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ARTICLE

A simulation-based approach to business model design and organizational Change

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ABSTRACT
While several practice-based approaches of business model design suggest ways to create new business models, there is limited understanding of why and how business models change. This exploratory study employs neural network analysis to simulate business model design and business model change. We conceptualise business model design as a schema of the organisation's critical resources, transactions, and value proposition. Elements of the schema are connected in a simple neural network. The network evolves based on a constraint satisfaction network until it converges to a stable state of a coherent business model. An in-depth case study of an entrepreneurial venture provides a real-world example to test the analytical framework. Using data from the case study, we run multiple simulations of business model design and business model change. The results suggest that business model change can be understood as a form of constraint satisfaction, linking managerial cognition with business model change. The simulation approach also helps identify possible, but unrealized business models. This novel approach paves the way for new research and practice in business model design and change.

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Introduction

The business model is a compelling framework for linking organisational design and venture outcomes (Amit & Zott, 2001). The robust literature on business models addresses uniquely entrepreneurial research topics (Ritter & Lettl, 2018). Studies adopt diverse approaches to explain business models and business model change, including organisational design and imprints (McDonald & Eisenhardt, 2020; Snihur & Zott, 2019), pivoting and stakeholder management (Hampel et al., 2020a, 2020b), cognitive coherence (George & Bock, 2012; Martins et al., 2015). Studies have also addressed sector-specific models (e.g., e-business) or application-specific models (e.g., tackling sustainable development) (Amit & Zott, 2001; George et al., 2020).

A business model is a boundary-spanning activity system that centres on a focal firm, yet may encompass activities performed by its partners, suppliers, and customers in the pursuit of value creation and capture (Amit & Zott, 2015). This activity system typically encompasses

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resources, transactions, mechanisms of value creation and capture, governance and structure, and a narrative that connects these elements (e.g., Bock & George, 2018; George & Bock, 2011; McDonald & Eisenhardt, 2020; Shepherd & Gruber, 2020; Snihur & Zott, 2019).

We propose a new approach to business models by developing a simple, formal representation of a business model to simulate how managerial cognition is linked to business model design and change. In this framework, the business model is a schema of organizational elements representing organizational resources, transactions, and value. The elements are linked based on managerial understanding of organizational connections. A simulation updates the network until a stable, coherent state is reached. The simulation is repeated thousands of times to identify the most likely stable business model outcomes.An in-depth case study of an entrepreneurial venture informs this exploration of business model design. The simulation results highlight three important contributions to the research on business models and business model change. First, business models can be simulated to explore realized as well as potential but unrealized business models. Second, the framework presents a compelling argument that managerial cognition can be linked to the firm's business model via a heuristic of constraint satisfaction. Third, cognitive confusion play an unexpectedly important role during business model change. The delay in business model convergence due to organizational confusion may be essential for firms to overcome inertia and realize new business model. Our study opens up new avenues for researchers and practitioners alike to understand business model design as configurations of elements and their connections, and factors that might influence organizational design choices. We briefly review the literature on business model design and business model change in the context of cognition and simulation-based approaches to decision-making. We then describe a rich case study of a technology-based entrepreneurial venture that informs our analysis. Key elements extracted from the case study inform a configurational simulation of the business model and business model change using a simple neural network. We discuss the results, including the role of uncertainty and confusion in emergent configurations, and explore the implications for research and practice.

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Cognition, coherence and choice in business model design

After emerging from practice in the late 1990s and early 2000s, the business model construct has received extensive attention across multiple research literatures. Recent reviews have surveyed the wide scope of business model research (e.g. Foss & Saebi, 2017; Massa et al., 2017; Ritter & Lettl, 2018), and provide adequate theoretical domains for reflection and action. We build on prior research directly related to the link between managerial cognition and business model design, with particular emphasis on the potential value of simulation for exploring business model change.

Studies have defined business models from diverse perspectives including elements, logics, activities, archetypes, and alignment (Ritter & Lettl, 2018). Across these perspectives, however, is a relatively consistent theme of design. George and Bock (2011) emphasised this as the core characteristic of a business model: 'the design of organizational structures to enact a commercial opportunity' (p. 99). Amit and Zott (2010) proposed a 'system of interdependent activities that transcends the focal firm and spans its boundaries' (p. 216). A similar approach describes the business model as 'the organizational and financial 'architecture' of a business' (Teece, 2010, p. 173). Practitioners are encouraged to recognise the value of the connections between elements and the importance of coherence across the various elements, reminiscent of strategic configuration and internal fit (Siggelkow, 2002).

A similar challenge is present in the literature of business model change. Foss and Saebi (2017) identified four primary streams of research on business model change: conceptualisation, process, outcome, and consequences. It has been linked to strategic agility and firm-level performance (Bock et al., 2012; Sohl et al., 2020), but definitions of business model change in the literature 'differ markedly, and are often ambiguous' (p. 207). Studies addresses business model change at one or more levels: elements (e.g. Demil & Lecocq, 2010), activities (e.g. Amit & Zott, 2015), imprints (e.g., Snihur & Zott, 2019), and holistic value-creating logic (e.g. Cucculelli & Peruzzi, 2020). Business model change is seen as a complex and dynamic process resulting in a unique change or transformation that could not effectively be predicted in advance (Hampel et al., 2020b).

At the core of business model design and business model change is cognition. The antecedents of specific business models may be linked to goals, constraints, and activities (Amit & Zott, 2015), but these antecedents must be perceived and processed via managerial cognition (Aspara et al., 2013). When addressing business model change, managers consider a variety of drivers and constraints, subject to the inertial effects of threat rigidity or prior experience (Osiyevskyy & Dewald, 2015). Managers generate a cognitive schema that integrates their understanding of organisational and exogenous information with a set of outcome expectations (Martins et al., 2015). Consistent with theories of strategic choice and planned behaviour, managers make business model choices intended to bring about preferred outcomes. This could include initiating, promoting, re-aligning, suppressing, or eliminating specific elements, activities, or transactions.

It is especially helpful to recognise that business models are inherently complex systems comprised of elements and interconnections among those elements (Massa et al., 2018). Both the elements and the connections are interpreted within managerial cognition as a basis for creating, maintaining, or changing an organization's business model. These design choices reflect managerial effort to generate configurations of resources and structures that optimize the organization's interaction with its environment (e.g., McDonald & Eisenhardt, 2020). Explicitly linking cognition and business models is a necessary step towards observable and testable models for business model design and change. In particular, it lends itself towards the use of constraint satisfaction as a decision-making heuristic. Organisational design choices reflect managerial effort to generate configurations of resources and structures that optimise the organisation's interaction with its environment (e.g., McDonald & Eisenhardt, 2020; Siggelkow, 2002). Resource complementarity and super-modularity optimise relationships among organisational elements (Milgrom & Roberts, 1995), which may yield stable configurations that may not be necessarily optimal (Thagard & Verbeurgt, 1998). Instead, they tend to be locally stable solutions that may incorporate incoherent relationships within a broader, coherent narrative (Pentland & Feldman, 2007).

Constraint satisfaction is a validated mechanisms linking cognition to decision-making and behaviour (e.g. Glöckner et al., 2014; Howes et al., 2004; McClelland et al., 2014; Simon et al., 2004). While not common in organisational studies, constraint satisfaction models are common in political science, psychology, and sociology. They are used to model cognitive and social processes such as jury decision-making processes (D. Simon, 2004), memory-based decision-making (Glöckner & Hodges, 2011), the development and testing of scientific observations (Thagard, 2007), belief formation in group thinking (Hutchins, 1995) and behaviour of members of a coalition (Axelrod et al., 1995). Managerial studies have used constraint satisfaction models, albeit less frequently, to examine strategy and structure (Milgrom & Roberts, 1995), narrative and technology adoption (Pentland & Feldman, 2007), strategic change (e.g. Siggelkow, 2002) and other topics. Modelling cognition and change with constraint satisfaction is attractive for decision-making in organisations. First, managers' decision-making context is informed by the architecture of formal and informal relationships (Gabriel, 2000), and their ability to absorb and manage knowledge (Zou et al., 2018). Design choices reflect the firm's need to allocate resources and employees across activities amidst varying degrees of uncertainty and bargaining power (Stole & Zwiebel, 1996). People instinctively use simplification and pattern recognition to deconstruct complex or unresolvable decisions into binary comparisons that generate higher-confidence choice options (Simon et al., 2004). Constraint satisfaction utilises a convergence process that explicitly links sensemaking to the decision outcome.

