Collective Intelligence and Algorithmic Governance of Socio-Technical Systems

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1 Introduction

The methodology of sociologically-inspired computing [10] endeavours to support systems engineering by developing formal and algorithmic models of social processes. The general idea, on encountering an application problem, is to introspect on how people solve such problems, and use that as inspiration for a technical solution. We note, *en passant*, that the paradigm of biologically-inspired computing operates in much the same vein (e.g. [1]), taking instead natural (biological) systems as its source of inspiration.

The methodology, itself a generalisation of Steels' synthetic method [27], is illustrated in Fig. 1. The steps involved are: given a problem, identifying a theory from the social sciences of how people solve that (or an analogous) problem (*theory construction*); developing a formal model of that theory in an appropriate calculus (*formal characterisation*), where by calculus we mean any formal language enabling symbolic representation and manipulation; implementing that formal model (*principled operationalisation*); and then testing the implementation to determine if it provides a solution to the original problem (*controlled experimentation*). Implicitly or explicitly, the methodology has been applied to Dennet's Intentional Stance [7] to produce the BDI agent architecture [25]; cognitive, psychological or physiological models to provide decision-support systems based on trust [15], forgiveness [29] and emotions [18]; legal and organisational models to provide a framework for agent societies [2], and learning by imitation for human-robot interaction [6].

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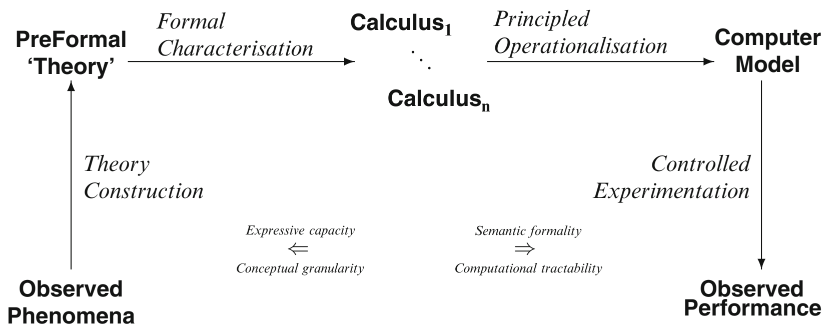

Fig. 1 Methodology of sociologically-inspired computing [10]

In describing the methodology, Jones et al. identify a number of adequacy criteria for the transition, at each step, between the conceptual theory, formal representation(s), and the implemented model. This is because the final model is *not* a precise testable model of the original social system with predictive and explanatory capacity; and nor is it intended to be. It is designed only to provide an algorithmic solution to an application-specific problem, and in applying the methodology there might have been 'theory loss' (simplification of the theory or the formal representation because the concepts are too complex to formalise or are computationally intractable) and 'application gain' (enrichment of the formal representation or implementation due to domain-specific aspects of the application, not conceptualised by the theory).

On the other hand, it is an intriguing question: *what happens when the algorithmic solution to the engineering problem is offered to the people who have to solve the same problem, i.e., the one that inspired the solution?*

This is the question that is addressed in this chapter. In applying the methodology of sociologically-inspired computing to the idea of self-governing institutions for common-pool resource management, we have established an algorithmic basis for self-organising resource allocation in open computer systems and networks [20, 23] based on *computational justice* [22]. This chapter investigates what happens when this algorithmic basis of 'justice' is made manifest to users in socio-technical systems, and when the technical components have to represent and reason with qualitative values of primary concern to the users.

The issue is investigated from the theoretical concept of 'justice' and the formal representation of different aspects of 'justice' in computational form (Sect. 2), and from the application perspective of decentralised Community Energy Systems (Sect. 3). Then we consider the injection of the algorithmic basis for these concepts of justice being manifested into a socio-technical system for 'fair' demand-side self-organisation in a decentralised Community Energy System. Two systems are presented, in Sect. 4 a system based on collective awareness in a 'serious game', and in Sect. 5 based on representation and reasoning with an electronic form of social capital. We summarise and conclude in Sect. 6.

2 Computational Justice

2.1 Open Systems: Some Issues

Open decentralised computer systems and networks often require the system components to share resources (e.g. bandwidth, memory, energy) in order to achieve their individual goals through the coordinated actions of a group. In the absence of a centralised controller and given the autonomy of the components (i.e. hereafter called agents), let us suppose, in the first instance, there is a system specification defining a set of rules giving the resource allocation method to be used in computing the actual resource allocation.

In fact, the resource allocation problem itself is compounded by a number of other requirements and complicating factors. This includes:

Self-determination. In a system of completely autonomous agents, which may vary over time, and the wide range of possible resource allocation methods available and different outcomes they can produce, the resource allocation method should be determined by the agents themselves. In particular, each agent is entitled to assess the subjective 'quality' of the resource allocation by whatever criteria it considers appropriate, e.g. fairness, equity, utility, etc.

