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COMPUTATIONAL MODELLING OF DESIGNER-USER INTERACTIONS AND VALUE SYSTEMS

Exploring how situated cognition and social interaction shapes innovation

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Abstract. This paper develops a multi-agent computational model to simulate the effects of designer-user interactions on the design of products, interactions that are both direct and indirect. The architecture of an agent-based computational system is described, with emphasis on how it models situated design computing and cognition, including both designer and consumer agents. Indicative results obtained from running simulations are presented. The primary contribution is to demonstrate that situated design computing and cognition can be modelled using Computational Social Science methods.

Keywords. situated design computing; multi-agent systems; agent modelling; designer-user interaction; innovation; simulation.

1. Introduction

This paper develops a multi-agent computational model (Ferber 1999, Weiss 2000) to simulate the effects of direct and indirect designer-user interactions. In particular, we are interested in studying how designers choose from alternative new product designs over time, where the consumer utility of design alternatives is shaped by the co-evolution of designer and user value systems through their direct and indirect interactions.

In the eyes of a designer, consumers often react to a new product introduction in surprising and unexpected ways. These unexpected reactions are both a source of risk – products may fail in the marketplace – and a source of innovation as new uses or new utility are discovered, which in turn create opportunities for new directions in product design. Both designers and users form their expectations prior to and during new product design, including their experience with previous designs. We call their cognition 'situated' because, for any designer or user, it matters where you are when you look at the world; it matters what you interact with and when; and finally, your values are a function of your past and of your present interactions. But behaviours in the post-introduction phase are not simply a matter of having expectations met or not. Instead, there is often a complex interplay between cogni- cognition, value systems, and social interactions that reshape the design landscape and, thus, cause designers to re-evaluate their plans and strategies for future designs. This can be illustrated as follows.

Over the course of several product design generations, a designer will probably develop design competency in some areas (e.g. high volume production, narrow tolerances, or ergonomic design.) and not in others (e.g. reliability in extreme environments, high performance, or small runs of custom configurations) (Thrane, *et al* 2010). Reinforced by success in the market, this designer will tend to value future designs that utilize the designer's competencies and exclude the design characteristics where the designer has little or no competency. Essentially, these design preferences are the designer's value system, which is also reflected in the designer's preferred stream of new product designs. We can view a stream of new product designs as a trajectory within the space of possible designs or within the space of possible performance/cost ratios. From their viewpoint, the designer prefers new product designs that are similar to those where the designer has the most experience and expertise, where it has relatively good profitability, and also where the designer expects user demand to be high or at least adequate. If users behave as the designer expects based on pre-design and design work, then the designer's strategic choice boils down to choosing the optimal design trajectory and then executing it effectively.

But if users do not always react as expected or if they engage creatively with new and existing products in the post-design phase, then designers must constantly re-evaluate their strategic choices. This might mean abandoning existing competencies and preferred design strategies in favour of new and untried paths. It might also mean that the designer might benefit from serendipitous events – e.g. product characteristics that were previously not valued by users suddenly come into favour, allowing a marginal designer to rise to market leadership. Designers that successfully observe and learn from users in the post-design phase can then adapt their strategies and plans in the subsequent pre-design and design phases, including the possibility of making fundamental changes in strategy or architecture.

2. Theoretical Foundations

Kaplan and Tripsas (2008) apply a cognitive lens to understanding technology trajectories across the life cycle by developing a co-evolutionary model of cognitive frames and technology, based primarily on case studies.

Nelson (2002) and many others have used agent-based modelling and simulation to study innovation. Dosi (1982) introduced the idea of viewing technology evolution as trajectories through the space of possible designs, and movement along a trajectory as the result of "normal problem-solving" and "progressive refinement" by producers as they find ways to improve trade-offs in design variables. As Dosi & Nelson (2010) describe, technology trajectories have a downward causal influence on agents, effectively circumscribing technological advances "within a quite limited subset of the techno-economic characteristics space" (also see Sahal 1985).

Saviotti (1996) presents a more formal model of technological evolution through design space (‘Space’ is defined by dimensions for each technical and service characteristic associated with a particular technology.) ‘Characteristics’ are formalized as a vector of variables that specify both a product’s internal structure (‘technical characteristics’) or services performed for its users (‘service characteristics’) (Saviotti & Metcalfe 1984). We apply this method for modelling the space of possible designs.

