directly after surgery:

> *"At that point in time… they're usually in braces, they're usually very restricted in what they can do, they're usually, often not ambulating on that leg, they've obviously got wheelchairs […]. So, it's really just to make sure they're safe and doing, probably a very small group of exercises. So, once they go back and see the surgeon, usually more closely to the three-month mark, they then are usually allowed to start taking off their immobiliser braces and start to, actually start putting weight down, or at least doing more from a rehab point of view. At that time, they need much more intervention."*

The nature of traditional surgery calls for significant amount of post-operative care due to risk of infection and slow healing as a result of chemotherapy and the extent of surgical intervention. Major surgeries can keep patients in hospital for 2-3 months, with an additional 2 months of rehabilitation at home, which may increase stress, anxiety or other adverse psychological effects. Professionals in this post-operative care phases are well aware of how time can affect a patient's recovery journey, as one rehabilitation specialist illustrates:

> "*we know the longer the length of time, the longer the anaesthetic, all of those things, and I know getting them out of bed for the first time, with blood loss, everything, I can only imagine that if all of those things were improved, particularly surgery time, less surgical sort of cutting and all that sort of stuff, it must have a positive impact on length of stay."*

The post-operative and rehabilitation phases are the longest in the patient journey pathway, often a patient may stay in the continuum of care path for up to 8 years.

2. Medimplant's shift to Value Network Strategy

These shortcomings in the existing value chain motivated Medimplant to shift toward the delivery of JIT patient-specific 3D printed tumour implants. Yet, despite the fact that multiple stakeholders are affected by the linear value chain structure in the industry, Medimplant's initial conception of how to create value was largely related to overcoming technology-related challenges, as a key industry engineer highlights:

> *"we are picking along the technology side……the handful of materials that you see largely used in additive right now are fairly standard … obviously we will always want better materials and better performance from the material. so the design piece is very interesting …, that we're always keeping abreast of the newest, up and coming great ideas that are coming out, so who has the best capability for producing, more complex, faster, you know whatever it may be, so those are interesting."*

Surgeons too seemed to have a similar outlook on technology being the manufacturer's sole domain of focus:

> *"The manufacturer's expertise is to manufacture, hospitals expertise is to care for sick patients and I think hospitals should not venture into manufacturing. It should leave it totally up to the manufacturers. And the manufacturers carry technology and the license to do that. And they have it because it's their job to do it, just like it's our job to carry the license to treat."*

Accordingly, Medimplant's initial approach to its strategic shift was largely inward-looking and technology-focused – looking at how to achieve JIT implants through additive manufacturing. Driven by such a technology-centric network logic, the components of the transformation project were focussed on specific technical areas, and fragmented sections of the process (for example: innovation on lattice structure, improvement in imaging, economic costing etc.). Another project partner highlighted the siloed conceptions of value creation by the collaborators within their boundaries of expertise:

> *"The additive researchers are working the advanced manufacturing precinct so everyone is on their own little piece of land.....their new manufacturing method...industry is very interested in this but from the surgeon perspective, what he sees is actually the use of the robot because it's what helps him to do the surgery."*

A Medimplant representative points to the need to reconcile such tensions across stakeholders, highlighting the value in working collaboratively:

> *'I think sometimes the surgeons don't appreciate the value that the engineers bring to bear because they have a lot of experience. We have some people on our team with 30 years' experience…so they have done literally thousands of these types of implants and they have worked with the surgeons and they have met the patients and they have seen how things work well and sometimes unfortunately that things don't work well. So there is a lot of value added from the engineer side. That being said we can't do without the surgeons because we don't know the patient care portion of it and we don't really know the biology and the archeologic concerns that they would have so I think it's one of those situations where together we can definitely do more than either one can do separately'*

As a first step in developing the strategy to achieve JIT 3D printed patient-specific implants, Medimplant therefore engaged in an environmental scanning exercise via action research implemented by the project's business school partner so as to gain a full stakeholder perspective. This 'stakeholder scanning' process helped identify all external stakeholders, and unpack the current and potential future patient and stakeholder journey.

Besides the varying conceptions on value creation across different stakeholder groups highlighted earlier, insights also revealed that there was cognitive inertia and resistance to change, and questions around whether JIT was necessary or could be achieved and how buy-in could be achieved across the stakeholders to move forward. One Medimplant engineer commented:

> *"I'm not totally clear on why we're all going down this journey, right, of discovering this and it was never about an economic benefit in 3 to 4 years[..] I don't think you're going to have an answer in 4 years"*

A surgeon challenged the need for JIT manufacturing:

> *"An osteo-sarcoma patient received chemotherapy, 3 to 4 cycles, that's months alright. So just in time manufacturing is possibly not needed… because you could build your custom implant and you've got plenty of time to do that. And so the just in time, you're really only going to use if you need to take the patient to theatre within a couple of weeks,.. and those numbers are small [..]I'm not sure you would be doing enough of it to make it viable."*

A radiologist was also skeptical about the need for JIT implants:

> *"There's only a need to change something if there's a problem, so the question I would ask then is what are the problems with what patients are getting currently in terms of modular prothesis or custom made prothesis. Because we need to identify if there are issues […] because if the patients are doing well then why do anything differently which includes increased dose of radiation for scanning."*

Thus, this stakeholder scanning exercise not only assisted Medimplant in assimilating information on stakeholder roles and relationships, but also triggered an internal sense-making process, that highlighted the need to overcome cognitive inertia and develop a common conception of the network model of value co-creation. To do so, Medimplant ran a collaborative stakeholder workshop through the business school researchers who developed a holistic representation of the problem space via artefacts (stakeholder map, current state journey map and future state journey map), that each stakeholder interacted with hands-on. This process helped participants understand the holistic stakeholder and patient journey, and collectively make sense of the broader stakeholder ecosystem surrounding this journey.