Uncertain resource variation. The system may vary from times in which there is an abundance of resources, to periods where it must operate in an *economy of scarcity* (cf. [26]) in which there are sufficient resources to keep the appropriators 'satisfied' in the long-term, but insufficient resources to meet everyone's demands at any a particular time-point, to times of crisis where the system faces complete failure.

Expectation of error. In the presence of competition from autonomous agents and conflicting goals, sub-ideal behaviour (everything from non-compliance to the specification to 'selfish' behaviour which diminishes the global collective welfare, such as free riding) is to be expected. However, errors may be a result of accident or necessity (e.g. as a consequence of resource variation), as well as malice: in such competitive or transient situations, there is an incentive to maximise individual utility by not contributing to the collective while still benefiting from the contributions of others, i.e. free riding.

Enforcement. Open systems might as well use random allocation and operate under the principle of *caveat emptor*, if agents are not monitored so can transgress at will, or can repudiate agreed rules and sanctions for non-compliance by refusing to abide by their outcomes.

Endogenous resources. In a system where all the resources are provided by the appropriators themselves, as in a sensor network or a micro-grid, all tasks such as determining the resource allocation method, computing the resource allocation itself, and monitoring the resource appropriation, must be 'paid for' from the very same resources. If so much resources are expended on these activities it might leave nothing for 'real' jobs (both [19] and [3] report how the costs of needless and/or excessive monitoring deplete resources in this way).

No full disclosure: the appropriators are autonomous and internal states cannot be checked for compliance (with conventional rules), so incoming agents do not have all the information required for necessarily reliable investment decisions (e.g. contributing to a common pool).

However, all these features are routinely encountered in social situations, and in fact, addressing each of these factors seems to involve some concept of 'justice'.

2.2 Computational Justice: The Programme

'Justice' is a concept that has been of concern in philosophy and jurisprudence (*inter alia*) since antiquity, and we do not intend to review this history or provide a formal definition. However, in the research programme of 'computational justice' we are, intuitively, trying to capture some notion of 'correctness' in the outcomes of algorithmic decision-making (specifically concerned with outcomes of resource allocation processes), thereby trying to accommodate some elements of fairness, utility, equity, proportionality and tractability in the process.

On this understanding, we observe that different 'qualifiers' of justice, that have been used in the social sciences, can be identified to address the key features of open self-organising systems previously specified:

- self-determination requires a concept of *natural* justice in dealing with a shared or common-pool resource (cf. [16]), specifically recognising both membership rights and the right of those affected by rules to participate in the selection of the rules, usually by voting;
- uncertain resource variation not only requires some self-determination in the selection of the rules congruent with the circumstances (abundance, scarcity and crisis), but some familiar fairness and efficiency criteria, like Pareto efficiency and envy/freeness, may be ineffective for all conditions, and a more flexible concept of *distributive* justice [26] is required, including a subjective agreement on fairness norms is required [9];
- expectation of error and enforcement of rules requires monitoring and assessing behaviour, and the enforcement of sanctions for identified non-compliant behaviour, requires a concept of *retributive* justice: this includes distinguishing between different types of error, ensuring that punishments are proportional to the extent of the 'wrong-doing', and offering the chance of redemption and allowing for appeals are essential aspect to consider;
- dealing with endogenous resources requires a concept of *procedural* justice: if the administration of the rules has to be 'paid for' from the same resources that are otherwise allocated for 'useful' jobs, then it is necessary to ensure that they are, in some sense, 'fit-for-purpose' [21]; and
- dealing with lack of full disclosure requires an element of interactional justice, namely *informational* justice, to force disclosure of relevant information.

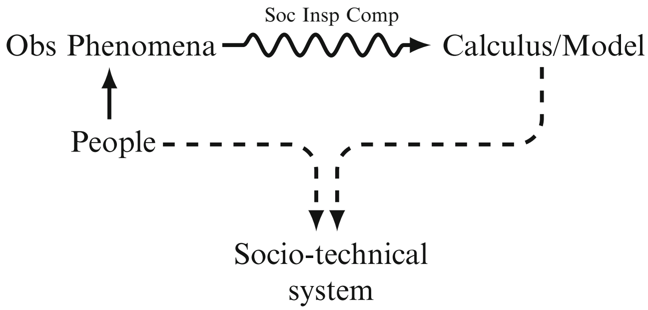

Fig. 2 Computational Justice: from technical systems to socio-technical systems

Therefore, our application of the sociologically-inspired computing methodology has focused on analysing theories of different aspects of justice, formalising them in a calculus—we have used the Event Calculus [11]—and then implementing them as computer models, either directly in Prolog or using the multi-agent system simulator and animator PreSage2 [12]. Amongst others, two significant results to highlight are:

- Showing that Elinor Ostrom's institutional design principles for enduring self-governing institutions [16], which essentially embody many principles of natural and retributive justice, can be axiomatised in computational logic and then used for specifying and implementing self-organising electronic institutions with corresponding properties of endurance and sustained membership [20];
- Showing that Nicholas Rescher's theory of distributive justice [26] based on the canon of legitimate claims can also be axiomatised in computational logic and as complement to Ostrom's principles, used to ensure fairness in resource distribution over time (according to a chosen fairness measure, the Gini index) [23].