Saviotti (1996) also proposes methods of analyzing population-level dynamics in design space such as movement along trajectories and changes to the ‘technological frontier’, which is the limit of what is producible with current costs and capabilities, while the designs in the set of the ‘adjacent possible’ are alternatives to expand the frontier.

Regarding user/consumer preferences, opinions, and consumer behaviour, Leggatt (2010) evaluates alternative methods for mapping consumer preferences at the population level using perceived product characteristics and their ‘ideal product’ that can be formalized as a vector of values for each service characteristic of the product. Leggatt also uses Multi-dimensional Scaling (MDS) to create a 2D map of a population of consumers’ ideal vectors relative to the available products. Friedkin & Johnsen (1999) explain how consumers influence each other’s values through social interactions.

Situated cognition (Clancey 1997, Smith & Gero 2005) provides the theoretical basis for our design of agent cognition. Through the lens of situated cognition, innovation in a social ecosystem is an emergent phenomenon that arises from the interplay of situations, constructive memory, and social interactions at the level of agents and networks of agents. Gero and Kannengiesser (2009) describes how innovation can be analyzed in terms of changing value systems of designers, users, and other agents.

3. Overview: The Multi-agent System

Our multi-agent system is a computational laboratory (Casti 1999) designed to support a wide variety of experimental settings and tests. Broadly, our research goal is to study emergent phenomena that are not simple aggregations of the micro-behaviours (Goldstein 1999, Gilbert 2002).

There are two types of agents in the current implementation – 'Consumers' (users) and 'Producers' (product designers) – and one type of artefact – 'Products'. Throughout each simulation run the population size is fixed for all agents and artefacts. Consumers seek to consume Products by moving around a geographic Consumption Space with micro-behaviour similar to foraging, but with social interactions. Consumers are not endowed with any knowledge or map of the Consumption Space, nor do they have any memory of where they have been. Consumers are social, while Producers are not. The social network among Consumers is initialized as a "small world" network with random assignments. Once the simulation starts, Consumers form new social relations when they meet each other or by referral through their existing social network. The initial strength of a social tie is proportional to the similarity between the two Consumers. Strength of social ties decay with time unless they are recharged by exchanges of information.

During simulation initialization, the full set of Product types are generated and these comprise the 'Product Design Set', i.e. the set of possible new Products that may be introduced during the course of a simulation run. A subset of these Products is selected as the initial set of 'active' Products. Each new Product type is selected from the 'adjacent possible' relative to the currently 'active' Product set. Each new product introduced expands the 'adjacent possible' to include Products that were previously not feasible for Producers. If the Product Design Set is large relative to the length of a simulation run and the rate of new Product introductions, then we are able to simulate a continuous stream of innovations.

Producers only take action when a Product is consumed or expires. When that happens they make a decision to either replace it with an identical Product type, a different Product type in the portfolio of available types, or to introduce a new Product type that had previously not been available. Producers have no direct interaction with or knowledge of individual Consumers; therefore they make their decisions based on historical data regarding the consumption and expiration Products of various types. In the results presented in this paper, the simulation was configured to have a single Producer.

4. Computational Modelling of Agents and Artifacts

4.1. PRODUCTS

Products are abstract and are constructed as a connected graph structure with six nodes and between 5 and 14 edges. There are 112 unique six node connected graphs, yielding a sizable design space for agent exploration, yet it is small enough to be tractable for enumeration and complete analysis.

Crucially, Products have both a surface characteristics and functional characteristics. During their search and evaluation process, Consumers can only sense and perceive a Product’s surface characteristics (its "signature"). The functional characteristics are only experienced through the process of consumption. A Product’s external appearance to Consumers is a function of its physical layout while its utility to Consumers is a function of its topology.

In addition to these two views that are relevant to Consumers, we also characterize Products in ways that are particularly relevant to Producers. This is an important feature to our design because of the need to model plural interests, perceptions, and value systems between Producers and Consumers. We have adapted the idea of "production recipe" from Auerswald et al. (2000). A production recipe is a vector of characteristics that is related to the production or assembly process, and therefore to the costs and complexity of manufacturing and the challenges of learning through experience. The Hamming distance between any two recipes is a measure of accessibility from one to the other through learning-by-doing and also explicit design explorations.

Cost to manufacture a given design has two components: 1) materials, a simple function of the number of edges; and 2) assembly, a function of the recipe and the Producer’s cumulative experience in each of the dimensions of the recipe. Initially most of the designs are too expensive to manufacture, rendering them infeasible. With experience the exponent of the cost function is reduced until to plateaus to yield a linear function of each recipe element value.