As part of the collective sense-making process, participants worked in inter-disciplinary stakeholder groups to validate the current patient journey, as well as co-design the future patient journey, to address stakeholder pain-points. Participants also ascertained the need for JIT bone tumor implants and how this would impact the different elements of the patient journey. This process led to the co-development of the ideal state patient-centric value network. At the same time, the use of explicit shared artefacts also led to a wider discovery process among Medimplant representatives enabling a shift in cognitive frame from technology-centric to stakeholder-centric. We discuss these in the following two sections.

3. Medimplant's Value Network and related stakeholder roles and interactions

As a first outcome of the workshop, the co-designed patient-centric value network represented a new bi-directional, network model of co-created value (Figure 2). It incorporated changes in roles and interactions among all key stakeholders, leading to improvements across all value drivers: *quality, cost* and *time* of treatment, as described below.

Diagnosis. Following the patient-centered workshop, surgeons took initiative to codify their knowledge and experience in order to develop interactive educational app/tool illustrating steps of the patient journey to develop informed guidelines based on real patient cases. This is designed to ultimately help patients and their families feel in control of their journeys. Moreover, the re-conception of the role of the oncology nurse as a 'sarcoma coach' "*being able to control [patient] anxiety; streamline the right investigation, and then making sure that the right person is available to give them the results"* brings a personal touch and is reassuring for patients. These evolved stakeholder roles at the diagnosis stage help improve the *quality* of patient outcomes.

Furthermore, custom implant treatment is proven to be cost-effective in the long term. This provides good evidence for health insurance reimbursement, giving further reassurance and peace of mind to patients. Besides easing financial burden of patients, over time, this can indeed also reduce *costs* of treatment across hospital and healthcare ecosystem.

In parallel, other stakeholder initiatives contribute to reducing the *time* for patient treatment. From the perspective of the radiologist, the sophisticated guided biopsy develops "all in-one" imaging/biopsy, all in one day, reducing the number of steps involved in imaging and diagnosis. The increased level of imaging accuracy and speed to detect tumour type, enabled by this advanced technology, makes the process more efficient and shortens lead-time. This in turn helps surgeons deliver their role more effectively, ultimately improving patient outcomes. In this phase, technology advancements also enable surgeons to receive communication on radiology scans and image analysis via cloud. This not only speeds up the diagnosis process, aiding surgeons in their role, but also benefits the hospital by capturing data for continuous improvement.

Hospital Pre-operative Pathway. Current technological, logistical and regulatory challenges reduce ability to move to real JIT processes. Furthermore, implementing localised manufacturing also calls for a cognitive shift in Medimplant. These manufacturer-level barriers translate into pain-points for surgeons in delivering their role. To overcome these challenges, stakeholders deployed a variety of actions.

By applying an imaging protocol for bone tumour cases surgeons can consistently rely on multi-modal data for detailed pre-surgical planning. Virtual pre-surgical planning enables the surgeon to get familiar with the patient's specific anatomy prior to the case and can speed up the surgical intervention. Surgeon use 3D model to determine margins with consideration of soft tissue, to speed up process and ensure accuracy for patient. 3D reconstruction of the tumour from CT and MRI files allow for auto-segmentation and visualisation of tumour relative to planned osteotomies. A surgeon elaborated on the importance of surgical planning:

> *"The tumour type is important, whether they're going to have chemotherapy or not and then whether it's receptible. So, can you perform limb salvage surgery? And if it's in the pelvis or other areas, like spine as well – Then, can I do a biological reconstruction? Can I use fibular grafting? Is there some way I can avoid using an implant? And then if that's no to all those questions, then what implant am I going to use? Does it need to be a custom-made implant?"*

Virtual planning design techniques improve information management and communication allowing better liaison between surgeons and implant engineers at Medimplant to speed up process of designing an implant that adheres to margins.

The use of auto-planning helps improve preplanning, precision cutting and tumour excise to preserve bone. Speed and accuracy are improved, and the whole patient-implant journey is reduced by two weeks, while quality is improved. By leveraging Medimplant's utilisation of HoloLens the operative plan for the case, including the tumour location and robotic kinematics can be visualized in augmented reality prior to the surgery. For Medimplant, this means a faster post-processing pathway, with JIT manufacturing reducing lead-time for delivery of custom implant.

It is evident that the evolved roles and associated actions of stakeholders result in enhanced *quality* of patient outcomes as well as reduced *time* for treatment. At the same time, adoption of these improvements also has *cost* implications. For Medimplant, localised manufacturing leads to less storage of implants, leading to reduction of inventory and waste of off-the-shelf prosthesis, saving money. For patients, robotic surgery and 3D printed implants provide complementary clinical options, that although may cost more in short-term, offer significant long-term benefit.

Surgery. Adoption of technologies such as robotic excision and 3D printing make surgeons' roles easier to navigate and outcomes more effective. Robotic surgery improves the accuracy of cut compared to manual excision. Moreover, 3D printed implants can deliver complex solutions that subtractive manufacturing cannot in terms of improved functional outcomes and reduction in likelihood of mechanical based failure. The improved precision and repeatability of excision improves the likelihood of the custom prosthesis fitting where intended. One surgeon remarked:

> *"[Robotic surgery and 3D printing] would just make us able to do things that we were not able to do before, with a level of precision and confidence that we're doing the right thing, with the best possible outcome, that we never had before. So, it will make us very, very happy surgeons undoubtedly…. completely ground-breaking because a lot of people think about new way of reconstruction but if you put together your engineering teams that really work on how that will have to work in that specific part of the body, how to fix that to the bone as well …and then really .. you can think about the biology side of things as well but once you have the mechanical in there"*

In all, preventing invasive and unnecessary cutting, improves overall *quality* of patient outcome, and opens up scope for treatment options. One surgeon related:

> *"Life is priority – but then the second priority is reconstruction and function of the patient. So, the more precise we can be, maintaining that safety, the better it is."*

There is also reduction in *time* of treatment for patient and surgeon, due to improved speed and accuracy of surgical procedure, and better turnaround times. Also, JIT manufacturing means that lead time for delivery of custom implant is significantly reduced.

