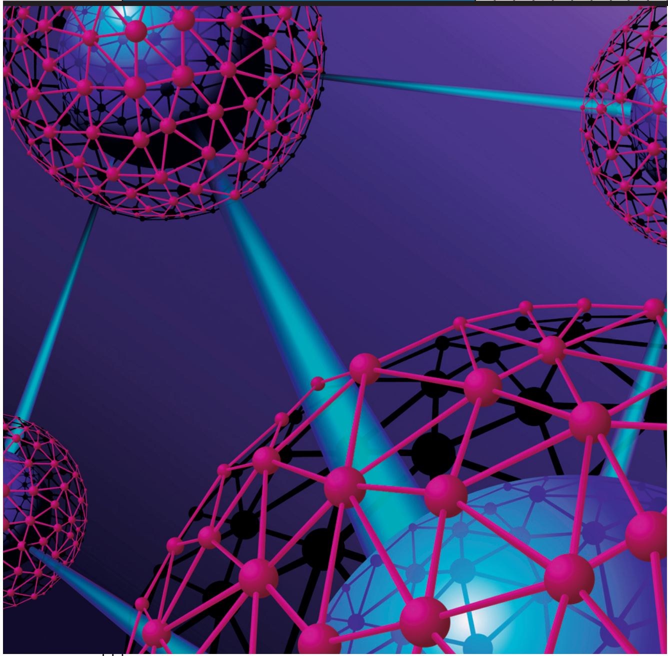

WHY CRITICAL SYSTEMS NEED HELP TO EVOLVE

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Classical engineering fails to model all the ways in which a critical sociotechnical system fits into a larger system. A study of orthotics clinics used projective analysis to better understand the clinics' role in a healthcare system and to identify risks to the clinics' evolution.

According to a 2009 report[1] on orthotic services in the UK, more than 1.2 million patients with conditions from diabetes to neuromuscular disorders rely on such services to enable them to work and live independently. In 2005, the report noted, it cost roughly £85 million (≈ US$128 million) to provide orthotic services, and service demand had since been increasing commensurately with the aging population and the complexity of clinical conditions. Yet despite this increase, there appeared to be no consensus on how to relate the funding changes to the changing demand.

Given that early orthotic intervention improves lives and saves money, an orthotic-service provisioning system is certainly critical from the perspective of its patients. To manage its evolution, providers must understand the system's place within the larger system of National Health Services (NHS), and how it should respond to its patients' needs.

The 2009 report confirmed earlier findings[2] that for every £1 (≈ $1.50) spent on orthotic services the NHS saves £4 (≈ $6). With current expenditure on orthotic-service provisioning estimated at £100 million (≈ $150 million), the NHS would save an estimated £400 million (≈ $600 million). Nevertheless, the report found that, because of inadequate funding, pilot sites that had enhanced service levels could not sustain them. A hospital could implement recommendations only with specific funding from its Primary Care Trust. Moreover, increased awareness, not modeling, revealed the latent service demand, suggesting that current procurement practice is "too dependent on a commodity product procurement model."[1]

Clearly, the report viewed the current operating environment of orthotic service providers as a threat to their ability to fulfill their mission. To improve patient care and provide real value to the NHS, the report recommended establishing a locally commissioned service based on clinical outcome. Such a solution is consistent with the 2008 Darzi report, which recommended transforming the NHS to a locally led, patient-centered, and clinically driven organization.[3]

Realizing this vision is not without challenges. Chief among them is the need to identify threats to the system, understand user demand patterns, and reach beyond classical engineering to adopt more appropriate modeling techniques for these more complex environments.

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THREATS TO A SOCIOTECHNICAL SYSTEM

The threats facing any sociotechnical system within a larger ecosystem such as the NHS extend beyond those of the familiar operational variety, where system components fail to perform as expected, individually or collectively. An orthotics service, for example, uses a model of how it should operate in providing orthoses to its patients. This model, in turn, determines how it actually operates.

Integral to an accurate system model is elaborating the distinction between "should operate" and "actually operates." A fully elaborated model, such as that in Figure 1, should reflect three kinds of distinctions, or *cuts*: Cartesian, Heisenberg, and endo-exo.