Through current production, Producers gain experience in recipes that have commonalities across different Products, not just those they are producing. Thus, Producers can lower the cost to manufacture for Products in the ‘adjacent possible’ region of design space that have similarities in recipes. It is not governed by foresight or planning. Instead the trajectory of design choices emerges through a series of local/limited decisions, adaptations, and also due to constraints of attention.

4.2. CONSUMERS

Figure 1 shows a simplified block diagram of the Consumer architecture. To implement situated cognition, this agent architecture includes both symbolic reasoning and sub-symbolic reasoning (Gero and Kannengiesser 2003).

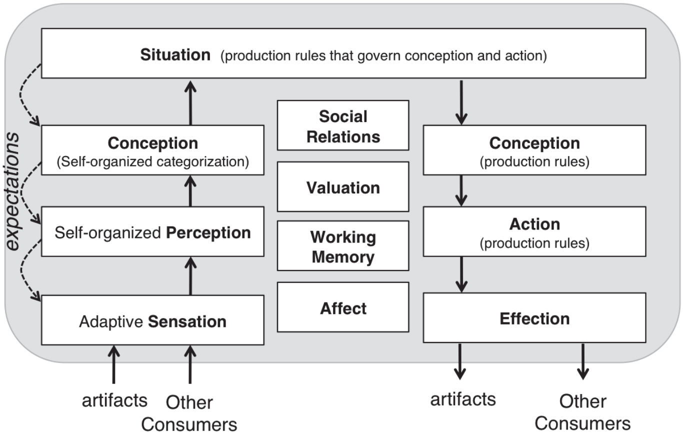

Figure 1. Consumer agent architecture

Consumers search the landscape for attractive Products to consume, and they form social networks in the process. Consumers modify their values through direct product interaction (evaluating and consuming Products) and through social interactions. Consumption decisions and subsequent learning are mediated by two independent variables – 'value' and 'utility'. 'Value' is the Consumer's appraisal of a Product based on its surface characteristics, relative to that Consumer's ideal. Thus, valuation is performed prior to any consumption decision. Consumers choose to consume based on their perception of product signature, perception of proximity to their ideal type, and a rough expectation of utility. Generally, Consumers choose to consume when the Product they encounter is close to their ideal type. The space of possible Product signatures, along with the utility of each Product, is called the Value Space. The value system for each Consumer centres on a single vector that represents the signature of its ideal product type. Consumers learn and adapt by adjusting this vector through experience and social interaction. Therefore, each Consumer's value vector can be represented as a point in Value Space.

In contrast, 'utility' is the benefit that the Consumer receives after consuming the Product. It can only influence future consumption decisions through agent learning and, indirectly, through social interactions. In the current implementation, there are three possible utility dimensions, described above, and the utility function is a weighted sum of the three dimensions.

However, the weights are adaptive and have a degree of random "jitter" to simulate trial-and-error exploration of alternative utility functions. Therefore, each Consumer evolves its own unique utility weights with experience and through interactions.

At a social level, Consumers create and maintain social relationships through physical contact in the Consumption Space or through social interactions. The social interactions focus on soliciting or offering information about another Consumers ideal product. We simulate the phenomena of opinion leadership and also susceptibility to influence from others.

4.3. PRODUCERS

Producer agents have a simple architecture focused on two decision processes. They use simple decision rules based on local optimization and, unlike Consumers, do not have any other cognitive capabilities for sensation, perception, conception, or affect. The only decisions they make are 1) *current production* – choosing a replacement product from existing designs to replenish inventory in response to Consumer acts of consumption, and 2) *new product introduction* – choosing a new product design to introduce from the designs that are in the ‘adjacent possible’.

Because of feasibility and cost constraints, Producers will initially produce the designs with lowest costs (both design and manufacturing) and therefore relatively low (unattractive) performance/cost ratios. Subsequent new product introduction choices are made from the designs that are next in sequence of performance/cost, given the Producer’s performance function (weighted sum). When more than one product design is in the ‘adjacent possible’, Producers face a strategic decision to either stay on their current design trajectory or to move on to a new trajectory. Where design trajectories diverge ("branching points"), Producer choices for which new product to introduce determine which design trajectory is realized and which are not. This creates path dependence in Producer and Consumer values.