Custom implants also provide opportunity for *cost* reduction for patients in the long term, with less chance of need for revision surgery. Significantly fewer instruments are required due to the use of robotic technology. The precision and accuracy of robotic surgery also reduces the need for cosmetic surgery.

In all, the use of robotic capability and additive manufacturing increases confidence in meeting the complex requirement of sarcoma surgery, as this quote illustrates:

> *"With sarcoma principles means that we need to do an operation that decreases the chance of that tumour coming back as much as possible. To do that, we remove them with what we call wide margins. So, what wide margins means is we – we have the bone, just think about the femur, we have the tumour in there, we need to remove that being at least 2 to 3 centimetres away from the tumour in all planes."*

It also extends treatment options for patients. For Medimplant, this provides significant market edge and expands the markets for its technologies to other potential surgeries.

Post-operative Care. In many ways, this stage can be viewed as the "beginning of the patient journey" (not the end) when the patient can be actively involved, rather than being passive during earlier stages, which can then have an "*active impact on their recovery and future life."* The utilisation of a more accurate fitting of the prosthesis allows for immediate weight bearing and functional mobility in patients. The surgeon's skill and Medimplant's technology ensure that exact leg length is achieved, so patient functionality returns quicker due to anatomical matching and the need for brace is reduced. The increased longevity of prosthesis also decreases the need for ongoing revision, which reduces the risk of infection. Patients play a more active and earlier role in rehabilitation, which ensures both mental and physical recovery and that long-term patient outcomes are improved, as evidenced in this quote:

> *"We know the longer the length of time, the longer the anaesthetic, all of those things, and I know getting them out of bed for the first time, with blood loss, everything, I can only imagine that if all of those things were improved, particularly surgery time, less surgical cutting and all that sort of stuff, it must have a positive impact on length of stay, as an inpatient, getting up, and I mean, I know it takes [the physiotherapist] probably three physios to get somebody up and get going.."*

This approach also helps in treating and managing sarcoma patients in rural and remote areas, who have more difficulty reaching specialists for revision and rehabilitation management.

While these improves the *quality* of patient outcomes, customised treatment also reduces the recovery *time* as it allows a patient to more quickly return to normal function. Preserving the patient's current functionality as close as possible helps minimise length of stay of patients in hospital. Pain management is reduced and patients can commence their rehabilitation exercise regime quicker.

At the same time, firms and healthcare providers need to provide more direct proof of these benefits to validate their hypotheses. Such evidence will help build the case for health insurance reimbursement and regulatory approval, making *cost* of treatments more viable and affordable. There is limited consideration for 3D printed implants and robotic surgery in current reimbursement pathways.

4. Medimplant's pivot towards an Open Innovation Ecosystem Strategy

Besides achieving the *structural co-design* of Medimplant's new value network described above, the stakeholder journey mapping workshop also led to a *cognitive reframing* towards a stakeholder-centric network logic. One Medimplant representative commented:

> *"The workshop helped us realise that we couldn't just focus on one part of the solution….that is not enough……we need to be holistic in our approach"*

The development and use of the Patient and Stakeholder Journey Map as an explicit shared cognitive artefact were critical to not only aid communication of data insights and system process flows, but also to achieve collective sense-making among diverse stakeholders about the central role of patients in value creation. It helped Medimplant representatives conceive the whole ecosystem and not just the technological aspects. This was the key to build collaboration and consensus among stakeholders about the direction and possible strategic initiatives to consider in evolving to an OI ecosystem. For example, the map was presented at conferences by leading oncology surgeons to articulate the wider value of patients.

Ultimately this artefact was adopted by Medimplant as a 'navigator' and guide for their strategy process going forward. The map is displayed in the Medimplant co-located BioFabrication facility in a leading hospital, and is used by the Medimplant project manager to showcase who is involved and how each part of the patient journey interacts with stakeholders and the wider ecosystem. The project manager stated:

> *"The journey map has been valuable to communicate the project from many different view-points".*

This artefact has been presented to key Medimplant divisions to show a broader continuum of care journey, how workflows can be designed with the patient in mind, and to identify key value propositions across the continuum of care. Health economics representatives of Medimplant applied the journey map to other projects they were working on and implant design engineers overlapped the journey map on the design process to better improve communication with surgeons. An implant designer mentioned:

> *"Nobody has shown the flow of the patient in such detail, this will really help us map the communication paths for other parts of the customer request system".*

Most crucially, the artefact was instrumental in generating an important pivot towards an OI ecosystem strategy – it was used to create the foundations of an R&D + Additive Manufacturing (AM) Hub. The Hub aims to create an ecosystem which brings together a range of partners including hospitals, industry (SMEs/Startups), government and universities around digital healthcare transformation, on a larger scale than originally conceived (Figure 3). The cognitive artefact was the trigger for the R&D Hub, and related ideas were brainstormed during the workshop. Medimplant's R&D Director reflected on how the artefact facilitated cognitive reframing towards a stakeholder-centric logic:

> "*The initial idea was part of a broader benefit that we hadn't really thought of…..bringing clinicians in to discuss this helped us to realise the whole potential……understanding the clinical problem and what matters to surgeons"*

In the months following the workshop, Medimplant's Research Director engaged with senior management, and the idea was championed internally. Through a series of meetings and presentations, Medimplant's sought internal buy in to develop an R&D + AM Hub. Over a period of six months, aspects covering all factors from funding, partner development, research focus areas were discussed with the R&D Council and additive manufacturing centre. The Medimplant internal stakeholders challenged the Research Director to create a Hub that has a clear open innovation-centered value proposition:

> *"What we need is a Hub that differentiates from the other innovation centres, how can the Hub bring together cross-divisional research with external stakeholders"*

Eventually, the firm decided to shift its strategy from its original network model of ecosystem conception to the R&D Hub - a newer, more radically different approach to value creation. Over the next few months, Medimplant (facilitated by the Research Director/champion of the project) began to broaden its stakeholder reach to present the case for the Hub to government, industry and health departments as well as key universities. This required a different level of engagement with a different group of stakeholders at different parts of the journey. In some instance, Medimplant engaged and presented to a larger group as well as presenting to key policy makers.