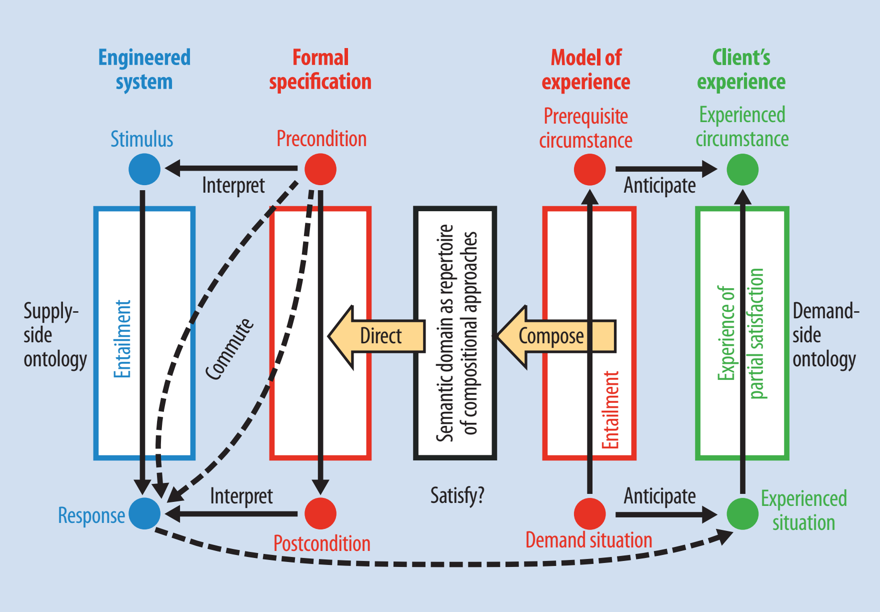

Figure 1. Fully elaborated modeling relation. A model that captures all the threats to a sociotechnical system must consider both the demand- and supply-side ontologies. Left: Construction of the modeling relation. Middle: Approaches used to compose the system, which the user must orchestrate. Right: Service demands on the basis of use context.

Cartesian cut

Like the scientific method, engineering techniques rely on the successful construction of a modeling relation, as shown in the left side of Figure 1. A valid scientific theory is a formal system with an interpretation that maps the symbols in that system to observable states and events in a natural system in such a way that physical entailment (causality) in the natural system commutes with logical entailment (deduction) in the formal system. Engineers also rely on the existence of components whose composition into systems they can analyze—and occasionally synthesize—using the formal system's calculus. Both science and engineering make the simplifying assumption that the natural systems they observe are *closed*, that is, immune to disturbance from all stimuli that the operative model does not account for. In other words, what you see is what you get.

However, unlike many systems, ecosystems are open because it is not possible to identify all the state components that some event does not alter. As such, these systems are exposed to the well-known frame problem.[4]

The distinction between what is and what is not accounted for by the observer's knowledge is the observer's Cartesian cut. The limitation is whether or not observers can assume that the system being modeled is closed. If the system is within an ecosystem, this assumption is invalid because *what you see is not what you get*.

In the context of orthotic services, the Cartesian cut presented a mismatch between the model of the clinic that defined its operational systems and the reality of its interactions with its patients and funders. The processes by which an orthotics service diagnoses particular patient needs are affected by both how it is organized and how patients present their symptoms. Neither perspective can be defined wholly independently of the other.

Heisenberg cut

Collaboration across multiple sociotechnical systems—a system of systems (SoS)—raises the possibility that operationally adequate systems collectively behave in ways that violate their specifications. The sidebar "Defining a System of Systems" explains this behavioral characteristic in more detail. Even in a closed SoS, if analysts knew all the relevant compositional approaches (middle of Figure 1) but did not know the SoS's behavioral domain, they would experience the SoS as open because its design did not fully determine its composition. Often, such systems engage in autonomous composition under the influence of user interactions, and their actual composite behavior differs from that interpreted from the composite model. In these instances, SoS behavior is considered emergent. An example of such behavior is when features interact in telecommunications systems.

The Heisenberg cut is the distinction between a system for which users can and cannot predict system behavior independently of their use of it. The limitation is whether or not observers can define the nature of the demands that a system is responding to independently of how the supplying system relates to those demands. For an ecosystem, it is impossible to make this assumption, since every observer is always also a participant within the ecosystem: Thus, *what you get depends on how you use it*.