The question we now address, see Fig. 2, is what happens when these systems of computational justice are made manifest to users in socio-technical systems. The specific socio-technical systems we use as an exemplar to explore this manifestation are decentralised Community Energy Systems, as described in the next section.

3 Decentralised Community Energy Systems

There are various aspects of power systems presenting situations which need to be solved by an aggregated body comprising a portfolio of smaller resources forming a kind of 'collective'. For example, the concept of *zoning* for self-managed network operation and control could be considered from this perspective as a partitioning/aggregation problem.

Similarly, for energy generation, the idea of the Virtual Power Plant has been studied and implemented [28], where many small(er) generation units are aggregated in an equivalent (virtual) big(ger) power plant. The advantages of these aggregated or collective power plants is threefold. Firstly, they can participate in the markets with higher quantities of energy or of related services, in order to have better prices. Secondly, there are markets where small quantities are not accepted in today's IT support platforms. In addition, some small un-synchronized efforts may not bring at all a visible effect in the network, so small contributors may not participate at all if they think that they are alone.

Usually, however, such aggregations are pre-arranged and usually are backed-up by legal contracts. When the focus is switched from the supply-side to the demand-side, it can be argued that there is a requirement for run-time self-organisation rather than pre-arrangement, and for social contracts rather than legal contracts.

Therefore, we propose that demand-side management of energy distribution and consumption can be addressed by applying a user-centric, self-organizing approach to the various partitioning, aggregation and provision/appropriation problems entailed. In the context of the UK EPSRC Grand Challenge 'Autonomic Power System' [14], we have been studying demand-side self-organisation in decentralised Community Energy Systems (dCES). In a 'traditional' community energy system, there is a central generator serving a set of consumers (e.g. households); in a decentralised community energy decision, both the generation and the decision-making is pushed to the edges, i.e. the households themselves.

An example of a decentralised 'community energy system' is the energy grid of Schönau, Germany [8]. The vision for this grid was a decentralised form of green-energy production, in terms of both increasing the efficiency of energy transmission and empowering citizens to take charge of their energy consumption and production. The idea was to turn energy consumers into prosumers (both producers and consumers), by motivating individuals to produce and save energy, and to sell the surplus back to the grid. This way of thinking initiated the process of equipping the inhabitants of Schönau with resources to produce energy and manage it through a citizen-owned social business, the Power Supplier of Schönau. Most households in this community produced energy by diverse means, and managed the process of its distribution.

In our conception of a decentralized Community Energy System, a group of geographically co-located residences is occupied by prosumers. The residence may have installed photovoltaic cells, small wind turbines or other renewable energy source; and the occupants have the usual requirements to operate their appliances. Note we also consider the issue of storage, and (looking forward) propose to consider the use of electric vehicles as a 'distributed battery' (see Fig. 3).

Therefore, in fact we have two concurrent and co-dependent provision and appropriation systems, one for generation and one for storage, and actions in one system have effects in the other. Furthermore, instead of each residence generating, storing and using its own energy, and each suffering the consequences of over- or under-production, the vagaries of variable supply and demand should be evened out by providing energy to a common-pool and computing a distribution of energy

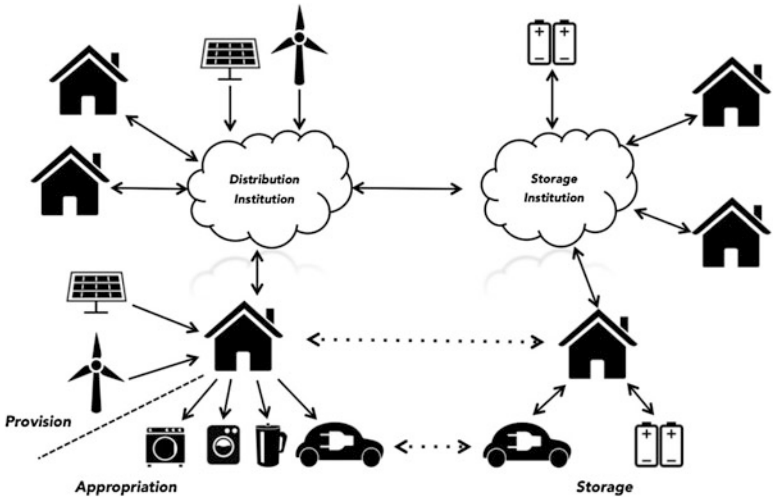

Fig. 3 Decentralised community energy system (dCES)

using algorithmic self-governance specified by institutions. These institutions would operate firstly, Ostrom's design principles for enduring and sustainable common-pool resource management, in which excessive demand, which would otherwise lead to a power outage, could be pre-empted by synchronized action based on collective awareness; and secondly, a social capital framework for successful collective action.