To formulate a clear strategy around the new ecosystem model, Medimplant ran a two-day business modelling workshop for its leadership team and several government representatives, in consultation with the project's business school partner. The purpose of the workshop was to collaboratively ideate the concept, structure and business model for the R&D Hub. The strategic focus here is to create an ecosystem to collaboratively develop treatment solutions that leverage 3D printing, robotics and other digital technologies which cannot otherwise be developed internally. By partnering with eternal stakeholders and leveraging cross-divisional technologies and skills, the R&D Hub thus aims to enable the development and commercialisation of complex solutions to problems impacting the future of healthcare (Figure 3).

The workshop helped develop a vision, operational model and interim business model for the Hub. Whilst the original strategy was to develop a technology-centric network, the Hub is intended to be a more fluid OI ecosystem, with less control by Medimplant, and based on key research areas driven by the expertise and capabilities of multiple stakeholders. Ultimately, the Hub will not only address current Medimplant business challenges but create a space for co-creating radical innovation by leveraging complementary capabilities of the stakeholders.

In this way, Medimplant saw a strategic transformation of its linear conception of value creation to a new bi-directional, ecosystem model of co-created value. This transformation was enabled by the use of explicit shared cognitive artefacts at the stakeholder mapping workshop, driving the firm's cognitive reframing from a technology-centric to stakeholder-centric logic, which led to a wider cognitive discovery process among Medimplant representatives:

> *"It was a broader service spectrum to think about and not just the technical solution….the workshop helped us reorder our priorities and thinking for the whole patient journey….definitely changed the pathway…and where to from here….".*

Discussion

This paper has examined how a company can use externally sourced technology and business research partners to transform its linear value chain into a more interactive and collaborative value network. It does so by examining how Medimplant is seeking to develop patient-specific prosthetic implants produced JIT for bone cancer patients within the context of the existing healthcare system. Although this transformation is still in progress, we believe it provides insights into how such ecosystem transformations can be managed, both in healthcare and for innovative products more generally.

The customized prosthetic implant process we study are an example of what has previously been termed mass customization, i.e. creating efficient, scalable processes for customizing products previously available only via mass production. Such an approach inherently involves the customer in the creation of value (Piller et al, 2010; Randhawa et al., 2018); in this application, the customer is as much the healthcare professional (particularly the radiologist and surgeon) as the end-user (patient). At the same time, firms using co-creation as part of their OI strategies must develop new processes (and often new job descriptions) to manage these interactions with and between external stakeholders (Piller & West, 2014).

This co-creation process is a particularly visible part of the change in roles and interactions necessary to implement the proposed value network approach to delivering customized implants, and the processes required to deliver value under the new ecosystem approach (Figure 2). This evolved value network model also entails much more cooperation between the manufacturer and the external healthcare professionals in the way the customized implant design is specified, communicated, evaluated and approved, during the period between diagnosis and (post-)surgery (Figure 4).

Furthermore, while there are clear processes for evolving ecosystems controlled by a single organization (e.g., Gawer, 2014), the path forward is slower and more difficult to manage when the change requires multiple independent actors without common ownership (Simcoe, 2012). This challenge is particularly complex if change can only happen if multiple parties are simultaneously willing to make the change (Maula et al, 2006). Such change is even more complex in regulated safety-critical industries such as aviation or healthcare. At the same time, incumbent firms must successfully manage such transitions, or find their existing products and business model displaced by rivals or new entrants who are better able to do so.

This study demonstrates the challenges for such an ecosystem evolution, which in OI has been primarily studied in cases with a strong central authority such as a platform sponsor (Maula et al, 2006; West & Wood, 2013). In many of these cases, smaller ecosystem members (such as independent software vendors) have little or no choice but to accede to the vision of the ecosystem sponsor. However, a vendor promoting adoption of a radical innovation into an existing value network (such as a healthcare system) is in a weaker position of control and authority. This study provides a model for identifying and integrating the potentially conflicting perspectives of a wide range of stakeholders, as well as how to use these constraints to create a new structure of the value network.

Our findings lead us to develop a framework of the transformation of linear, vertically-integrated supply chain into an OI ecosystem model of co-created value (Figure 5). The framework reveals how firms can shift their conception of value creation when a potential ecosystem has multiple categories of stakeholders with multiple possible configurations. The ecosystem transformation process begins with the firm’s existing value creation logic, a crucial subset of the firm's conception of its business model and ecosystem strategies. The move from a linear to network value creation logic is well-served by active, deliberate stakeholder scanning followed by internal sense-making, a form of reflective action – to gather and analyse the varying and/or competing stakeholder goals and motives, and related cognitive inertia and barriers to adoption.

At the same time, the transformation of its linear conception of value creation to a new bi-directional, ecosystem model of co-created value also calls for cognitive reframing from a technology-centric to stakeholder-centric logic. A firm’s existing cognitive framing shapes both the information available to manager and how that information is used, by retaining relevant data and filtering out data deemed irrelevant (Bettis & Prahalad, 1995). However, breaking those cognitive frames is often essential to discover and pursue new approaches to value creation – particularly when such new approaches require coordination with partners outside the firm (Prahlad, 2004). This cognitive shift required for pivoting to an OI ecosystem is enabled through the use of explicit shared cognitive artefacts that induce collective sense-making and value-creation ideation, social activities that trigger the reciprocal interaction of information seeking, meaning ascription, and action (Weick, 1995; Thomas, Clark, & Gioia, 1993). This allows stakeholders to collectively make sense of the value-creating opportunities in the broader ecosystem.