DEFINING A SYSTEM OF SYSTEMS

A directed system of systems (SoS) is treated as if it were still a single system, but its components have operational and managerial independence in the way they determine their respective behaviors.[1] A central authority predetermines the uses of these component systems, which is typically a universal ontological commitment as to what the system will be.

The integrated SoS is built and managed to fulfill specific purposes, such as air defense, to which the component systems' normal operational mode is subordinated. In practice, however, an SoS requires collaboration among its component systems concurrently with many other collaborations using the same systems. The agreed-upon central purpose thus depends on the way the component systems support these concurrent collaborations, which defer some ontological commitment to the time of use. Consequently, any centrally determined ontological commitment must underdetermine the component systems' uses. Central management organization cannot coerce the component systems, which are autonomous to the extent that they voluntarily collaborate to fulfill agreed-upon purposes. The Internet, for example, started out as directed, but its components can no longer be centrally managed.

In a virtual SoS—for example, an economy—there is not even a centrally agreed-upon purpose, so the component systems' support for the concurrent collaborations must rely on relatively invisible mechanisms (rules) to sustain the SoS.

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In the context of orthotic services, the Heisenberg cut was reflected in the underuse of orthoses relative to latent demand. The clinics measured demand in terms of acute episodes of care, rather than as multiple episodes of care within the context of a patient's chronic condition. An orthotics clinic is a practice that emerges from the composite effects of all its different parts interacting with aspects of its patients' lives and conditions. No observer, not even a participating observer, can wholly capture the nature of a clinic's practice. Any intervention must therefore take its place within the ongoing operational nature of that practice. A clinic cannot somehow stop and redesign itself, even though as a practice it can die.

Endo-exo cut

As expectations change, an individual system that meets its specification might fail to satisfy its users' demands when the system becomes part of an SoS. Exposure to these threats generates evolutionary pressures that require the system's stakeholders to understand its place within the SoS sufficiently to make strategic decisions that can mitigate those risks. The composite functionality that a collaborative SoS delivers is expressed as services composed by actors that are anticipatory systems[5] within the larger ecosystem. These anticipatory systems define service demands from their formulation of how those services affect their use context (right side of Figure 1).

Because these anticipatory systems are necessarily open, modeling their clients' needs also suffers from the frame problem. However, the system can model a client's need as an organization of demand that constitutes a pragmatics of use.[6] That is, the client cannot know his needs directly, but can know them indirectly because he has experienced their effects.

The client's endo-exo cut is the difference between what the client can and cannot know directly about his needs. This distinguishes the knowledge that is implicit in a sociotechnical system's behavior (ontic knowledge) from what those observing the system can know about it (epistemic knowledge).[7] For example, the behavior of a sociotechnical system is a result of both how it endogenously chooses to interact with its clients and how the design of its systems exogenously constrains it. This cut is a consequence of attributing agency to the sociotechnical system.

The limitation is whether or not service providers can grasp the full nature of the underlying reality, in which anticipatory processes are unfolding. In the context of the ongoing interactions within an ecosystem, such a full grasp is never possible: *What is wanted is never exactly what is asked for.*

In the context of orthotics services, the endo-exo cut reflects the failure of the larger healthcare ecosystem to evolve compatibly with a model of the clinic concerned with managing the lifelong development of a patient's condition.

MODELING A SOCIOTECHNICAL SYSTEM

Classical engineering is limited because it is impossible to fully separate any sociotechnical system from its context of use within an ecosystem. However, by enabling the members of and stakeholders in the sociotechnical system to analyze and project their participation experience, it is possible to understand how the sociotechnical system is defined in terms of the Cartesian, Heisenberg, and endo-exo cuts.

The techniques and tools of projective analysis facilitate this understanding, and support members and stakeholders in formulating and evaluating alternative evolutionary strategies with respect to the larger ecosystem. In the orthotics case, we used PAN,[8] a particular implementation of projective analysis.

Modeling a client enterprise as a sociotechnical system requires accepting that the observer's perspective is always exogenous to the system, which is why any modeling is always a projection of the observer's model of the system in and of itself. For example, to work with the orthotics clinics, we had to model the way the clinics worked from the point of view of the clinicians and managers. Likewise, to understand how doctors and specialists refer patients to the clinics, we had to model the referral pathways used by clinicians in the larger system.