In the next two sections, we present progress in developing frameworks for what are effectively decision-support mechanisms for decentralised community energy systems. The first one is based on collective awareness within a Serious Game (Sect. 4), while the second one is based on social capital for concurrent and co-dependent provision and appropriation systems (Sect. 5). Both are critically dependent on interleaving social and computational intelligence and reasoning with respect to some notion of justice

4 Collective Awareness

Demand-side self-organisation of energy systems depends upon user engagement and active consumer participation. This self-organisation for common pool resource allocation should observe and address different principles, encapsulated by the user-infrastructure interface. This user interface extended to a 'serious game' should support the users in a decentralised community energy system and emphasise on collective awareness, securing at the same time the active participation of users who can be both individual consumers or group of prosumers.

The drive towards demand-side self-organisation of the electricity distribution and supply network is particularly motivated by Elinor Ostom's principles for enduring self-organising institutions. These principles characterise who is a member of the institution, how the resources are managed and allocated, who is affected by the rules of the institution and who can participate in their selection and finally, that no external interference is accepted. These principles are the foundation for user engagement and active consumer participation inside an energy system.

The key issue is how Ostrom's principles can be encapsulated and supported by a user-infrastructure interface, ensuring at the same time that users can actively participate in a decentralised energy system. Serious Games could be a plausible solution; digital games in which Ostrom's principles are supported by both the interface and the rules of the game. Adding ICT to the user-infrastructure interface enables the users to become active participants and make choices which ensure the endurance and fair distribution of the resources in the electricity network.

4.1 Visualisation of Ostrom's principles

Table 1 presents how Ostrom's principles and user participation can be encapsulated in a Serious Game for a Decentralised Community Energy System. Serious Games are digital games, simulations and virtual environments whose purpose is not only to entertain and have fun, but also to assist learning and help users to develop skills such as decision-making, long-term engagement and collaboration. They are experiential environments, where features such as though-provoking, informative or stimulating are as important as fun and entertainment [13]. They can also be used for modelling and simulating new and complex systems, empowering at the same time different groups and communities to exploit the most of the system's possibilities and characteristics.

Principle 1 states that there should be clearly defined boundaries in the institution. This is represented by the player's access to the game. The institution is visualised and represented by a virtual community, where the members of the community need a membership for getting access and having an avatar in the game. Principle 2 refers to the congruence between the rules for appropriation and provision of resources and the state of the local environment. This can be achieved through the collective awareness. Collective awareness among the members of a community enhances the sense of collective responsibility, whereas if it is missing, the members of the community cannot understand the present situation or occurred changes to their local environment. The third principle concerns collective-choice arrangement, stating that those affected by the operational rules should participate in the selection and modification of these rules. This can be represented by a participatory deliberative assembly where all the players can gather and make common choices and decisions concerning the electricity distribution. Principle 4 refers to monitoring behaviours and current state. Smart Meters are assigned this monitoring agency role.

Table 1 Ostrom's principles encapsulated by a serious game

Ostrom's principles	Visualisation in serious games
(1) Clearly defined boundaries	Game access
(2) Congruence between rules and local environment	Collective awareness
(3) Collective choice arrangements	Participatory deliberative assembly
(4) Monitoring	Smart meters
(5) Graduated incentives	Sanctions and rewards
(6) Conflict resolution	Conflict resolution mechanisms

Principle 5 states that there should be graduated sanctions for those agents violating rules, as well as incentives for those complying. This is visualised through a rewarding/sanctioning scheme that it is introduced in the game. This scheme is endorsed to reward the successful game players, whereas it imposes penalties in case of inappropriate behaviours. Finally, Principle 6 is concerned with access to fast, cheap conflict-resolution mechanisms. The game provides different mechanisms such as jury, negotiation or mediation that are used to resolve occurred disputes. Ostrom defines two more principles: no interference from external authorities to ensure that the game cannot be controlled or monitored from the external environment (Principle 7) and systems-of-systems (Principle 8) to allow for nested institutions. However, these two last principles are not represented in the game [5].

4.2 Visualisation of a Decentralised Community Energy System

Collective awareness is an important component of a community, as it strengthens the sense of collective responsibility and enables the members of this community to adapt better and easier to their environment. A system based on collective awareness in a serious game can support the demand-side self-organisation of a decentralised Community Energy System. Collective awareness combined with gamification techniques observed in a virtual world, could promote the user engagement and active consumer participation. Gamification is basically the use of game design techniques and mechanics to non-game applications in order to teach, motivate and engage users in a different way.

Drawing attention to these two aspects could enable and support the users of the virtual world to feel part of an online game-based community, where sustainability and adaptability are promoted. The concepts of serious games and gamification can be extended and include social rules and norms, empowering in this way the users who are now enabled to control their avatars, take part in an everyday scenario and being incentivised and driven by social capital rather than money (see Sect. 5).