Our study thus also contributes to the very limited research on the effect of managerial and organizational cognition in OI, particularly for adoption of OI and creating an OI ecosystem. While cognitive artefacts can play an important role in negotiating creation of a new bilateral OI collaboration (Christensen, 2006), here we show how crucial it is in managing the orchestration of a new OI network of value-creating business relationships. At the same time, it points to how ecosystem strategies have multiple possible configurations, and thus a premature cognitive reframing will limit the ability of the firm to identify and implement the most viable strategy. Our findings are in line with previous research that show that firms in stable industries with similar cognitive maps are less likely to adopt openness (Alexy et al, 2018). Such stable industries are particularly vulnerable to technological change that renders obsolete previous competencies and business models (Tripsas & Gavetti, 2000), and particularly need cognitive reframing to stimulate the forward-looking processes necessary for strategic transformation (Gavetti & Levinthal, 2000; Narayanan et al., 2011). Additionally, our findings also show that external consultants can help firms break existing frames — particularly if the external advice is treated as relevant and credible (Davidson, 2002).

Finally, this study examines the role of non-economic motives in open innovation, which have only recently been considered (Chesbrough & Di Minin, 2014; Randhawa et al, 2019). In this and many other cases, adoption of a technological, organizational or social innovation is aided by a shared sense of social purpose — in this case, improved outcomes for bone cancer patients. While such motives have been documented in solving a specific major problem such as sending a human to the moon, the challenges of harnessing such motives is more difficult for permanent ongoing efforts such as improving public health or environmental protection (Mowery et al, 2010). Thus, convincing stakeholders to "opt in" to change is an ongoing challenge.

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Tables and Figures

Table 1: Potential quality benefits of innovation adoption

Stage	Stakeholder	Other Stakeholders involved	Motive for evolution	Potential Benefits
Diagnosis	Surgeon	Patient	Unknown pathway & process causing patient & family anxiety	Develop interactive educational app/tool illustrating steps of the patient journey; informed guidelines based on real cases
	Nurse	Patient		Nurse acts as 'sarcoma coach'; Personal touch of nurse is reassuring.
Pre-operative	Surgeon	Nurse, Patient	Leg length change can prolong surgical intervention, delay patient rehabilitation and hamper patient outcomes	Exact leg length achieved. Reductions in surgery time, anaesthesia and blood loss.
		Radiologist, Nurse, Patient	Tumours can be hidden (skip lesions)	Increasing level of imaging accuracy/speed to detect tumour type, enhances current process and shortens lead time.
		Radiologist, Manufacturer, Nurse, Patient	Tumour margins differ between surgeons	Autoplanning = precision cutting, tumour excise to preserve bone Automated margin calculation, excision geometry and surgical cutting path Auto-segmentation and visualisation of tumour relative to planned osteotomies 3D reconstruction of the tumour from CT and MRI files
Surgery	Surgeon	Patient, Manufacturer	Lack of consistent treatment protocols	Joint sparing chances increased. Bone implant interface is maximised and allows design of soft tissue interface. Robotic excision to assist surgeon and improve accuracy of cut. 3DP can deliver solutions that subtractive manufacturing cannot Speed and accuracy. Improved patient functional outcomes and reduction in likelihood of mechanical based failure Improved precision and repeatability of excision, improving the likelihood of the custom prosthesis fitting where intended
		Patient, Manufacturer,	Can be non-bone preserving surgery – may cut more bone and tissue than required	
		Patient, Manufacturer	Sometimes all too hard to design/manufacture custom, so surgeon will treat differently depending on the case	
		Manufacturer	20th century surgeons 'sticking to the way they have always done things'; Limiting treatment options and innovation in surgery and implant design	
		Manufacturer	Curettage all of benign hard to monitor	Opportunity to scale i.e. benign tumour curettage, complex revision.
		Health insurance, Regulatory bodies	MAKO platform under-governed and underutilised, needs to be open platform	Improved software + robotic + AM capability = confidence in precision surgery and extends treatment options.

Stage	Stakeholder	Other Stakeholders involved	Motive for evolution	Potential Benefits
Post-operative	Surgeon	Health insurance, Regulatory bodies	Limited consideration for 3DP implants and robotic surgery in reimbursement pathways	Need for evidence based data
	Nurse	Patient, Surgeon; Rehab	Significant amount of post-op care and rehab, Exercise regime and pain management	Utilisation of a more accurate fitting of the prosthesis allows for immediate weight bearing and functional mobility. Preserving patient current functionality as close as possible = minimise LOS, reduces need for cosmetic surgery, psychiatric treatment, pain management and OT visits. Patient commences rehab exercise quicker and has more active role in post-operative care. Need for brace is reduced Increase longevity of prosthesis and decrease need for ongoing revision. Reduces risk of infection.
			Psychological battles	More active and earlier role in rehab ensures both mental and physical recovery and long term patient outcomes is improved. The ‘beginning of the patient journey’ (not the end) - patient can be actively involved in this stage rather than passive at diagnosis.