5. Experimental Methods

The phenomena of interest are *design trajectories* in the space of Product types, as measured by performance/cost ratios over time. Divergences between alternative design trajectories represent discontinuous change and (potentially) disruptive innovations. Our experiments compare three settings:

- Setting 1. A single Producer acting in isolation from Consumers, with a deterministic consumption rule.
- Setting 2. Consumers acting in isolation from Producers, with a deterministic Product replacement rule.

Setting 3. A single Producer interacting with a population of Consumers, with endogenous consumption and production/innovation processes.

Within these settings, we evaluate alternative rules for Producers' new product introductions – minimize cost, maximize performance, or maximize performance/cost ratio.

6. Results

Figure 2 shows design trajectories for a single trial for Setting 1 "Producer only", with three Producer rules. Trajectories are overlaid on a background graph of the 112 members of the Product Design Set. Proximity in the layout implies similar recipes. Under Rule 1 in Fig. 3a, the trajectory converges quickly to simple designs because of the positive feedback between production volume and cost reduction, and Consumer values don't have much influence. Under Rule 2 in Fig. 3b, the trajectory explores more of the space of possible designs, and eventually reaches the most complex designs. Here, evolving Consumer values has a dominant influence. Under Rule 3, the results are similar to Rule 2 but the trajectory is more complex. Here, both Producer and Consumer values influence the trajectory, leading to more diverse mix of designs in the active set.

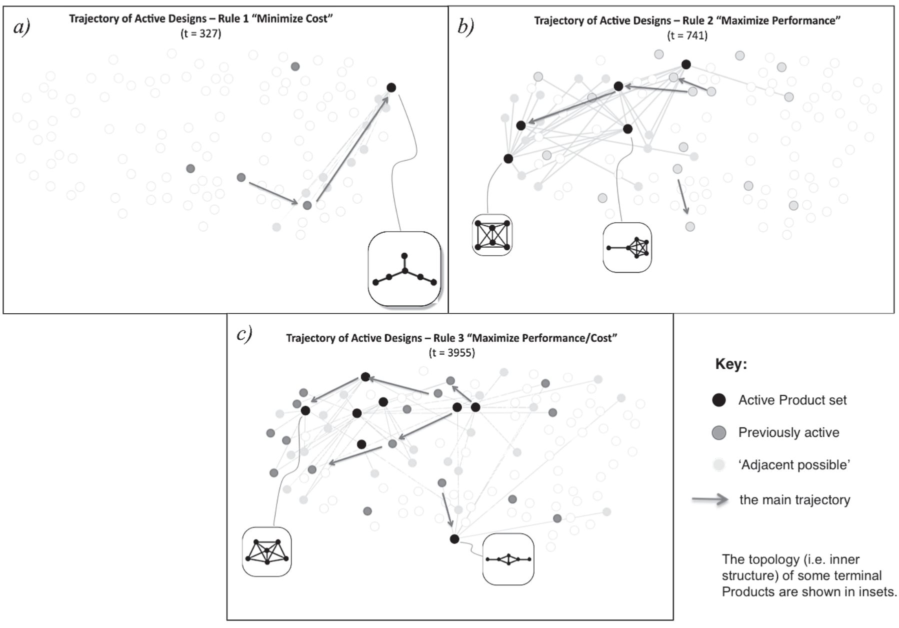

Figure 2. Design trajectory from a single trial in Setting 1, "Producer only", under a) "Minimize cost", b) "Maximize performance", c) "Maximize performance/cost ratio".

Figure 3 shows the influence of Consumer values and learning processes. In both a) and b), the Producer is using Rule 3: "maximize performance / cost ratio". With no interaction with Consumers (a), the Producer advances farther on the design trajectory. Pace of advance along the trajectory is slower in (b) because Consumer’s values don’t change as fast as new products are being introduced.

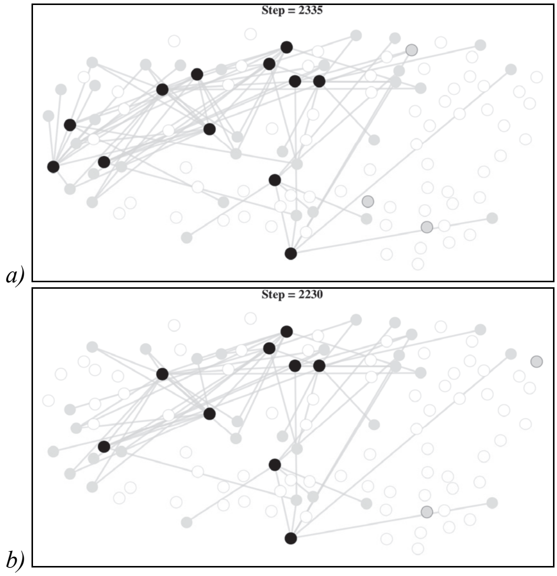

Figure 3. Snapshots of active product sets (black dots) for a) Setting 1 "Producer only" and b) Setting 3 "Producer-consumer interaction", with the same initial conditions and stopping at the same target value for "performance/cost ratio".