Fig. 4 A 3D serious game virtual energy community

A 3D serious game virtual community can provide the necessary requirements for human inclusion and active participation in a decentralised energy system. Five different activities can be defined, enabled and supported through this online virtual community: *(i) Decentralised Energy System Representation*, the virtual community (three different houses one for each type of player—single, couple and shared—with electrical appliances connected to Smart Meters) where the user can control and observe in real time the energy consumption, *(ii) Private & Public Messages*, messages (energy feedback) concerning the energy consumption that users receive in real time and they can be provided both on an individual and common basis, *(iii) Assembly*, another house in the virtual community where all the players can gather and self-organise in a way so that the grid sustainability can be achieved, *(iv) Smart Meters*, an ICT-enabled device that allows both monitoring and reporting of electricity consumption and *(v) Rewards & Sanctions*, where the good players can be rewarded and get prizes, whereas the inappropriate behaviour is sanctioned and the bad players receive penalties (Fig. 4).

When the player gets access to the implemented virtual community, he has to select among three different profiles/houses—single, couple, shared—based on the profile that reflects his everyday life. This real-based choice will enable us to better understand how users are going to consume electricity when they will exit the virtual world and return to their everyday house routine. All the players have to self-organise and coordinate their actions in a way that their electricity consumption in each time slot does not exceed the maximum available energy capacity of the whole community. The different 'installed' blackboards in the houses and in the *Assembly* room display the individual and common energy consumption, whereas the residual capacity is known as well among the players. The demand-side self-organisation is based on collective and coordinated actions among the players and comparative feedback. Collective awareness is particularly important as it supports the collective action and the social networking.

This virtual community can provide decision-support mechanisms for enduring, self-organising institutions and in coordination with gamification mechanisms and techniques a better grid management and resource allocation could be achieved. Demand-side self-organisation based on a common-pool resource management for decentralised community energy systems comes as a user empowerment which highlights collective awareness and choices, whereas consumer behaviour is regulated and organised so as the use participation in the grid is increased.

Users will now have more discerning options and choices inside the virtual energy community system. They are entitled to organise and control their energy consumption and production and as a result they better comprehend concepts which concern grid sustainability, resource allocation and investment decisions. The consumers' inclusion and participation in an energy system require not only a better understanding of the energy consumers' behaviour, but also getting energy consumers to better understand the effects of their behaviour and actions on the electricity network.

4.3 Smart Meters and Systems of dCES

Smart Meters are an ICT-enabled device installed 'at the edge' of a decentralised community energy system, that allow both monitoring and reporting of the energy consumption and production. On top of these services, the two-way communication between the Smart Meters and the central electricity network is enabled and supported. Even though the Smart Meters are not just passive devices which display the energy consumption but they can also serve as agent-based assistants and non player characters, they are received as a "can't-opt-out" technology both centrally imposed and controlled. This obstructs generativity and raises concerns for trust, privacy and security. The end users do not own this technology, although it is their behaviour that is being monitored and controlled.

The introduction of Smart Meters in domestic residences as the basic interface for displaying information needs to be received as an innovative technology for enabling users and making their everyday lives easier [4]. As the energy users cannot spend all their time in front of a screen to monitor and control their energy consumption, intelligence needs to be added to the Smart Meters which will empower them to be adaptive to users' needs and preferences. The user-centric orientation of the Smart Meters will provide awareness to the consumers and visualisation of the different forms of information concerning the energy consumption and production. With this generative, opt-in and at-the-edge technology, the energy users will be able to program their electrical appliances in a more sustainable and efficient way for a community energy system.

Smart Meters being a fundamental element of a decentralised community energy system could provide the computational intelligence, a key aspect which is missing from those systems. The 'intelligence', such as it is now, is definitely not 'at the edge', nor it is operating on behalf of the end-user, i.e. the electricity consumer. Smart Meters should be perceived as assistive-enabled devices which promote and maximise the capabilities and choices of the consumers or prosumers. If the computational intelligence interleaves with the social intelligence coming from the collaboration among the different decentralised community energy systems, then issues such as resource allocation and distribution, investment decisions and energy system's sustainability could be better forwarded and advocated.

5 Social Capital

It has been noted that people's 'attention' is limited, so that users won't spend all their time monitoring their energy consumption. Instead, in the previous section we were relying on social networks and reporting of exceptions to provide the collective awareness to support synchronised, coordinated action. However, to manage the quotidian operation of the system, people need to know how to delegate to the Smart Meters, which in turn need to reason about qualitative values of concern to people. To do this, we propose to use social capital as a way of optimising demand-side self-organisation in provision and appropriation situation; moreover social capital also has significant potential when dealing with multiple concurrent and co-dependent provision and appropriation systems.

5.1 Self Organising Flexible Demand

In decentralised community energy systems, peak consumption times can force them to consume electricity from energy providers. When a community invest in photovoltaic cells, small wind turbines or other renewable energy source, consuming more energy from this source (instead from the energy provider) will be translated into lower electricity prices for them. One method of lowering the consumption peaks is flattening the demand. It implies reducing the difference between the peaks and troughs in electricity usage by creating a levelled usage pattern that lessens the deviation from the average usage.