Relationships among the cuts

The model must be able to account for the three cuts that the system makes in defining itself. As Figure 2 shows, the relationships among these cuts are in terms of a behavior domain and four quadrants that layer the client's relationship to demand: what, how, for whom, and why. The behavior domain comprises the kinds of behavior that define the client system and its customer interactions: for example, the clinical orthotic practices and the contexts for engaging in them.

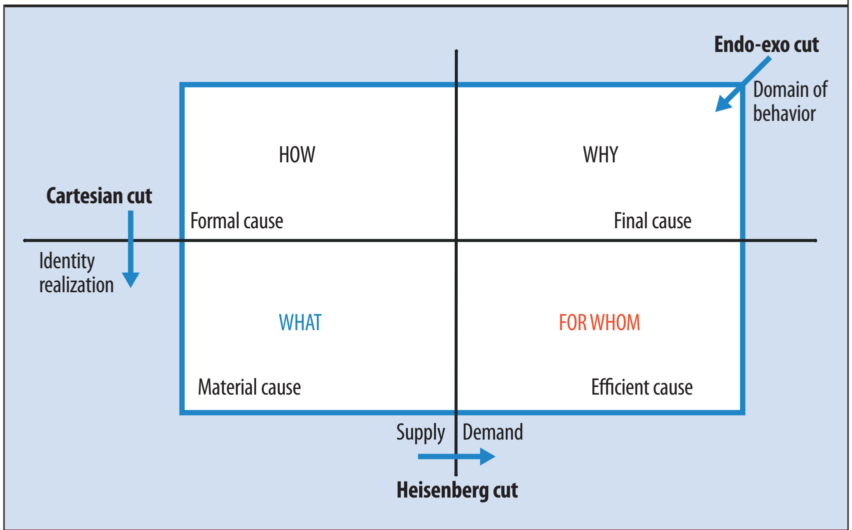

Figure 2. Modeling the Cartesian, Heisenberg, and endo-exo cuts and their interrelationships partitions the behavior domain into four quadrants. These four quadrants—what, how, for whom, and why—stratify the client's relationship to demand.

What. This perspective reflects what the clinic does, or the material nature of the clinic's work, as in what an orthotist actually does. As such, it describes the clinic as a system in terms of its realized behavior: what critical technologies it has mastered and the source of its products or services (constituent performances). The *what* perspective might be an observation of the way the overall clinic functions day to day, for example.

How. This perspective identifies the clinic's characteristics: What makes a clinic unique? What organizational aspects define that clinic's identity, such as how a clinic organizes its work to be effective? This perspective describes the clinic's authorized models. It looks at the key constituent performances it needs to construct the output performances it provides to its patients (customers), such as understanding how the clinic is actually organized.

For whom. This perspective clarifies whom the clinic is serving and identifies the economics of this service, such as the specific conditions the orthotics clinic is treating. This perspective also describes the patients' demands in the clinical environment. How must the clinic customize and orchestrate its outputs to generate the composite capabilities its patients need for their particular situations, and how will the clinic synchronize these composite capabilities with those situations? An example is seeking to understand how clinics actually apply orthotic treatments within the context of their patients' daily lives.

Why. This perspective looks at what makes the clinic's identity-defining characteristics of value within the NHS, particularly in relation to its patients. That is, what in the NHS drives the clinic's value, such as what is the larger context of the patient's life and condition that is giving rise to the presenting symptoms? This perspective also describes the environmental models that prompt demand. What use context is generating the demand that the clinic is targeting, and what is driving that context? For example, this perspective might bring to light the characteristics of the NHS and patient environment in which the clinic's practice is situated.

Identifying asymmetries

The stratified relationships among cuts also underline three asymmetries that must be addressed if the client is to manage its relationship to changes in its demand environment. The what and how perspectives span the first asymmetry: *The technology does not define the product*. The ability to manage the technology generates economies of scale in production. The manufacturing methods per se should not define how clinics use orthoses to treat patients.

The *how* and *for whom* perspectives span a second asymmetry: *The business model does not define the customer's solution*. The ability to manage the business model generates economies of scope in the various markets that can be served, but the ways in which the clinic organizes its treatment process should not define what treatments it can provide particular patients.