Table 2: Potential time benefits of innovation adoption

Stage	Stakeholder	Other Stakeholders involved	Motive for evolution	Potential Benefits
Diagnosis	Nurse	Radiology, Surgeon	Long diagnosis time; Delay in initial treatment plan	Image co-registration and radiology scans, image analysis Increasing level of imaging accuracy/ speed to detect tumour type, enhances current process and shortens lead time. Sophisticated guided biopsy (‘all-in-one’ imaging/biopsy) Cloud-based communication on radiology scans and image analysis Speed up diagnosis and capture data for continuous improvement.
	Radiologist	Nurse, Surgeon	Limitations in image analysis technologies affect accuracy and timeliness of diagnosis and surgery	
			Imaging process currently consumes lots of time and resources	

Stage	Stakeholder	Other Stakeholders involved	Motive for evolution	Potential Benefits
Pre-Operative	Surgeon	Manufacturer	Hard to locate off-the-shelf and design iteration takes time, how can this be streamlined?	Speed up implant design and manufacture = 1 week Improve auto-implant design - increasing level of accuracy and speed to detect hidden tumours and changes Surgeon determines margins based on 3D model, with consideration of soft tissue, to speed up process and ensure accuracy for patient Virtual planning enables surgeon to speed up surgery and implant design – improves information management and communication Medimplant's utilisation of HoloLens: Visualisation of tumour prior to surgery and robotic kinematics with augmented reality Build upon current Medimplant Performance Solutions Reduces questions on the day of surgery
		Hospital	Surgery timetables are planned in advance and difficult to change (when awaiting implant)	
		Manufacturer	Long process to order custom and not synchronised with information management systems	
		Manufacturer	New process every time or envelope of templates	
		Manufacturer	Delays and inaccuracies in margin determination and implant design	
	Manufacturer	Radiologist, Surgeon	Manufacturing in advance is limited by current imaging	
		Hospital	Lose control of lead time by using external vendors	
		Hospital, Surgeon	Current limitations in technology and materials reduce ability to move to 'real' JIT	Identify and speed up post processing pathway. JIT manufacturing reduces lead time for delivery of custom implant
Post-Operative	Nurse	Surgeon, Rehab	Significant amount of post-op care Chemotherapy can slow down the healing process.	Functionality returns quicker due to anatomical matching, thus less psychiatric and OT treatment required. Length of stay reduced, reduced risk of infection, increase longevity of prosthesis
			Sarcoma management training lacking for outreach services in rural and remote area - can delay rehab and mismanagement.	Tele-health applications will help manage remote clients Significant for remote patients and healthcare providers who are not familiar with treating or managing sarcoma patients
			Limited regulatory leadership and decision making impedes lead time	Involve insurance and regulatory stakeholders early in the process
			Locating/negotiating accurate prosthesis code is time consuming	
			Reimbursement paperwork and cost is slowing down implant design and manufacture	

Table 3: Potential cost benefits of innovation adoption

Stage	Stakeholder	Other Stakeholders involved	Motive for evolution	Potential Benefits
Diagnosis	Nurse	Surgeon; Manufacturer; Hospital; Health insurance	Unknown pathway, costs & process causing patient & family anxiety	If treatment can be cheaper or proven to be cost-effective in long term = good evidence for health insurance reimbursement and patient peace of mind
				Reduces costs to healthcare ecosystem and patient recovery
Pre-Operative	Manufacturer	Surgeon, Hospital	Limited local post-processing solutions	Localised manufacturing leads to less storage of implants = no waste
		Surgeon, Hospital	Implant may be wasted if tumour has changed; May be left on the shelf and expire (Excess and Obsolescence)	Decentralised manufacturing leads to less storage of implants = less wastage Reduction of inventory and waste of off-the-shelf prosthesis, saving money.
		Patient; Hospital; Health insurance	High cost due to one-off design nature Achieving COGS efficiencies	Robotic surgery and 3DP implant is a complementary clinical option for long-term benefit, but may cost more in short-term
		Health insurance, Regulatory bodies	No reimbursement code that fits bone tumour implant, imaging or robotics category	Develop working relationship with TGA and Dept. of Health
Surgery	Surgeon	Nurse, Hospital	Invasive and unnecessary cutting and prolonged surgical procedure	Reduce the need for significant numbers of instrument trays by using robotic technology
		Patient, Nurse, Hospital, Health insurance, Regulatory bodies		Limited cosmetic surgery required. In the long term, patient benefit ROI is improved with less chance of need for revision surgery
Post-Operative	Manufacturer	Surgeon, Nurse, Health insurance, Regulatory bodies	Limited consideration for 3DP implants and robotic surgery in reimbursement pathways	Greater rigour in monitoring prosthesis and disease. Need for evidence based data.
				Different parts of the bone require different surgical approaches – develop patterns and prepopulate robotic programs. Will help with development of templates for regulatory and reimbursement requirements
	Nurse	Surgeon, Patient	Significant amount of post-op care; Major surgeries can remain in hospital for months	Customised treatment will allow a patient to fully bear weight more quickly, speeding recovery and reducing cost Length of stay reduced, reduced risk of infection, increase longevity of prosthesis and need for ongoing revision. Pain management reduced and patient can commence rehab exercise regime quicker. Length of rehab reduced