A further advantage of constraint satisfaction is the potential for stable, but imperfect configurations. Constraint satisfaction optimizes relationships among organizational elements (Milgrom & Roberts, 1995), which may yield stable configurations that are not be necessarily optimal (Thagard & Verbeurgt, 1998). Instead, they tend to be locally stable solutions that may incorporate incoherent relationships within a broader, coherent narrative (Pentland & Feldman, 2007). Further technical details on constraint satisfaction networks are provided in the section describing the simulation.These advantages of constraint satisfaction are particularly relevant in entrepreneurial contexts because constraint satisfaction presumes imperfect information, multiple possible acceptable outcomes, and limited cognitive processing capacity. Entrepreneurial firms often lack clear success metrics and competitive frameworks (Parrish, 2010). Venture performance may require designs that emphasise the entrepreneur's role and enable flexible execution (Van de Ven et al., 1984). When ventures strive to bring novel innovations to market, design and strategy decisions are linked to sensemaking narratives that support resource assembly and legitimation (Martens et al., 2007).

Case study of a technology venture

We conducted a longitudinal case study of a venture that faced high technological and market uncertainty. Early stage firms present less path dependence and equifinality, thereby reducing constraints on decision-making parameters. Structurally speaking, smaller firms present less embedded structures and fewer stakeholders. These firms are embryonic, facing complex and uncertain choices with limited information and resources. This provides an ideal context to examine the relationship between managerial cognition and the choice (and change) of business models over time.

The case study firm CELL was commercialising a radical scientific discovery based initially on human embryonic stem cells. There was significant uncertainty surrounding the viability and promise of the underlying technology, regulatory oversight of commercial products, and market adoption potential. The firm implemented a significant strategic decision during the course of the study. This presented a unique opportunity to attempt to connect individual cognition with the explicit change in business model. There were additional attractive aspects of the case study situation and interview data. First, the team had been given access to interview a variety of individuals, ranging from the executive management team to line staff, with no constraints on topics or time. Second, the interviews serendipitously took place before and after the observed business model change event. Third, the Company grew from less than 50 employees to more than 100 during the study, suggesting a highly dynamic context for participant cognition regarding the purpose and goals of the organization. Fourth, the President of the organization was willing to participate in follow-up discussions, which ultimately enabled validity testing of the original model specification. We briefly describe the case study context and then the data collection methods.

CELL initiated operations in 2004 after licencing the core technology from the Wisconsin Alumni Research Foundation, the technology transfer authority at the University of Wisconsin – Madison. The founding team included both the inventing scientists and professional life science business managers. The team immediately launched a second business, SCP, to separate therapeutic development from the core tools and diagnostic products in development at CELL. Separate legal entities avoided challenges associated with equity allocations across different founder sets and apparently distinct business models. The entities, however, shared some physical facilities and even management team members.

The subsequent discovery of induced pluripotent stem cells (iPS) at the University of Wisconsin presented an important, disruptive technological development. First, it reduced reliance on embryonic stem cells, which were politically and ethically problematic. Second, it offered the potential for a more efficient, unified production platform for stem cells, regardless of ultimate market use. CELL in-licenced the iPS technology from Wisconsin in 2006 and simultaneously made the technology available to the sister entity, SCP. Provisions were made for the separate entities to utilise the technology for research towards distinct product types: therapeutics and drug development research tools.

In 2008, senior management reconsidered the organisational structure and ultimately recommended merging the firms into a single entity. A variety of factors appeared to be at stake, including access to venture capital, IP management and strategy, stock transfer pricing, research and development management, and the overall structural complexity of the combined operations. The merger was implemented in 2008 and 2009. CELL reassigned members of the SCP research team to development work as the firm prepared to launch its first commercial product. The customer-facing side of the business expanded to explore new types of research partnerships with pharmaceutical companies. The successful development of a high-output cell manufacturing process based on iPS led to the launch of the first product based on cardiomyocytes in 2009. As of 2014, the firm offered 10 cell lines and was the largest producer of iPS derived stem cell assays in the world. Ultimately, the firm was acquired by a larger multinational corporation.We conducted approximately 25 hours of interviews with a cross-section of employees during and after the restructuring process with the following individuals: President, COO, CTO, Chief Business Officer, VP Marketing and Sales, Senior Financial Accountant, Senior Accountant, Product Group Leader, Senior Product Development Scientist, and Scientist. This sample represented approximately 30% of firm's full time employees at the start of the study and 10% at the end of the study. We conducted these interviews at CELL in a private office setting. The interviews followed a semi-structured interview script that ensured consistency between interviews but facilitated discussion of topics and issues specific and relevant to each interviewee. Long-form interviews were conducted with each informant. Interviews were conducted in a private setting and participants were guaranteed confidentiality. We audio recorded each interview and took handwritten notes. A semi-structured script was used to prompt discussion about each informant's role and activities, as well as their perceptions about the organization's purpose and functions. The script explicitly avoided the use of the phrase "business model." This was done specifically to avoid interviewee use of business model terminology and to focus instead on their perception of key organizational elements and process. Instead the script used prompts such as "What does the company do," "What resources does the company utilize to create value for customers," and "What activities and processes does the company regularly complete?" Respondents were asked to provide detailed examples of their work routines to complement the general information provided regarding resources and activities. Interviews lasted between 30 and 60 minutes. At the end of the data collection process, the research team met to discuss approaches for simulating business model change. The team selected constraint satisfaction simulation to extend a validated methodology to the emerging field of business model analysis. Populating a constraint satisfaction model required generating a set of business model elements and the relative connection weightings between those elements. A team member who had not conducted any of the interviews reviewed all of the recordings and field notes and generated an inductively derived set of organizational elements and proposed connection weightings. This set of elements was then mapped onto the business model framework of resources, transactions, and value to ensure that key business model design requirements were addressed. This explicitly moved the analysis from word frequency to semantic meaning. The team reviewed and refined the schema based on observations of the broader themes described by organizational participants and used comparison between those observations and our interpretations to converge to a final framework (Strauss & Corbin, 1990). Due to the focus of our study, we placed a heavier emphasis on primary information from senior team members including the President, Chief Business Officer, Chief Operating Officer, and Chief Technology Officer. The simulation is therefore based on inductively derived constructs. As such, it is inherently descriptive. The results of the model must therefore be interpreted within the limited context of the case study. At the same time, one of the advantages of simulation is the potential generation of unanticipated outcomes that go beyond the description of the observed data. In our study, some of the most interesting findings fall into this category. To preserve the epistemological validity of the findings, we discuss those in detail in the Discussion section, rather than the Simulation section.

Simulating business model design and business model change

The modeling approach approach relies on generating cognitive schema based on the data collected from informants which express underlying cognitive processes of exploration and sense-making (e.g. Gavetti & Rivkin, 2007). A schema is a non-interpretive representation of the relationships among non-hierarchical elements (Harris, 1994; Rumelhart et al., 1986). The schema-based approach applies fewer assumptions about the underlying meaning or importance of organisational elements. It focuses *only* on how elements are related to each other. In this framework, the meaning of the schema is co-created with the configuration rather than inherent to the configuration itself.

To simulate business model design configurations, we use a coherence modelling framework that incorporates a constraint satisfaction network (Glöckner & Hodges, 2011; Rumelhart et al., 1986; Thagard & Verbeurgt, 1998). We note that other heuristics exist for this type of modelling, such as strictly logical models, goal-seeking, min-max models, models of strategic complementarity, and n-k models (e.g. Kunc & Morecroft, 2010; Levinthal, 1997). A constraint satisfaction network is attractive because it allows the use of heterogeneous organisational elements (Pentland & Feldman, 2007) rather than requiring predefined entities and levels of analysis. This is more aligned with the fluidity at an early stage technology venture. Goal seeking, min-max, and similar models require applying an artificial and exogenous structure that would likely distort the subjective assessment of elements as understood by managers.