The *for whom* and *why* perspectives span the last asymmetry: *The patient's demand does not define the experience that the patient wants*. The ability to manage the relationship to demand generates economies of alignment in the way the customer's experience is supported. For example, the demands of the symptoms in a single episode should not define the larger multi-episode treatment strategy that a patient might need throughout the condition's life.

The first two asymmetries assume that providers can define the demand environment to be independent of the client enterprise's behavior. The classical engineering disciplines are therefore well suited to mitigating the threats

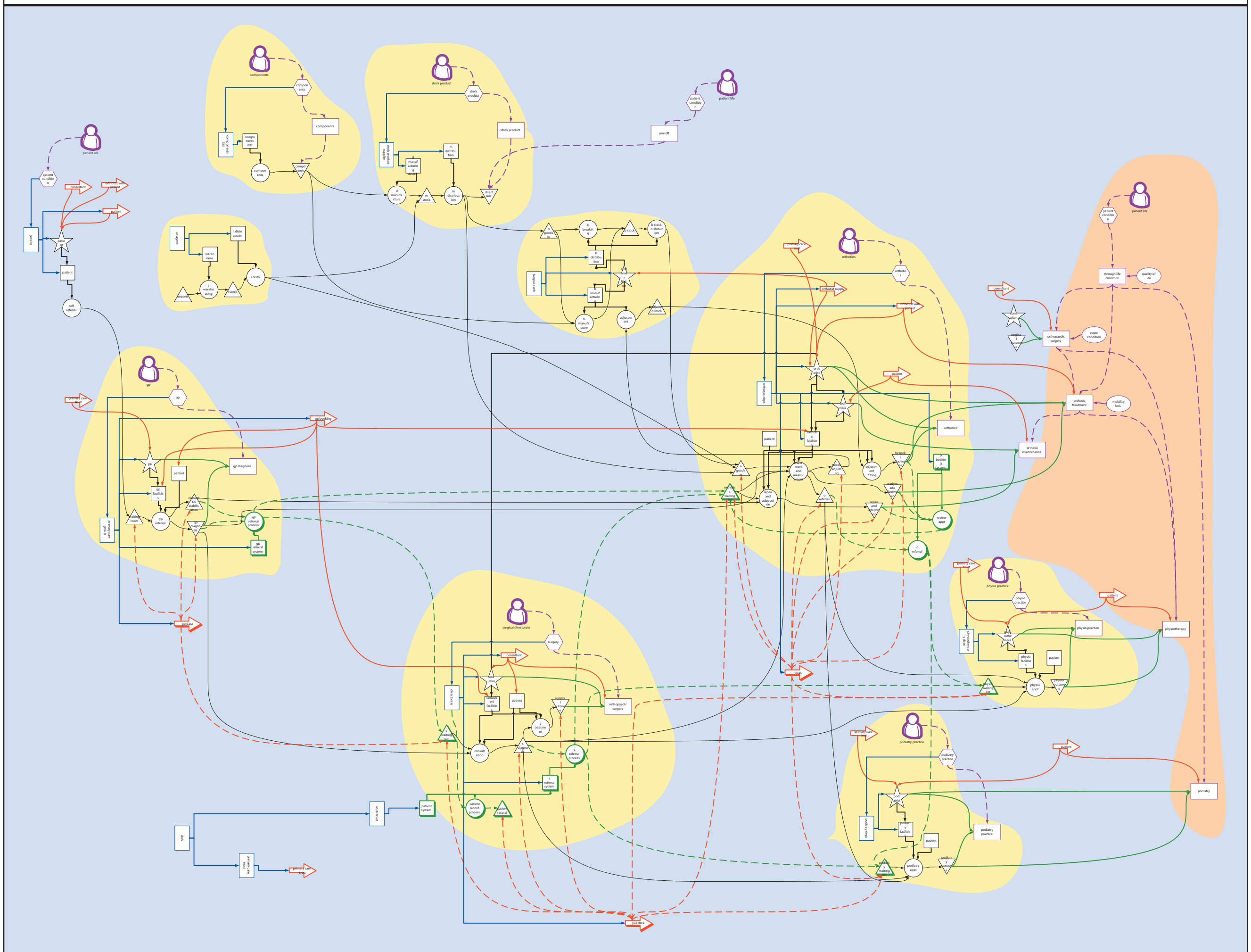

Figure 3. Model for orthotics services that combines the *what*, *how*, *for whom*, and *why* perspectives in the context of orthotic services. The model is a layered graph, with each layer corresponding to the structure, function, hierarchy, synchronization, information, and demand of the client enterprise, which in this case is the clinic. The colored regions represent clinical functions (such as orthopedic surgery and outpatient services), patients' conditions, and supplier services.