7. Discussion

While the results in this paper are preliminary and illustrative, we believe they begin to show the benefit of Computational Social Science methods. The architecture of the simulation system demonstrates that it is feasible to build rich computational models to study the simultaneous influence of several factors at once, and across different social levels.

A significant benefit of computational modelling is the ability to run both exploratory and controlled experiments that have demonstrable relevance to real-world settings. Another benefit is the ability to measure and evaluate changes in value systems in the context of innovation, both at the level of an individual, in a group, and in a population. With further experiments and results, we expect that our experiments will reveal emergent patterns of organization shape the Producer’s design choices.

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References

Auerswald, P, Kauffman, S, Lobo, J, & Shell, K: 2000, The production recipes approach to modelling technological innovation: An application to learning by doing, *Journal of Economic Dynamics and Control*, **24**(3), 389–450.

Casti J.: 1999, The computer as laboratory: Toward a theory of complex adaptive systems, Complexity **4**(5), 12-14.

Clancey, W. J.: 1997. *Situated Cognition: On Human Knowledge and Computer Representations*, Cambridge University Press.

Dosi, G.: 1982, Technological paradigms and technological trajectories, *Research Policy* **11**(3), 147-162.

Dosi, G., and Nelson, R. R.: 2010, Technical change and industrial dynamics as evolutionary processes, *in* Hall, B., Rosenberg, N. (eds.), *Handbook of the Economics of Innovation*, Amsterdam: Elsevier, 51–127.

Ferber, J.: 1999, *An Introduction to Multiagent Systems*, Addison-Wesley.

Friedkin, N.E. and Johnsen, E.C.: 1999, Social influence networks and opinion change, *Advances in Group Processes*, **16**, 1-29.

Gero, J.S. and Kannengiesser, U.: 2003, Function-behaviour-structure; A model of social situated agents, in Sun, R. (ed), *IJCAI03 Workshop on Cognitive Modelling of Agents and Multi-Agent Interaction*, IJCAI, Acapulco, 101-107.

Gero, J. S. and Kannengiesser, U.: 2009, Understanding Innovation as a Change of Value Systems, In *Growth and Development of Computer Aided Innovation Third IFIP WG 5.4 Working Conference; Proceedings, CAI 2009*, Harbin, China, 249–257.

Gilbert, G.N.: 2002, Varieties of emergence, *in* Macal, M. and Sallach, L. (eds.), *Social Agents: Ecology, Exchange and Evolution*, University of Chicago Press, pp. 41-50.

Goldstein, J.: 1999, Emergence as a construct: History and issues, *Emergence: Complexity and Organization*, **1**: 49-72.

Kaplan, S. and Tripsas, M.: 2008, Thinking about technology: Applying a cognitive lens to technical change, *Research Policy*, **37**(5), 790–805.

Leggatt, R.E.: 2010, Multivariate approaches for relating consumer preference to sensory characteristics, *PhD Dissertation*, Graduate Program in Food Science & Nutrition, Ohio State University.

Nelson, P.R.: 2002, A simulation-based approach to understanding the dynamics of innovation implementation, *Organization Science*, **13**(2), 109-127.

Sahal, D.: 1985, Technological guideposts and innovation avenues, *Research Policy*, **14**(2), 61-82.

Saviotti, P. P.: 1996, *Technological Evolution, Variety, and the Economy*. Cheltenham, UK: Edward Elgar Publishers.

Saviotti, P. P. and Metcalfe, J. S.: 1984, A theoretical approach to the construction of technological output indicators, *Research Policy*, **13**(3), 141-151.

Smith, G. and Gero, J.S.: 2005, What does an agent mean by being "situated"?, *Design Studies* **26**, 535-561.

Thrane, S., Blaabjerg, S., and Møller, R. H.: 2010, Innovative path dependence: Making sense of product and service innovation in path dependent innovation processes, *Research Policy*, **39**(7), 932–944.