The process of convergence via constraint satisfaction is based on the 'connections of intelligibility among the elements in view' (Harman, 1986, p. 65). The primary heuristic in constraint satisfaction is the minimisation of local conflict between elements. The constraint satisfaction network focuses on the strength of interaction between those elements rather than hierarchical ordering or prioritisation. This generates a specification that reflects the sense-making context of the organisation, highlighting the interactions of elements relevant to the interpretation of entrepreneurial action and organisational change. This takes into account that adaptation is not a costless activity, especially in entrepreneurial contexts of scarce resources and accelerated time requirements.

While similar to a framework of adaptation to fitness (Siggelkow, 2002), constraint satisfaction does not require complete complementarity. Systems with positive and negative relationships between elements (e.g. complementarity and substitution, friendship and hostility) are unlikely to achieve perfect coherence. In most real world systems, some conflicts remain unsolved, yet the organisation continues to function. These systems may be 'frustrated,' but they are still coherent and stable (Bélair et al., 1996). In other words, they make sense, despite some internal consistencies.

This modelling approach offers numerous attractive characteristics. First, it yields the most *probable* stable configurational outcomes. Second, it emphasises coherence as an interpretive lens (Fisher, 1994) without requiring the assumption that organisational actors are constantly engaged in complex decision computations. In other words, it recognises that, in the real world, people tend to settle on solutions that make sense rather than indefinitely pursue perfection. Third, it provides a framework for assessing alternate plausible configurations, which provides a basis for assessing the narrative fidelity of the model.We now present the development of the neural network model and the constraint satisfaction simulation. This explanation may be redundant for readers familiar with this type of simulation method. Because such methods are less common in the management and entrepreneurship literatures, we present more detailed explanation of the model mechanics.

Model elements

We conceptualise business model design as a schema of heterogeneous elements understood by practitioners, especially executives (e.g. Davis et al., 2009; Pentland & Feldman, 2007). We generated the model elements by collecting interpretations of the firm's key elements and activities from employees. Figure 1 shows the relative word frequency of the most common meaning-carrying words from informant descriptions of the firm's core activities before and after the technology adoption. Emphasis shifts from certain elements at the start of the study (stem, research, blood, product, develop, business) to others (cardio, drug, assay, people, ips) at the end of the study.

Based on the verbalized descriptions of the organization's function, business model components were organised into a multi-level schema conducive to modelling. The four components of the schema, shown in Table 1, are based on prior research on business models (c.f. Baden-Fuller & Morgan, 2010; Bock & George, 2018; George & Bock, 2011; Teece, 2010; Zott & Amit, 2007). The first component comprises the critical resources or competencies the firm anticipates leveraging to generate entrepreneurial returns. The second component comprises the activities and transactions most germane to the firm's current or expected value creation mechanisms. The third component establishes the opportunities or targets associated with the firm's current or expected value creation mechanisms. The final component is the overall design or narrative orientation that represents the firm's holistic understanding of its role or position in the broader industry or

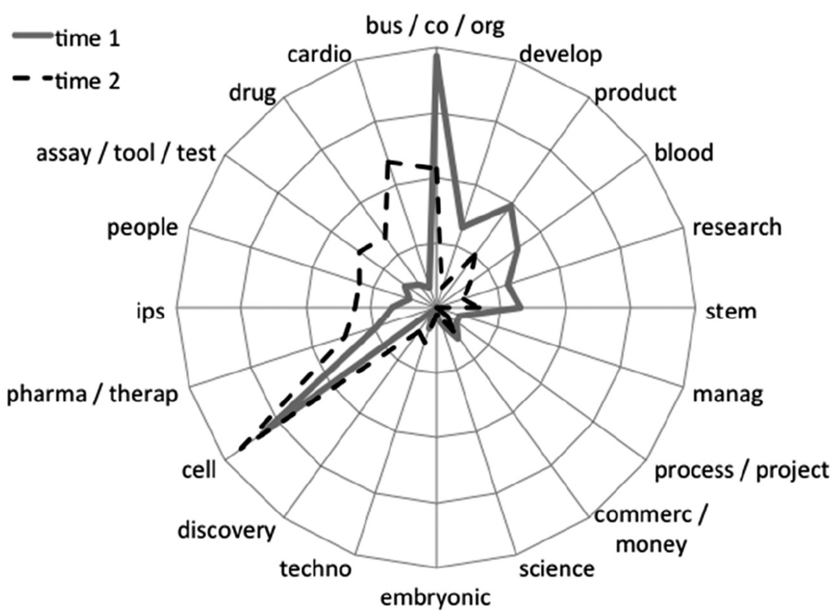

Figure 1. Word frequency in business model description before and after disruption.

Table 1. Business model levels and elements.

Level	Organisational element	Word frequency codes
Resource structure	Automation skills (dropped)	Cell (dropped)
	Stem cell culture skills	Stem cell, embryonic
	ips know-how	ips
Transactive structure	Blood research	Blood
	Materials development	Product, assay/tool/test
Value structure	Development orientation	Develop, technology, commerc*/money
	Research orientation	Research, science, discovery
Narrative	Tools company	Technolog*, assay/tool/test, cardiomyocytes
	Therapeutics company	Drug, pharmaceutical/therapeutic
General/Discarded		Manage*, Business/company/organiz*, process/project, people

Note: The * represents a wild card to capture word variants

value network. Components general to all aspects of firm activity (money, people, process, business, organisation) were discarded as non-specific to a given business model.

The investigators then reviewed the audio recordings and transcripts of the interviews to clarify the concepts identified in the word frequency analysis and specify model nodes at the semantic rather than word level. Although interviewees had been selected to ensure variation in tenure, hierarchy, and specialisation, our review emphasised the interviews with the President, CTO, COO and Chief Business Officer. The general network of nodes with all possible connections is shown in Figure 2.

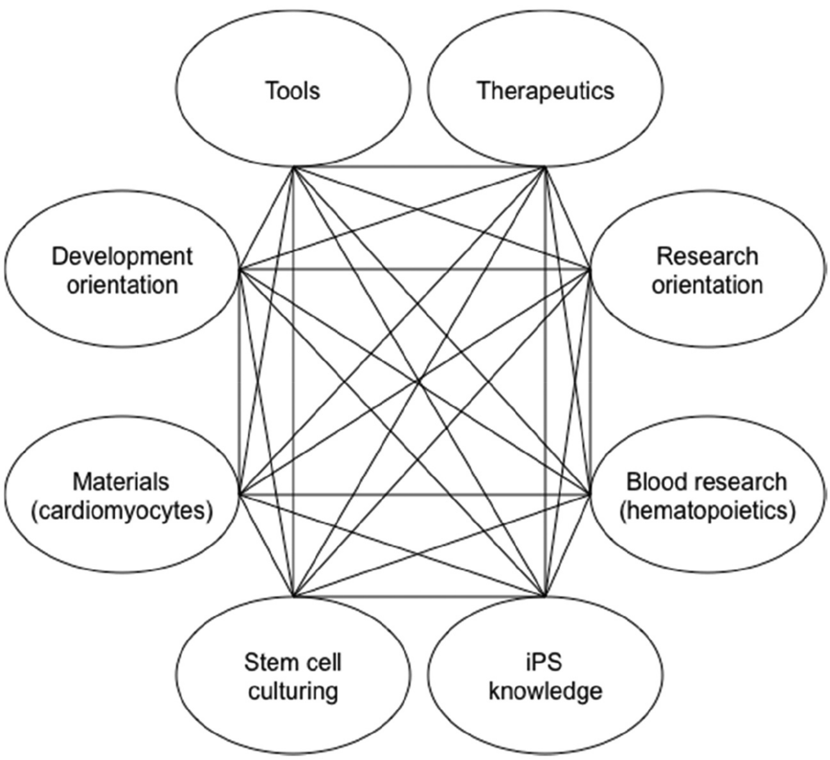

Figure 2. Full set of all network nodes and possible connections.

Network elements exist in one of two ‘active’ states, represented computationally as {+1, −1}. In addition, elements may devolve to an ‘inactive’ state represented computationally as {0}. A node in an inactive state does not interact with other nodes. It is important to remember that element status {+1, 0, −1} have no implied organisational interpretation. The representations are only computational placeholders for determining configurational outcomes.