Figure 1: Existing prosthetic implant value chain

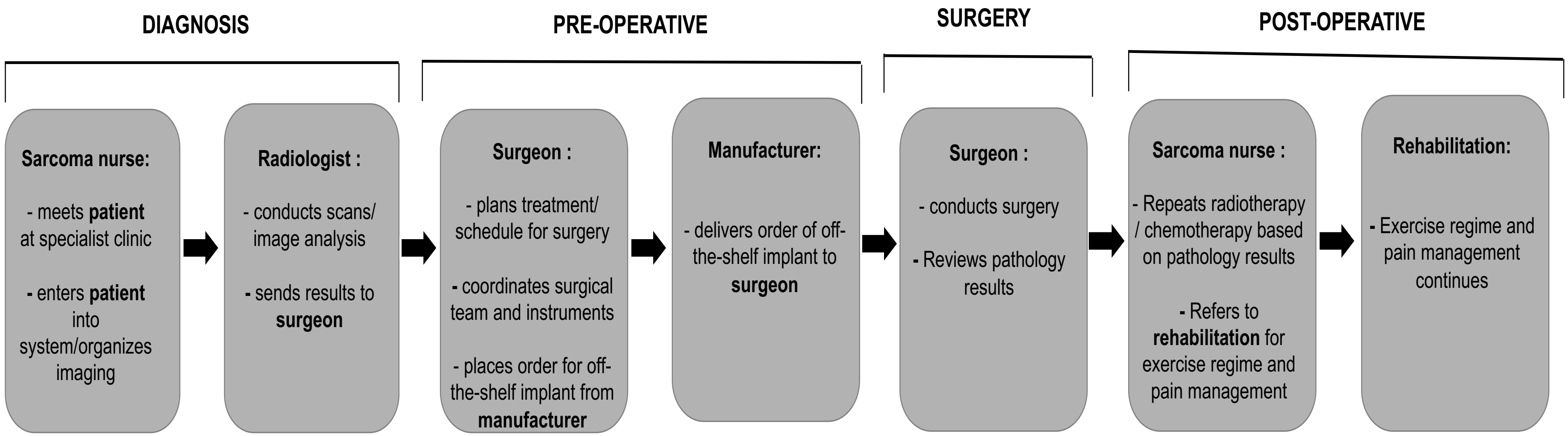

Figure 2: Future prosthetic implant value network

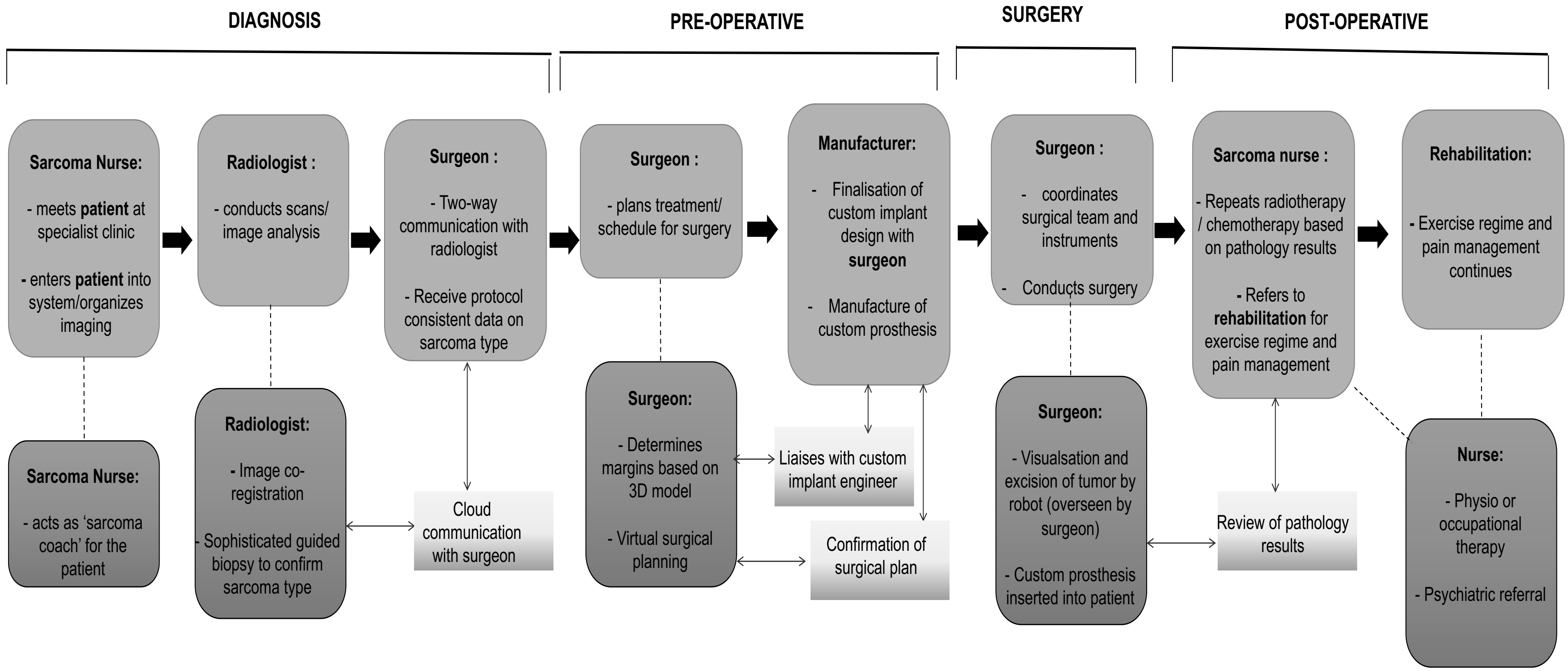

Figure 3: Future prosthetic implant ecosystem