We propose self organising flexible demand, where consumers can demand an amount of electricity for a certain period of time. Once it is allocated, they can exchange these allocations among them to better satisfy their time preferences. Since consumers might not be available to perform this actions, or not interested in, they can choose their time preferences and delegate the task of exchanging the allocations to their Smart Meters. Furthermore, by introducing the use of Social Capital, consumers cooperate and help each other in order to obtain the allocations they need.

5.2 Electricity Exchange Arena

To enable consumers to self organise we set up an exchange arena in which each day is divided in 24 time slots of 1 h. Consumers can demand amounts of electricity for each time slot based on their needs. Initially, a predefined allocation method performs the first allotment of the consumers' demands. Depending on the method chosen, consumers can receive allocations that are not in their preference; however, the amount of electricity assigned to them is always as much as demanded. Once all the allocations are received, consumers can start to exchange them.

In order to exchange an allocation, consumers can publish which of their allocations they are willing to exchange. All such allocations are publicly visible in a kind of classified advertising board. Consumers can check the ads board and send offers for those allocations they are interested in. The exchange is only between two consumers and they trade only allocations; there are no payments involved. Consumers will accept or deny an offer depending on their preferences or needs of electricity consumption.

5.3 Social Capital in Decentralised Community Energy Systems

Social capital is defined as "the features of social organization, such as networks, norms and trust, that facilitate coordination and cooperation for mutual benefit" [24] and furthermore as "an attribute of individuals and of their relationships that enhance their ability to solve collective-action problems" [17]

The creation of social capital among the consumers not only benefits them individually, but also as a whole. And, since consumers must perform exchanges to obtain the allocations they need, the more they all collaborate the higher the chances they will have to get what they want.

In this work, we implemented a simple form of social capital. At every exchange, consumers check if the received allocation is in their interest. If so, they count it as a "favour received" from the other consumer. In the opposite situation, they count it as a "favour done" to this other consumer. Since the favours calculation is internal for each consumer, an exchange where both consumers get an allocation they want is perceived as a favour received by both of them. These win-win situations help to create social capital among the system.

Our research is focused in developing a framework for representation of and reasoning with social capital. The self-organising processes that social capital facilitates generate outcomes that are visible, tangible, and measurable. The processes themselves are much harder to see, understand and measure.

In the next section we present the experiments done using favours as initial form of social capital.

5.4 Experiments

We have used PreSage2 [12] to develop a simulation of the electricity exchange arena and analyse the self-organisation of flexible demand. The arena was populated with 96 consumers who demanded 4 time slots with 1 kWh of electricity for each. Consumers chose randomly these 4 slots over the 24 available. Two allocation methods were tested; a Random Allocator and an Optimum Allocator. The first, assigns the demands randomly to the available slots. The second, performs the allocations maximising the average consumer satisfaction, which is defined as the proportion of electricity received in their preferred time slots. Both methods allocate up to the daily average for each time slot, i.e. 16 kWh for each slot.

Two type of consumers were added to the system:

- Selfish Consumers: They only accept to exchange if the offered allocation is in their interest, i.e. a time slot that is in its preferences, but was not received at the initial allocation.
- Social Consumers: They check at every exchange if the received allocation is in their interest, and keep the count of favours done and received. They will accept an offer if it benefits them, as the Selfish consumers, but also if they owe a favour to the consumer sending the offer. Through this behaviour, Social consumers will start acting selfishly, but after some exchanges they will start accepting offers in which they are not interested. These exchanges will not decrease their satisfaction, since they are not interested in any of both allocations (the sent and the received), but it will improve their Social Capital.

With this set up, consumers demand, get the allocations and perform the exchanges for a day. The simulations were run for 200 sequential days and the results were averaged over 100 runs.

Figure 5 shows a snapshot of the experiment graphical interface. Each circle represents a consumer and the colour, from red to green, their own satisfaction. The average consumer satisfactions is also showed as a bar on the right. Through the experiment, at each round, an arrow between two consumers will graphically show an exchange of consumption slots among them. When an exchange occur, at least one of the consumers will increase his satisfaction and his colour will change getting greener.

In Fig. 6 we compare the average consumer satisfaction at the end of the exchanges round for each day. The Optimum allocator achieved the highest consumer satisfaction average, and since there is no better allocation distribution, no exchanges were performed. Using this allocation method an average consumer satisfaction of 90 % was achieved. All the values have been normalised to this allocation method. The random method, without any exchange, achieved the lowest consumer satisfaction. By allowing exchanges, the Selfish Consumers considerably improve the results exchanging allocations between them, although their average satisfaction does not vary over time. With the inclusion of Social Capital, Social Consumers start