that arise in these environments. The third asymmetry, however, places the client enterprise explicitly within a dynamic ecosystem. A client enterprise that fails to comprehend and accommodate itself to this will limit its possible competitive behaviors, exposing itself to threats created by the changing nature of demand inherent in an ecosystem. It is these threats that a model based on all four perspectives can locate and identify.

PROJECTIVE ANALYSIS OF ORTHOTICS CLINICS

Figure 3 shows the model we elicited for orthotics services using Visual PAN, an application of Microsoft Visio with a customized stencil. The model is in the form of a layered graph, with each layer corresponding to an aspect of the clinic that several perspectives share.

This graph is effectively a heterogeneous binary relation that PAN tools can manipulate algebraically to generate the dependency structure matrix (DSM) in Figure 4. This structure was the basis for the commodity product procurement focus identified in the 2009 survey of orthotic services.[1] Figure 5 illustrates the stratification matrix, which is more complete and hence much more complex.

As the DSM and stratification matrix show, the complexity of managing the third asymmetry—aligning the ability to generate treatment with the patient's particular needs—overshadows the relative simplicity of the underlying activities.

Using an extended form of Q-analysis,[9] an analyst can generate 3D histograms, or landscapes, from selected submatrices of the stratification matrix. Figure 6 shows a landscape for the orthotics services system showing the relationships among major organizational components.

We also analyzed the roles of the clinics' various data platforms. Figure 7 shows the landscape for this analysis. Although the platforms overlapped on appointment

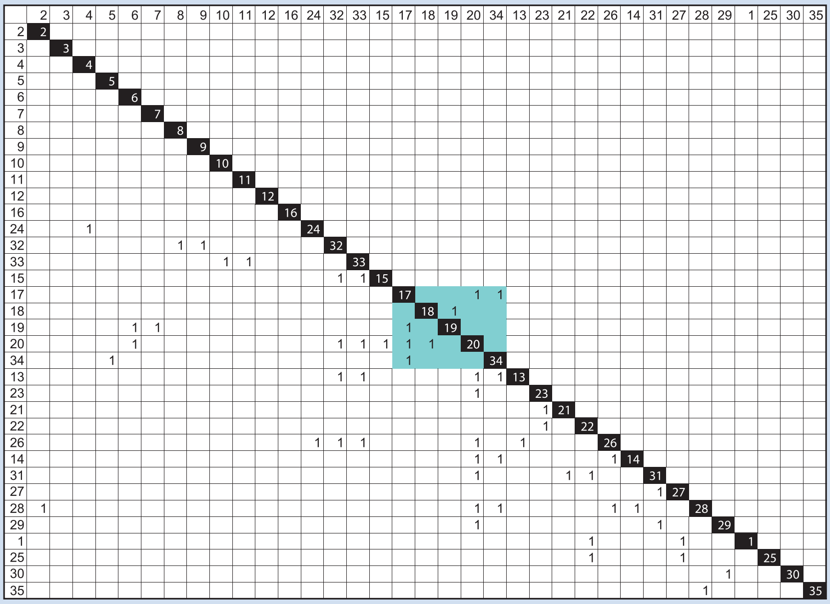

Figure 4. Dependency structure matrix for the model in Figure 3. The DSM captures only one of the aspects in the model, showing a relatively simple supply structure with some feedback relationships (blue box) around the actual orthoses fitting. The names of the rows and columns (not shown for simplicity) are the processes derived from the fully elaborated model.

and patient details, all the clinical data relevant to the particular patient condition were held in separate, unrelated silos.