Model relationships

The relationships between elements are considered as constraints on the preferred state of each element. Each constraint has two characteristics: the strength of the relationship and whether it is complementary or inhibiting. A positive interaction between elements represents a reinforcing or complementary relationship. A negative interaction represents an inhibiting or conflicting relationship. For example, if element A is currently {+1} and element B is currently {+1} and the relationship between them is positive (reinforcing), then the two-element configuration is stable. If element B is currently {-1}, *ceteris paribus* the updating process enacted on one of the elements would be likely to change its status. Note that if the updating process occurred on element A, the result might be that both elements would be {-1}, while if the updating process occurs on element B the result might be that both elements would be {+1}. From a configurational perspective these are equivalent, in that the positive, reinforcing interaction constraint is met when both elements are in the same state. Similarly, a negative interaction effect tends to result in element pairs with opposite states. A {0} state represents a node that is temporarily ‘undecided,’ but such states may persist in cases where nodes are effectively excluded from nearby groupings. In the simple modelling framework we employ, these relationships are presumed to be symmetric. In other words, the effect of element A on element B is equivalent to the effect of element B on element A.

The node relationship matrices derived from the data collection tool are shown in Figure 3.

Prior to technology adoption

	1	2	3	4	5	6	7	8
1	0	-4	5	0	5	0	0	0
2	-4	0	0	5	0	4	0	0
3	5	0	0	-4	5	0	0	0
4	0	5	-4	0	0	4	0	0
5	5	0	5	0	0	0	0	0
6	0	4	0	4	0	0	5	0
7	0	0	0	0	0	5	0	0
8	0	0	0	0	0	0	0	0

Post technology adoption

	1	2	3	4	5	6	7	8
1	0	0	5	0	5	0	0	5
2	0	0	0	5	0	4	0	5
3	5	0	0	-4	5	0	0	0
4	0	5	-4	0	0	4	0	0
5	5	0	5	0	0	0	0	0
6	0	4	0	4	0	0	5	5
7	0	0	0	0	0	5	0	-5
8	5	5	0	0	0	5	-5	0

1 therapeutics 3 research orientation 5 blood research 7 stem cell culture
2 tools 4 development orientation 6 materials development **8 ips**

Figure 3. Node relationship matrices.

Constraint satisfaction heuristic

For any configuration, we can identify the level of frustration ***(H)*** by measuring how many constraints are satisfied and how many are not, weighted by their strength. This can be written as Equation 1:

$$(Eq1)H = -\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}S_iS_j$$

where S_i, S_j are the states of a nodes i and j and w_{ij} is the weight of the connection between nodes i and j. In effect, Equation 1 states that:

- frustration diminishes when the states of two elements are aligned coherently with the sign of their relation ('friends' have state with the same sign, 'enemies' have opposite sign);
- frustration increases when the states of two elements are aligned incoherently with the sign of their relation ('friends' have state with opposite sign, 'enemies' have the same sign);

This measure is consistent with prior studies in organisation science. Near-decomposable systems may be organised by aggregating the most coherence elements (H. A. Simon, 1977). Thompson (1967) organisational design framework recognises as a prominent principle the partitioning activities by grouping together maximally coherent activities and minimising within-partition conflicting activities.

Each node's state depends on the state of the nodes to which it is connected. The preferred node state makes it maximally coherent with the other connected nodes, thus minimising local frustration. This principle can be captured by a simple rule, according to which the state of the i^{th} network node, S_i, may be determined:

$$S_i = sgn(h_i) = sgn\left(\sum{}_j w_{ij} * s_j\right) \quad (2)$$

where $sgn\ (x) = \{1\ if\ x\ 0;\ 0\ if\ x = 0;\ -1\ if\ x < 0\}$

If each node updates its state according to Equation 2, the system will converge towards a (local) minimum of the function ***H*** in Equation 1 (c.f. Hertz et al., 1991; Hopfield, 1982). There may be multiple minima, which means that a given network of constraints can support multiple locally coherent configurations. Emergent coherent configurations depend on the initial configuration of the system and on the specific path of node updates.

A model run is initiated by randomly assigning a state {+1, 0, −1} to each element. The simulation updates the model in a stepwise fashion by randomly selecting a node and updating the status of that node based on the application of Equation 2. A stable configuration, corresponding to a local minimum of the function *H*, occurs when updating according to Equation 2 no longer produces changes in node states. A run consists of a reasonable number of updates (we use 1000) to determine whether a stable configuration emerges. The simulation is then repeated many times to develop the stochastic profile of the most likely outcomes.

Populating the model

We derived a configurational model of the organisational narrative, including sign and weighting of node relationships, based on our review of the interview data. We generated preliminary results for the business model configuration prior to the technology change. The results matched the actual business model of the firm. At this point, additional steps were taken to increase the validity of the analysis and decrease the dependence on the team's evaluation of node relationships.

First, a follow-up interview with the President confirmed the face validity of the constructs. One node was dropped from the model based on feedback and clarification provided by the President, but this adjustment had no significant effect on model output. We also administered a simple survey to the President to collect quantitative element relationship data, in which node relationships were characterized on a scale from -5 (business model elements significantly conflict) to +5 (business model elements significantly complement). Note that these weightings of the connections *between* nodes are distinct from the *status* of any given node; as previously stated, nodes can be in one three states: +/- 1 or 0 (inactive).

The data were then used to re-run the simulation and all further analyses. We did not observe any significant differences in node relationships between the investigator-derived model and the model based on the survey data. We report on the specification based on the survey data; the specification and results were not significantly different from the original specification generated by the researchers. The node relationship matrices derived from the data collection tool are shown in Figure 3.

In effect, the simulation models participant cognition about organizational configurations. The nodes are organisational constructs expressed by informants relevant to the firm's existence and activity. Although the model configurational outcomes carry no intrinsic interpretation, the natural fit between the identified constructs and business model dimensions lends itself towards an organizational design interpretation. Senior executives repeatedly mentioned the issue of business model design explicitly, especially during the first series of interviews. While business model design was not mentioned as clearly by line staff or managers, the more general question of organizational structuring was top-of-mind for the majority of informants. The uptake of the iPS technology and the subsequent structuring event were the most important organizational events, other than financing rounds, in the organization's history. A design-oriented interpretation for element configurations is both intuitive and supported by informant data.

This approach is inherently attractive for thinking about business model choice and change. It provides a simplification of the manager's otherwise complex understanding of context, organisational circumstances and relationships. Research has suggested diminishing returns to the complexity of managerial representations (Calori et al., 1994). In Table 2, we provide the complete set of organisational configurations that emerged from the full set of model treatments. Each configuration can be interpreted as possible strategies, incorporating one, two, or three groupings of elements.

Table 2. Potential organisational configurations.

Configuration	Structure 1	Structure 2	Inactive
A) Parallel stem cell businesses	therapeutics, research, blood research	tools, development, materials development, stem cell culture	iPS
B) Stem cell platform	therapeutics, research, blood research, tools, development orientation, materials development, stem cell culture		iPS
C) iPS platform	therapeutics, research, blood research, tools, development orientation, materials development, iPS		stem cell culture
D) Parallel iPS-based businesses	therapeutics, research, blood research	tools, development, materials development, iPS	stem cell culture
E) Drug discovery	therapeutics, research, blood research, materials development, stem cell culture		tools, development, iPS
F) Null firm			therapeutics, research, blood research, tools, development orientation, materials development, stem cell culture, ips

First model treatment: convergence to initial coherent equilibrium

The first simulation treatment modeled locally coherent configurations based on the firm element relationships prior to the uptake of the iPS technology. In this, as in all subsequent phases, we ran 1000 simulations. We report the full set of model outputs in Table 3.

Repeated model runs based on randomized initial conditions generated a most-common stable configuration shown in Figure 4(a). Continuous connections are "complements," dashed connections are "conflicts." Connection thickness approximates the connection strength used in simulations. The dark and light node coloring represents final node status (+1 or -1). In other words, nodes showing the same color are complementary (grey-grey, black-black), while nodes with different color are in conflict (grey-black). Nodes with dotted lines are inactive. The "iPS Knowledge" node is always inactive in the pre-change model, because iPS technology had not yet been in-licensed. In some final configurations, however, nodes are inactivated because model updating found a preferred configuration in which that node had no interactions with other nodes. As a side note: one of the fascinating and unexpected results of the simulation is the identification of a stable solution in which all nodes are inactive—suggestive of the firm simply ceasing to exist.