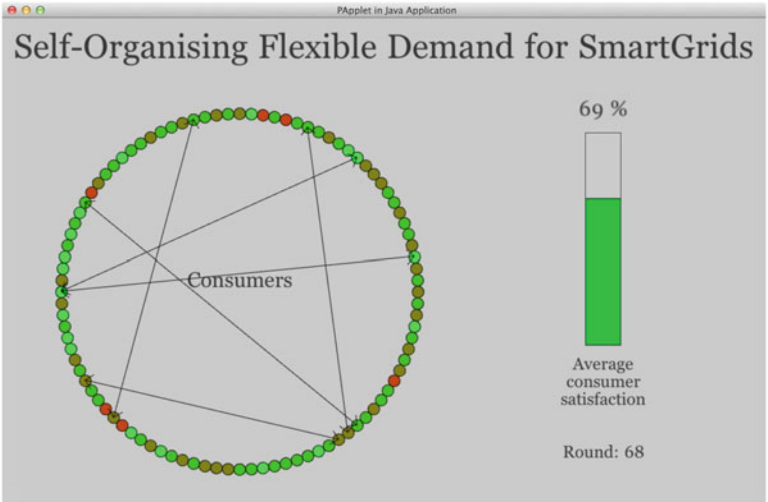

Fig. 5 Snapshot of the experiment graphical interface

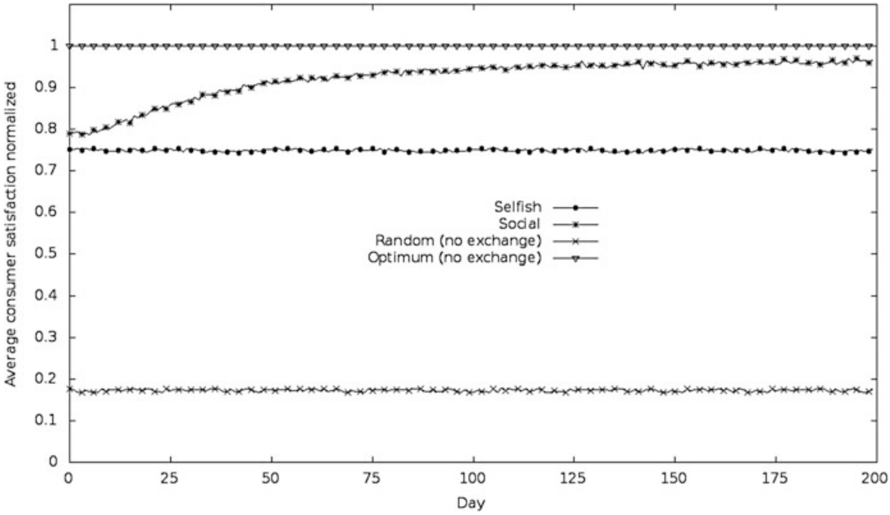

Fig. 6 Average consumer satisfaction normalised at the end of each day

performing as the Selfish Consumers, but their satisfaction increases as they perform exchanges with other consumers. They help other consumers to get the allocations they need as a return of the favours received.

Despite the fact that using a centralised allocation method shows better results, our approach slightly under-performs and frees the systems from the scalability issues. The Optimum Allocation method does not take into account the consumer

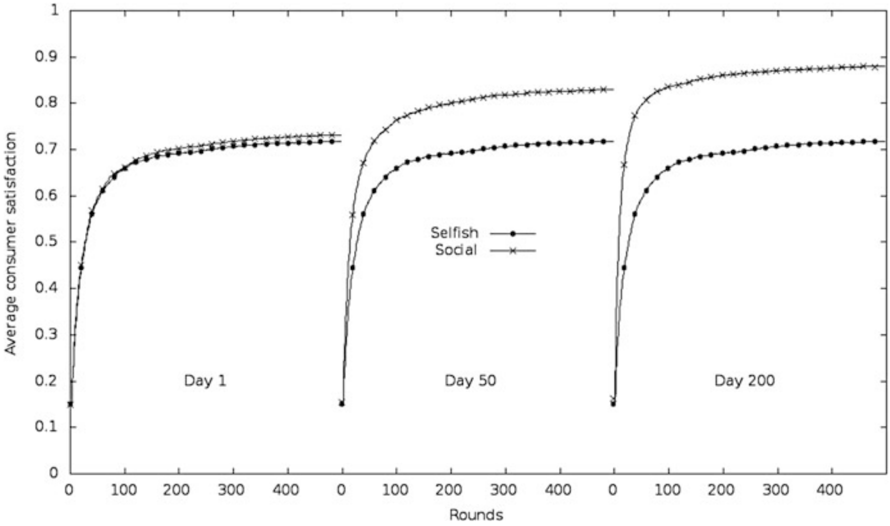

Fig. 7 Average consumer satisfaction during the first, fiftieth and two-hundredth day

flexibility, and including it will require a more complex algorithm. On the other hand, with exchanges, the more flexible a consumer is, the more Social Capital it will be able to generate. Eventually, consumers can also add more constraints or more flexibility to their demands without altering the operation of the whole system, which is not possible in a centralised allocation.

Figure 7 shows the average satisfaction during the exchange period for the first, the fiftieth and the two-hundred day for Selfish and Social Consumers. During the first day both perform equally since very few favours take place. After 50 days, Social Consumers have got a high satisfaction average, because they pay back favours received from previous days. At last, on day two-hundred, the consumers' satisfaction is higher because more exchanges occurred.