The projective analysis supported several actions and interventions that significantly improved orthotic clinics' ability to deliver quality care. Not the least of these was the need to support the alignment processes themselves. According to the original 2004 survey of pathfinder clinics,[2] no clinic reported outputs by episode or analyzed referral by condition. The only reporting was on the clinic's cost, and "even this was generally poor." As a result, clinics had no shared experience reports or information base to help them improve operations or justify any investment. The report also noted the lack of data related to the chronic nature of the conditions being treated. In addition to the inac-

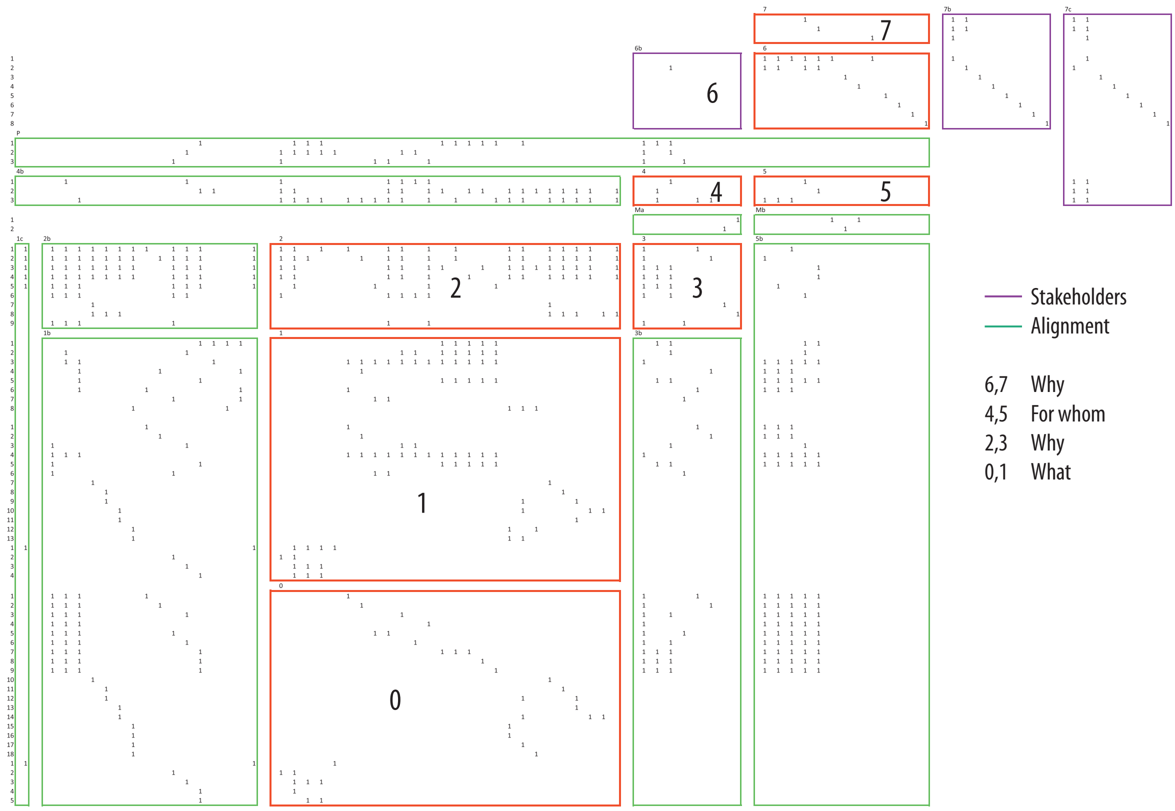

Figure 5. Stratification matrix for the model in Figure 3. This matrix is much more complete and thus much more complex than the DSM in Figure 4. The red matrices correspond to the stratification, the mauve matrices show the stakeholder influence, and the green matrices show how the DSM activities align to patient demands. The names of the rows and columns (not shown for simplicity) are events and processes, respectively, both of which are derived from the fully elaborated model.