The most likely configuration shows two groupings of nodes. The set of dark nodes incorporates therapeutics, research orientation, and blood research. The set of grey nodes links tools, development orientation, materials development, and stem cell culture skills. This outcome does, in fact, closely match the business models of the CELL and SCP legal entities in 2007. It is important to note this locally stable solution, although overwhelmingly more likely than the others, is not without alternatives. The 'stem cell platform' business model that corresponds to merging CELL and SCP is a possible, though less

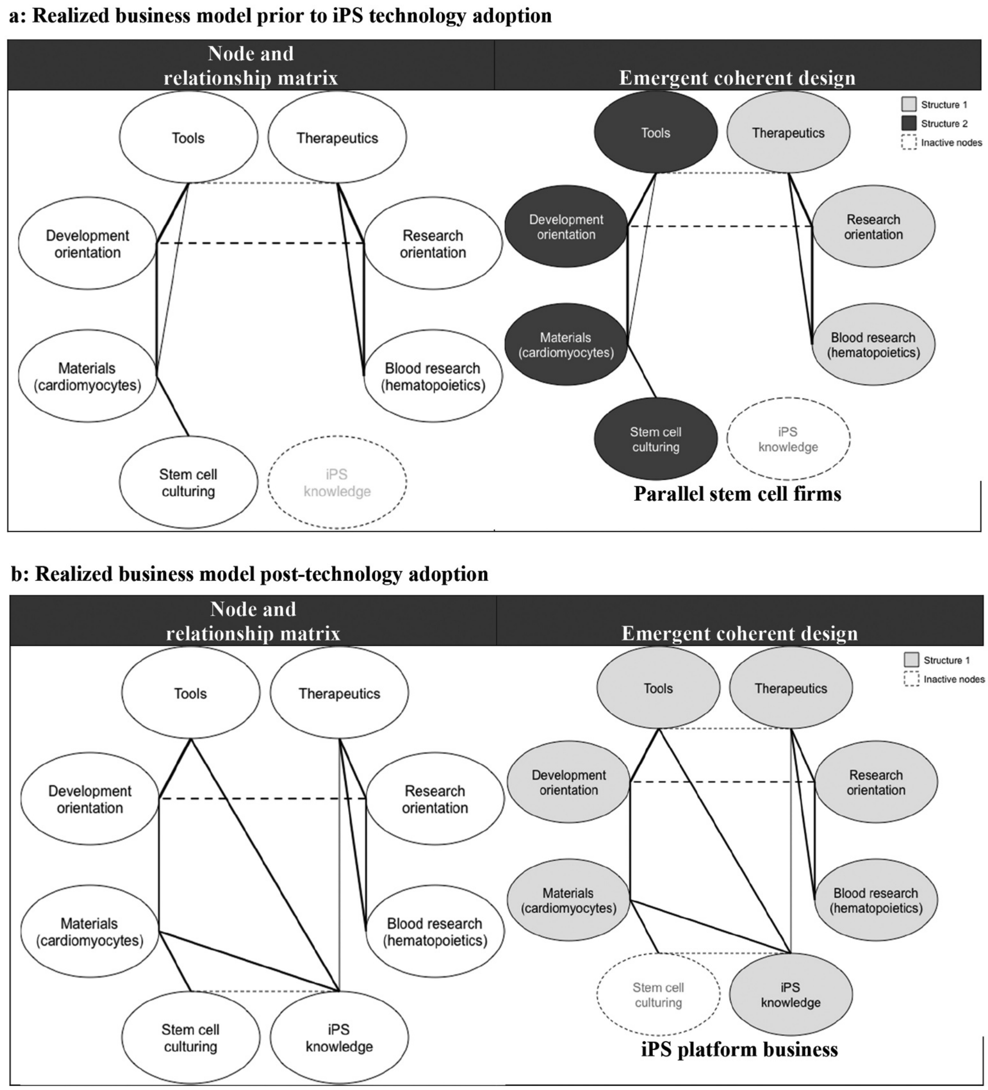

Figure 4. (a) Realised business model pre-disruption. (b) Realised business model post-disruption.

Table 3. Emergence of dominant business model configurations.

	Pre-uptake stage	Post-uptake stage		
Configuration	Initial conditions	Independent stages	Narrative arc, no confusion	Narrative arc, confusion
A) Parallel stem cell businesses	662	216	690	333
B) Stem cell platform	270	0	0	0
C) iPS platform		474	202	417
D) Parallel iPS-based businesses	0	308	0	250
E) Drug discovery	61	0	0	0
F) Null firm	7	2	8	0
N (TOTAL)	1000	1000	1000	1000

N = 1000 runs for each model stage

likely outcome. It corresponds to a single entity, multiple business model option debated and discarded by management in 2006.

Second model treatment: disruption and convergence to new equilibrium with path independent stages

The second simulation treatment sought a locally coherent configuration based on the mutated set of relationships after the disruption. This required a choice of new initial conditions for the second stage of the simulation. One option is an 'independent stages' approach to the narrative coherence problem: run the model with the new set of relationships based on random initial conditions. In other words, the starting point of the network after the disruption is not related to the configuration of the network at the end of the first stage. This narrative architecture is effectively a combination of two independent stories linked chronologically, but not causally, by the changeevent.

In the independent stages treatment, the iPS node was incorporated into the network and the transformation matrix expanded to incorporate the relationships between the iPS node and other nodes. The relationships among elements induced by the emergence of iPS were adjusted to account for the new node based on the quantitative data provided by the company president. We performed 1000 runs starting from random initial configurations. The most common stable post-disruption configuration emerging from the simulations is shown in Figure 4(b). Rather than two distinct organisational structures, a single primary structure emerges that excludes the 'stem cell culture skills' node.

This result replicates the actual events at the organisation, in which management chose to merge the distinct entities. It is useful to note that the final configuration incorporates conflicting interactions. In other words, the most coherent solution includes conflicts between organisational elements. In addition, while the model effectively reproduced the organisational structuring event as the most coherent configuration, it also demonstrates the possibility of alternative histories as unrealised designs. The persistence of a configuration with separate organisations was possible, though less likely.

Third model treatment: confusion and path dependent stages

While remarkably successful in recapitulating the actual outcome, the independent stages approach assumes no interdependence between the two firm stages. This is not satisfactory to model business model design choice within a framework of organisational continuity. Common sense suggests that when a firm decides to change its business model, it does not design that new business model entirely from scratch. Putting aside the presence of existing activities, resources, and transactions, it would be reasonable to expect that managers' cognition would be influenced by the recent experience of designing and running the original business model.

The obvious approach, more consonant with organisational inertia and path dependency, takes as a starting point the emergent configuration from the first phase. The disruption then represents a perturbation of the otherwise stable business model configuration. A fundamental aspect of disruption is surprise or confusion induced by unexpected or unfamiliar circumstances that generates a search for new meaning or purpose. This type of response is especially likely in this case example due the high level of uncertainty in the regenerative medicine industry. Businesses based on stem cell technologies operate amid unresolved regulatory frameworks, changing intellectual property landscapes that vary by country, and unproven business models. While regenerative medicine tools have experienced market growth, no stem cell therapeutics have been approved for treatment. Firms operating in fields targeting end-use therapeutics have little or no information on when such products will be market-viable, as key factors are partly or entirely out of the firm's control.

Was there evidence of this type of confusion within CELL? Word frequency analysis of the most common meaning-carrying words from interviews reveals the potential for multiple interpretations of organisational strategy and purpose at CELL following the disruption. Figure 5 shows the relative change in key word frequency for staff and executives' explanations for the firm's value creating activities between time 1 and time 2. The chart is ordered by relative difference in frequency (∂CXO – ∂Staff). Constructs on the left showed proportionately reduced emphasis by CXOs compared to staff between time 1 and time 2. Constructs in the middle showed roughly similar change in emphasis by CXOs and staff. Constructs on the right showed proportionately increased emphasis by CXOs compared to staff between time 1 and time 2.