6 Summary and Conclusions

In this paper, we have considered decentralized Community Energy Systems, wherein the objective is to create a self-sustaining community of prosumers who provision and appropriate the generation, storage and distribution of energy amongst themselves, independent of a fixed grid infrastructure.

We have considered such systems from the perspective of common-pool resource management; in which case, questions about the 'robustness' of the community and the 'fairness' of the allocation can be addressed using formal theories of natural (or social) justice due to Elinor Ostrom. Furthermore, the co-dependence of concurrent provision and appropriation systems, whereby decisions and actions in one system are leveraged (as social capital) to support and sustain the other, and vice versa, can be addressed using the formal theory of distributive justice due to Nicholas Rescher.

In fact, formal representations of different qualifiers of justice have contributed to a research programme called Computational Justice, providing algorithms for self-regulation of open computer systems and communication networks. The question was then posed, what happens when these computational theories of justice are injected into, and made manifest to the users, in socio-technical systems, i.e. providing an algorithmic basis for self-governance.

Based on this, we discussed how the research programme of computational justice can inform the application Ostrom's theories to the self-organisation and visualization of 'fair' demand-side energy management. We described two approaches, firstly the use of collective awareness within a Serious Games, and secondly the formalisation of social capital mechanisms underlying successful collective action in concurrent, inter-dependent provision and appropriation systems. Two demonstrator systems for 'fair' demand-side self-organisation have been developed, and prospects for combining social and computational intelligence(s) in decentralised community energy systems have been presented.

In both systems, there remains much further work to do: for example, as we move from Serious Games to *gamification* (the use of game-like mechanisms to manage real-life situations), we need to find the correct balance between constant intervention and monitoring by the prosumers and the delegation of their attention to a SmartMeter operating on behalf of (and perhaps programmed by) the users themselves. Having delegated to SmartMeters, the simulation results have shown that a simple form of Social Capital, which creates win-win situations, improves the performance of the demand-side system. We will continue this line of work by developing a Framework for representing and reasoning based on Ostrom's [17] forms of Social Capital. However, we argue that it is *justice* (in its computational form) rather than trust which is the glue between different forms of social capital and successful collective action in socio-technical systems of the kind we have been discussing here. Further specific links between the two self-organizing socio-technical systems and the different qualifiers of justice is illustrated in Fig. 8.

Furthermore, we observe that a decentralised community energy systems can emerge in multiple scales of time and geography. We could have a dCES that could operate as a socio-technical system on a local geographical scale and operate on individual prosumer decision-making. Therefore, we could have a dCES that operates as a 'socio-technical system' composed of individual consumer, but was itself operating as an individual 'technical system' across national boundaries, enabling a community of 'twinned towns' to trade energy. Finally, there could be a dCES which uses concepts of trust, self-organisation and social capital to form a generating body (i.e. we return full circle to the Virtual Power Plant). In particular, we propose to undertake a comparative evaluation of optimisation based on market-based vs. (or with) institution-based approaches to community energy systems, from both business case and operational bases (e.g. computational cost, efficiency, fitness for purpose, compliance, social justice, etc.).

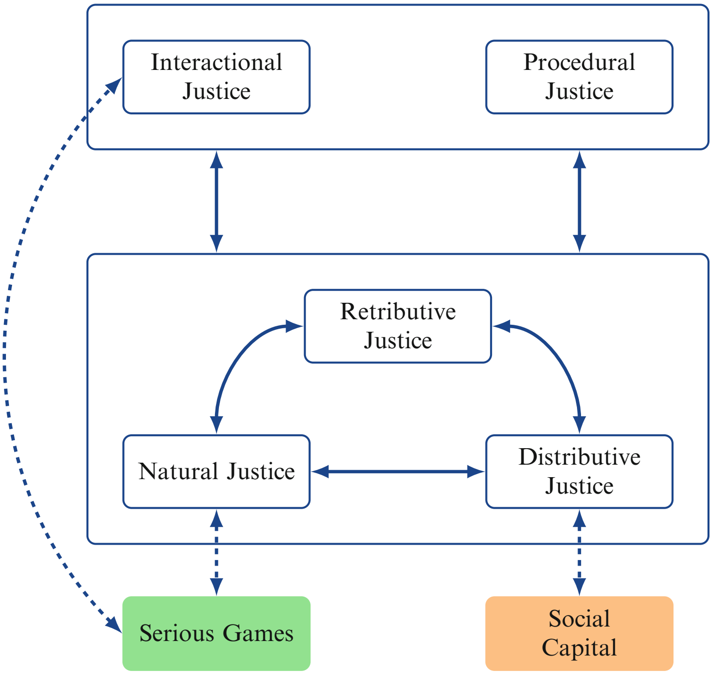

Fig. 8 Link of the presented self-organised systems and computational justice

In conclusion, this chapter has illustrated the potential for using computational justice in open socio-technical systems, such as decentralized Community Energy Systems, and how they can help deliver social justice to the prosumers so involved. However realising the full potential of computational justice in such domains is critically dependent on successfully inter-leaving social and computational intelligence across multiple scales: this is the critical challenge that lies ahead.

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