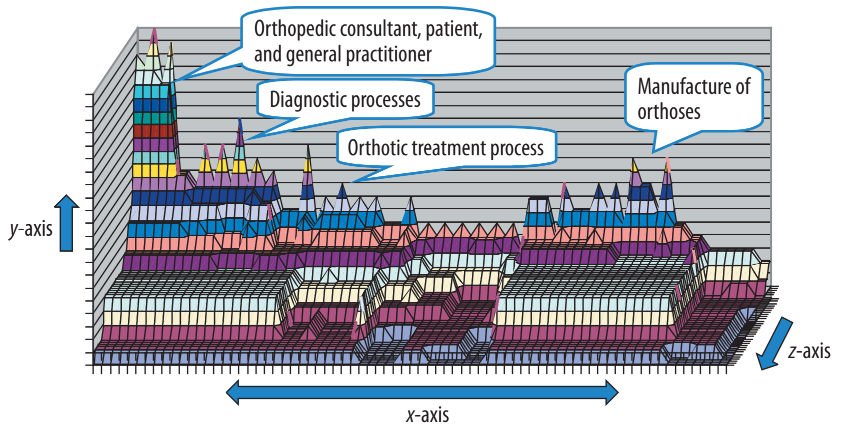

Figure 6. Cross-sectional landscape. A landscape shows gaps in the relationships between the major components of the organization being modeled, revealing the risks to stakeholders. The component outputs (not shown for simplicity) are ordered along the *x*-axis, the *y*-axis shows the complexity of alignment behind each output, and the *z*-axis shows the extent of overlapping complexity between outputs. The peaks represent areas of alignment that must themselves be aligned by social processes within the ecosystem as a whole.

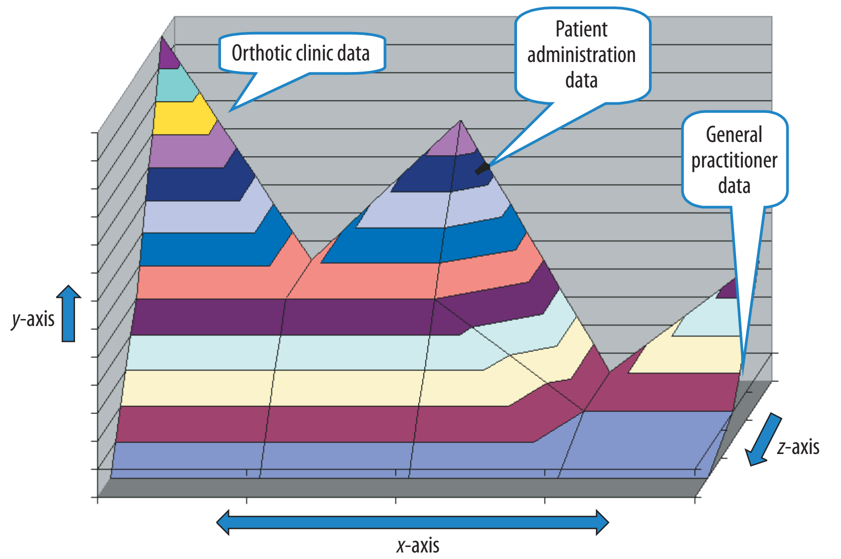

Figure 7. Data platform landscape. The data platforms are ordered along the *x*-axis, the *y*-axis shows the number of data elements synchronized by platform, and the *z*-axis shows the number of platforms with this synchronization level.

cessibility of patient records, the report found holes in the data on the conditions that defined an episode, on referral pathways, and on episode characteristics.

The application of projective analysis to orthotics clinics revealed the complexity of the alignment processes needed to deliver effective care to their patients. It also identified holes in the data being collected—gaps that not only prevented the clinics from acting in the most efficient and effective way, but that also kept the larger healthcare system from attaching value to a changed way of clinical operation. One of the recommendations made, therefore, was to have the clinics deploy a data platform to pull the missing information as it was generated and make it available for the stakeholders in their subsequent decision making.[2]

However, given its other funding priorities, the NHS rejected the proposed transformation of the clinics on cost grounds, despite the evidence that the returns in efficiency and patient care would be roughly four times the investment. Why should there be such an obstacle to this critical system's evolution?

At first glance, the recommendation to deploy a data platform seems similar to a recommendation for any traditional information systems requirements analysis. However, the data platform was a by-product of our analysis, not its primary objective. From the perspective of the clinics' role, deploying the data platform would have seriously affected the NHS's trust structure and the centralized patient record system that it was installing. The obstacle was therefore at a much higher level of understanding—that of the ecosystem itself and its reluctance to address the consequences of the third asymmetry.

Requirements analysts have often reported similar results, considering them merely exceptions to an otherwise classical engineering analysis. We suggest that, as they evolve, critical systems are inevitably exposed to higher-order risks, which classical engineering methods fail to identify. Projective analysis offers a more cost-effective alternative. C

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