The significantly different change in word use across subpopulations at the firm highlights the dynamic, discourse-centric nature of business model change. Executives and line staff reflect differently on the importance of key business model constructs, in particular the tension between near-term sales (cardiomyocytes), product development, and long-term research on therapeutics. The evidence demonstrates the impact of confusion at organisations during change. The uptake of iPS cells was generally understood by participants to be beneficial to the organisation. The event, however, had non-obvious implications for business model design, reflected clearly in simple semantic interpretations of the interviews and in first-level discourse analysis of changes in word frequency.

We introduced into the path dependent treatment a mechanism to simulate surprise or confusion following the perturbation. This was achieved by generating noise in the perception of relationship values during the element state updating process. Noise would be maximal at the moment of breach, and then decrease with time as the new situation becomes

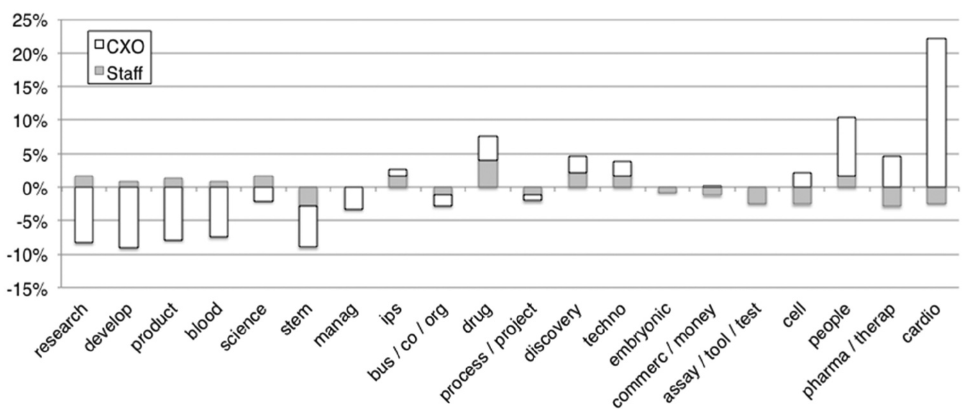

Figure 5. Relative change in word frequency before and after the disruption by informant subpopulation.

familiar. In the case of no confusion, actors are able to perfectly interpret the new relationships. In the confused case, noise after the breach induces false evaluation of the preferred node state in approximately one third of assessments. The error rate declines quickly to zero before a new equilibrium is reached, simulating participant learning. In the version of the model reported, noise decreased linearly to zero during the first 40 simulation periods. We tested other models of decay, including an exponential form, yielding comparable results. The model outputs for all of the path dependent simulations are shown in Table 3.

Clearly, confusion matters. In the path dependent, no-confusion case, the disruption is not sufficient to move the business model out of the locally stable equilibrium established in the first stage. In other words, the business model gets trapped in the initial stable configuration and is unable to respond to the disruption. As confusion is introduced the model becomes more reactive. Previously invalid configurations are reconsidered, albeit via potentially false interpretations of component relationships. This effectively reduces dependence on the liabilities of the past.

Figure 6 shows how the level of coherence changes along a simulated 'narrative arc' for one simulation run. Configurational coherence is the inverse of the level of frustration (*H*) in the network, where values of *H* represent higher coherence. The sample run output shows the relatively rapid convergence to stable initial configuration. The breakdown induced by a disruptive event, the change in model structure and relationships, generates a transient phase of high incoherence, followed by the convergence to the new equilibrium.

The results of the path dependent/confusion treatment resonate with narratives of business model change. The original coherent solution is both locally stable and carries significant organisational inertia. Coherent business model configurations are not, in fact, easily changed. They may not, in fact, be deterministically affected by relatively significant changes to the underlying network of structural relationships. The second result shows that when surprise or confusion is added, the observed outcome of the story tends to emerge, though not as dominantly. This reinforces prior investigations of organisational change suggesting that confusion plays an important role in decision-making and outcomes. In addition, it

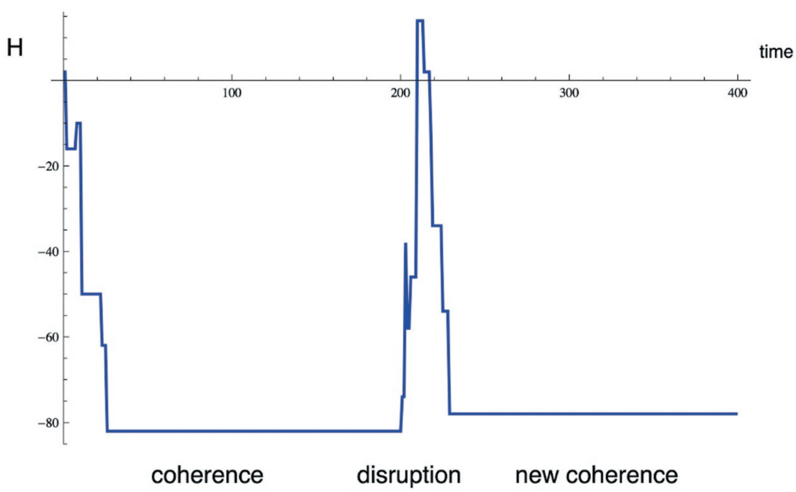

Figure 6. Network frustration (*H*) for sample simulation run.

emphasises that convergence to coherence is not instantaneous, and can be effectively modelled with an experimentally-driven search process.

Discussion

The case study and simulation results present numerous threads for discussion.Because the simulation is based on a single case study, we separate descriptive observations from prescriptive implications. Our descriptive findings focus on three observations. First, the constraint satisfaction system effectively replicates the business model of the study organization before and after the technology adoption. Second, the model presents an entirely new research finding: potential but unrealized business models. Third, uncertainty and confusion play an important role in the context of business model change. On the prescriptive side, we discuss how constraint satisfaction could explain business model design at entrepreneurial firms. Then we explore potential practical implications of the model for firms embarking on business model change.

Business model simulation validity

The simulation recapitulates realized business models at a study firm using a relatively simple network design. The model is methodologically more compelling when applied to the steady state prior to the technology adoption. Treating the "before" and "after" states as independent also replicates the realized business models but is methodologically inaccurate. Treating the "after" state as dependent on the "before" state more clearly reflects the nature of organizational change. The organization does not close and re-form from scratch—it must transition from one state to the next. Incorporating confusion into the simulation is consistent with the findings of the textual analysis of the interviews and replicates the realized business model change, although with less statistical certainty. We conclude that the model has face validity in replicating realized business model design and change, but clearly requires further investigation to be applied to more generalised situations.

The simulation also operationalises perceived relationships among organisational elements in a manner consistent with established strategic theories of fitness. While researchers argue that strategy is about relative advantage while a business model addresses viability (George & Bock, 2011), many scholars have noted key linkages between business models and strategy. It would be problematic if the fundamental heuristics determining business model configuration were drastically different from the factors that drive strategy formulation.

The framework also provides a mechanism for linking micro-level cognition with observed business model designs. Prior research has shown that business model configurations and narratives are co-created by participants, but no formal mechanism has been presented to show how individuals arrive at interpretations of business models that can be implemented at the organisational level. The predictive power of the convergence model shows that entrepreneurial cognition during uncertain choice likely utilises a heuristic of coherence to rapidly narrow decision sets. This is consistent with a sense-making interpretation in which entrepreneurs compare alternatives rather than attempt to evaluate unbounded choice sets. Business model design as coherence-seeking co-creation Turning to prescriptive implications, the results point towards the long-term potential for simulating business model design and change. On a theoretical level, the framework suggests a compelling mechanism for linking micro-level cognition with observed business model designs. Prior research has shown that business model configurations and narratives are co-created by participants, but no formal mechanism has been presented to show how individuals arrive at interpretations of business models that can be implemented at the organizational level. The predictive power of the convergence model shows that entrepreneurial cognition during uncertain choice likely utilizes a heuristic of coherence to rapidly narrow decision sets. In other words, entrepreneurs compare alternatives rather than attempt to evaluate unbounded choice sets. This is consistent with a sense-making approach to decision-making that has been extensively developed in psychology and legal research.