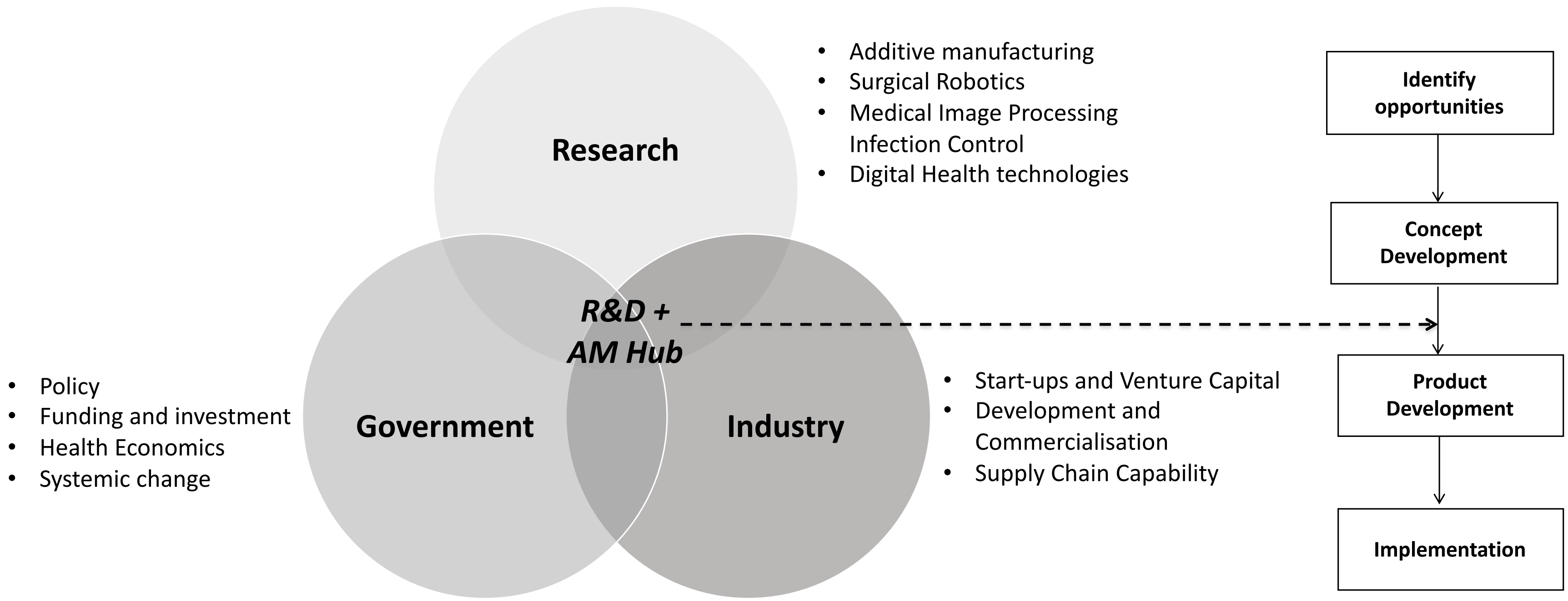

Figure 4: Interactions with external stakeholders to co-create customized implant

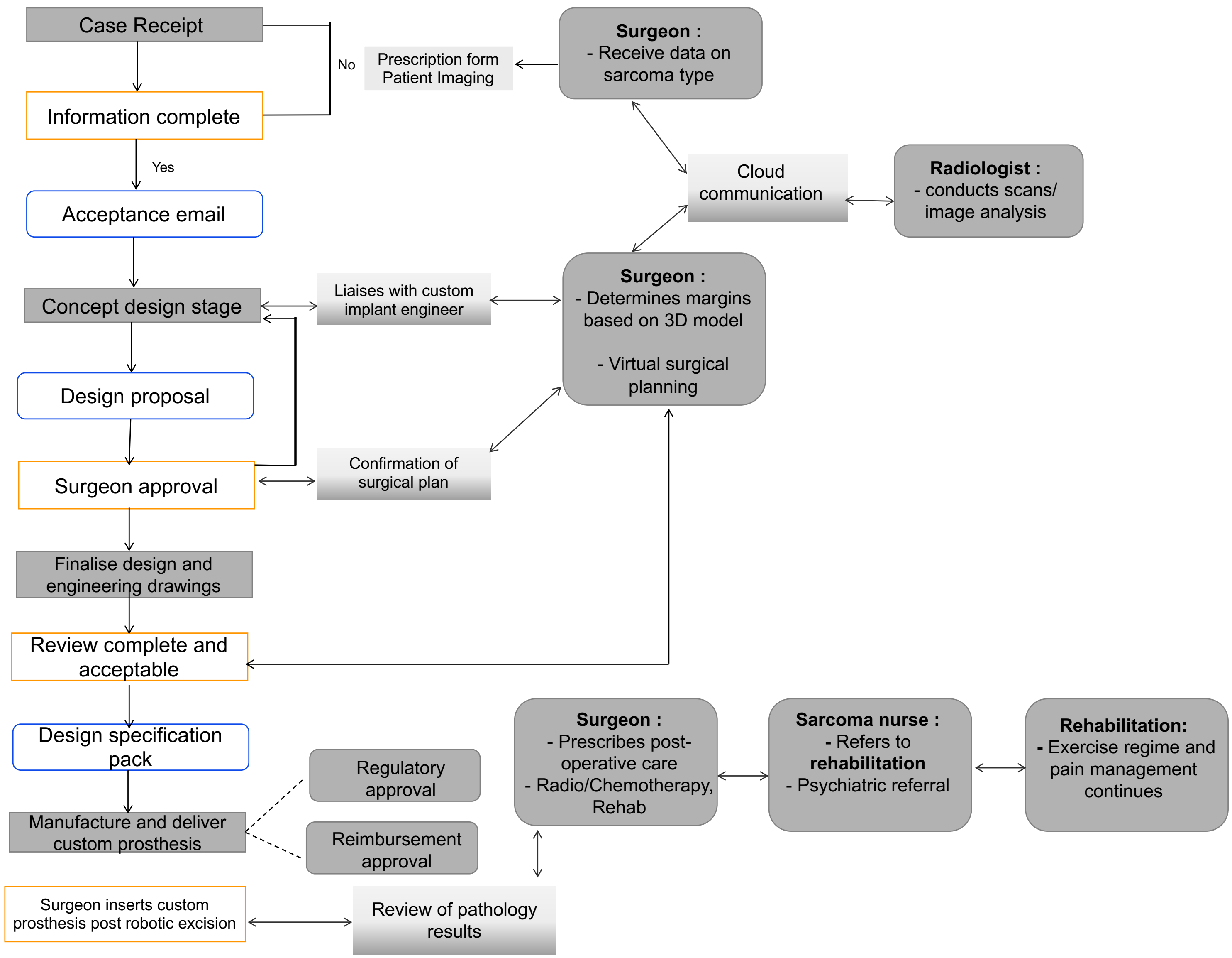

Figure 5: Framework of open innovation ecosystem transformation