We suggest that organizational agents co-create business models through the lens of perceived endogenous relationships that incorporate information from the broader environment. Managers observe resource value and complementarity relative to the overall configuration of elements and their constraints. Decision-makers rely on fluid and flexible evaluation, rather than hierarchical ends-means reasoning, to assess possible business model configurations. The dynamic nature of the model allows for investigation of configurational evolution in the context of changing cognition and organisational elements. Figure 7 presents this conceptually, showing the transition from cognition about the baseline configuration to the exploration and comparison of alternative configurations and convergence back to a single design.

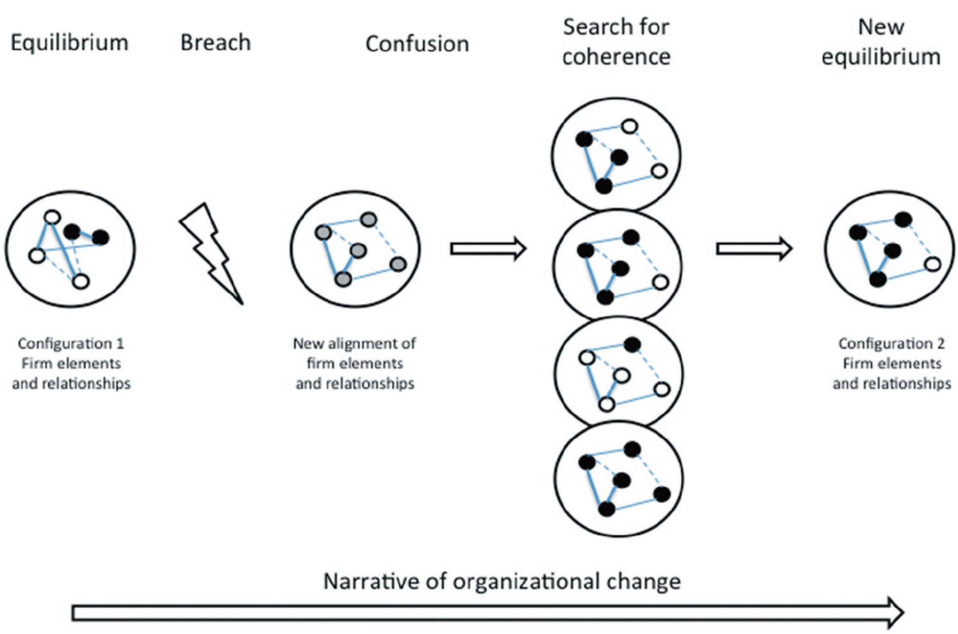

Figure 7. Model of business model change.

Surprise, uncertainty and confusion in business model change

Our study reinforces the role and relevance of surprise, uncertainty and confusion in models of organisational adaptation and change. Although such effects have been reported (e.g. Siggelkow & Levinthal, 2003), outcomes have not generally been linked to actual observed events at firms. Operationalising surprise or confusion as the mis-interpretation of element relationship proves surprisingly powerful in ‘nudging’ the model out of the local optima to the more distant, but higher value business model. The modelling exercise confirms prior research suggesting that delays and experimentation may enable managers to investigate or evaluate more distant or non-obvious options. The value of this cognition-centric approach is increased when natural language or communication limitations hinder quantification or specification of circumstances, variables, or relationships. This would be expected when firms bring radical innovations to market or when choice and implementation converge in time.

Potential but unrealised business models

To date, business model research has focused on “realized” business models where a specific design is selected or emerges. Our study is the first to reveal “potential” business models. The simulation run outputs in Table 3 show a number of potential but unrealised business models both prior to and after the technology adoption. These configurations are stable and coherent outcomes of the cognitive constraint satisfaction process. In other words, they represent business models that could “make sense” to managers were either not identified or not selected by managers. Figure 8(a,b) show these configurations for pre- and post-disruption respectively.

The simulation predicts the potential for dissolution of the business (‘null firm’) as well as configurations that reflect separation of value chains or even parallel business models. The study considers ‘what-might-be’ design choices, which until now has received very little attention in organisation studies (Burton & Obel, 2011). These are especially fascinating, because some represent outcomes that could be reasonably predicted from current theory (e.g. the parallel business model configuration could represent purposefully separating value chains based on transaction cost economics) while others may represent possible outcomes for which we have no obviously current theoretical justification.

The theoretical and practical implications for this type of simulation are significant. To our knowledge, no published studies have demonstrated a mechanism for methodically generating ‘potential’ business models. Could such unrealised design choices lead to potentially interesting configurations otherwise unobtainable from the realised design? In other words, is it possible to generate a science of organisational design in which imperfect business models are purposely chosen to expand opportunity sets and enable better outcomes? We did not experiment with the unrealised configurations in the initial phase (the ‘drug discovery’ and ‘stem cell platform’ firms shown in the Table 3), but future studies could do so.

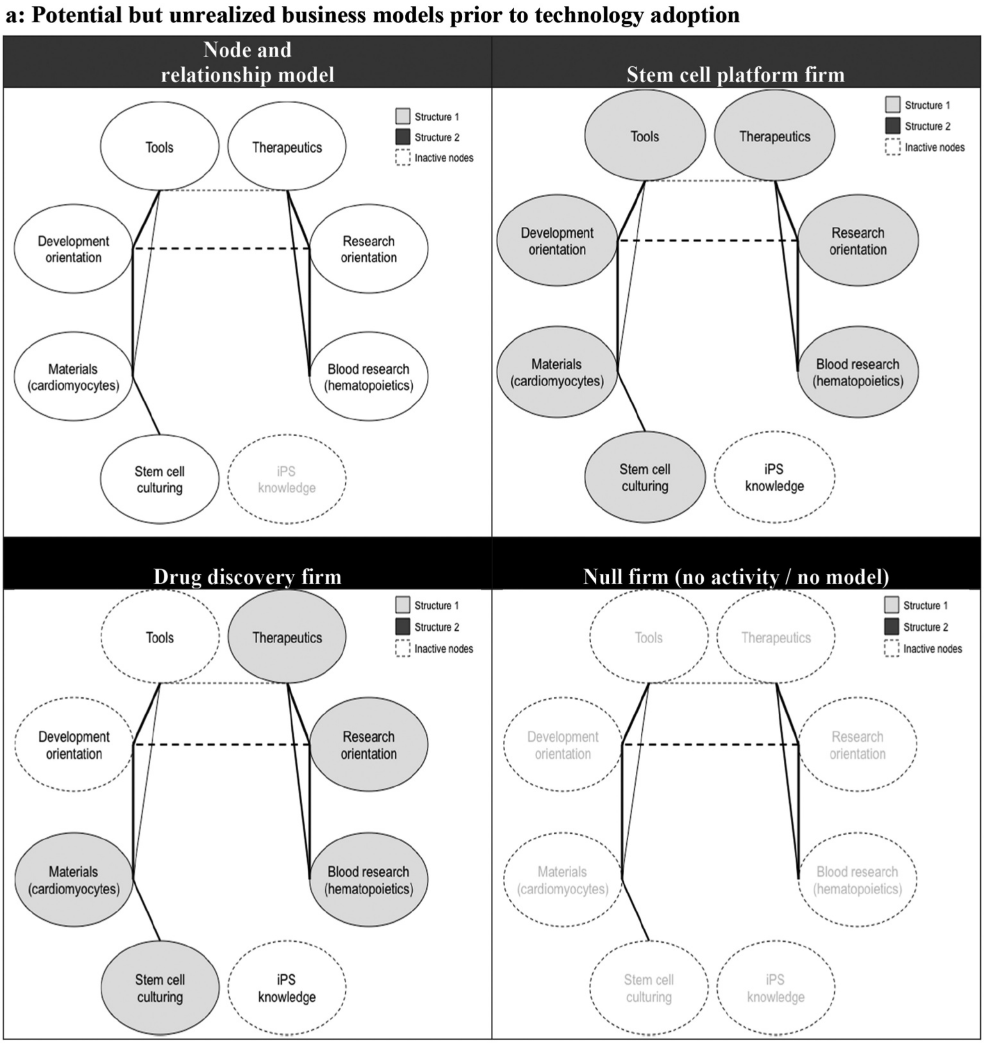

Figure 8. (a) Potential but unrealised business models pre-disruption. (b) Potential but unrealised business models post-disruption.

Implications for research and practice

At a practical level, the simulation provides a mechanism for exploring business model design where the constitutive elements of the network are treated on a basis of equal footing. This is valuable because it enables modeling based on information from potentially unsophisticated sources. It would be unrealistic to expect all entrepreneurs and managers to be capable of prioritizing or weighting business model elements. The specified model only requires weighting the connections between the elements.Practice tools such as the Business Model Canvas or Lean Startup Methodology present a consistent approach, but resulting configurations are entirely subjective. Recent studies call for more experimentation in these methodologies to create alternative models (e.g., Hampel et al., 2020a). As noted previously, the constraint satisfaction model represents a

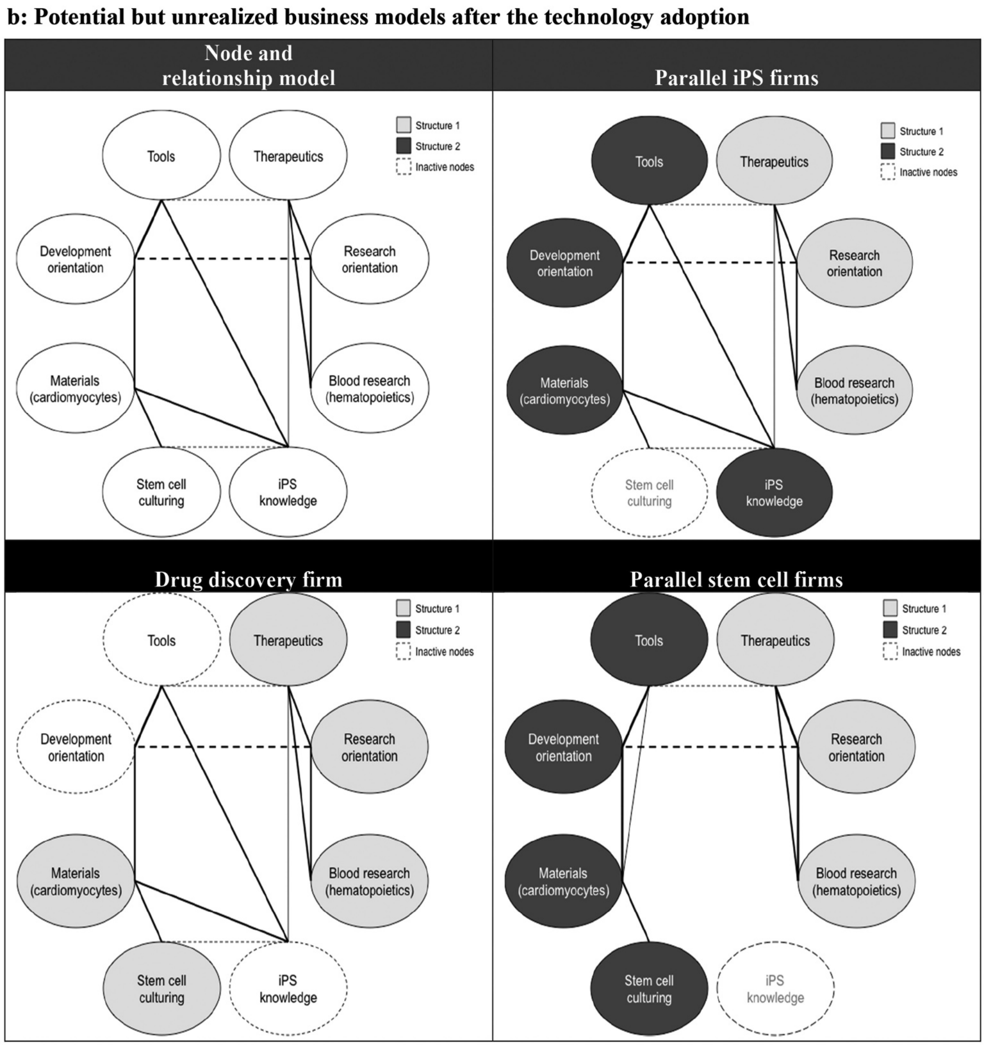

Figure 8. (Continued.)

different simulation approach from agent-based modeling. But more sophisticated modeling could embed the constraint satisfaction model into a larger agent-based simulation. This could incorporate asymmetric and/or asynchronous weighting of multiple voices or coalitions within an organization. Each agent (node in the larger model) is represented by the underlying cognitive constraint satisfaction model, which could be homogenous or heterogeneous as data availability and modeling sophistication allow. Connecting the nodes into an agent-based model could explicitly reveal how business model cognition propagates through organizations, providing further insight into business model inertia as well as how some business model configurations are de-emphasized. This could even be extended to larger in which organizational sub-structures are perceived as sub-groups of nodes or connected sets of nodes.

The interconnections of business model elements are as important as the elements themselves (Massa et al., 2018). Arbitrarily changing business model elements could therefore generate entirely unintended consequences in resulting business models. This should serve as both a cautionary tale for entrepreneurs as well as a call-to-arms for business model researchers. Simulating business models offers a unique opportunity to generate tools that complement entrepreneurial decision-making, precisely by identifying potential business model outcomes that are unlikely to be generated by human brainstorming. Entrepreneurship researchers might take a page from the application of neural networks to chess, which has generated entirely new (e.g. "non-human") interpretations of strategies and configurations (Kasparov, 2018).These results point towards entirely new research directions on business models. First, we need to know how effectively the coherence heuristic replicates managerial decision-making about business models. Was this case an anomaly or indicative of the how managers really think? Second, does the coherence heuristic have any connection to business model viability? Third, the simulation provides a powerful tool for re-examining developing theories on business model change (Shepherd & Gruber, 2020). Although the framework requires further investigation to be generalized, it presents a more formalized approach to business model configurations than previously described in the literature. Our case study venture is also a university technology-based spinoff in the life sciences. University technologies often suffer from the lack of clear commercialization pathways and business models for nascent technologies (e.g., George & Bock, 2012; Johnson et al., 2019). Having simulation as a tool to understand potential organizational design choices could be useful in such contexts where multiple potential pathways to success exist.

The study has certain limitations. The context of the study is specific to a small, high-tech entrepreneurial organisation. It seems likely that the evolution and propagation of business model sense-making within these organisations differs from larger firms in more stable industry environments. Our data validation was also limited to the key decision-maker at the firm. At the same time, significant value may be obtained from a single informant, especially at entrepreneurial organisations (Lyon et al., 2000). Research demonstrates the value of investigations based on single-source analysis, where 'the CEO has a particular integrative function within the top management team' (Calori et al., 1994, p. 439), especially when that individual effectively determines the type of significant corporate change event described in the study. Finally, we cannot show causality in the relationship between organisational narrative and business model design. Continuous micro-level data might reveal directional effects between narrative and design.One additional concern is the possibility that our interviews, some of which were conducted immediately prior to the business model change, might have influenced managerial thinking about business models. This is of particular concern as the lead interviewer has also started and run similar types of biotechnology ventures, and might have been viewed by interviewees as a knowledgeable source of information or even an expert on biotechnology business models. While all such investigations are understood to have some effect on individual and organizational cognition, we believe the impact in this situation to have been especially limited. First, the phrase "business model" was not used in the interview script; interviewees were never prompted to discuss the firm's business model. Second, although the business model change was executed between rounds of interviews, executive discussion and option generation around the firm's situation had been ongoing, motivated by the impending financial needs of the organization. Finally, the lead interviewee was never directly asked for his opinion about either the firm's business model or any other aspect of the firm's long-term plans. While some influence cannot be entirely ruled out, the risk of direct and substantive influence on firm behavior appears limited.

Conclusion

This study reports the first theory-based simulation of business model design and change. In contrast with prior work, we explicitly model the components and relationships of a business model using a constraint satisfaction network. The simulation effectively replicates observed business models at a relatively small technology venture and highlights the role of confusion during business model change. Of special interest is the generation of potential but unrealised business models. In bringing simulation into the study of narratives and managerial cognition, our study contributes to theories of business model design and change and the broader field of modelling organisational phenomena.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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