Faculty of Design

2019

Modelling stigmergy: Evolutionary framework for system Design

Sharma, Shanu

Modelling Stigmergy

Evolutionary Framework for System Design

Shanu Sharma,
Department of Design SPA Bhopal

Abstract

Stigmergy is an evolutionary phenomenon of self-organised collective problem-solving mechanism in nature among simple agents (ants, termites, fireflies and so on). Stigmergy is a simple, robust and self-regulatory framework of modelling emergent global order by localised actions of distributed agents without any central planning, control and direct communication. The phenomenon of stigmergy is also prevalent in numerous bottoms up “computational or non-computational” coordination among human agents with complex cognitive capabilities. Heylighen envisioned the great potential of stigmergy in the emergence of the global brain (i.e. coordinated actions and the collective intelligence of ‘human mind and the artefact’) capable of resolving some of the complex problems that we are witnessing today such as pollution, water scarcity, climate change and so on. However, stigmergy among human agents is still underdeveloped and demands further attention to investigate the potential in harnessing the collective intelligence of human agents in complex problem-solving. To study the phenomenon of stigmergy among human agents, we have designed the game as a research tool for studying holistic aspects of self-organised complex problem-solving. In this paper, we aim to present the potential of stigmergy as a system design framework for modelling self-organised complex problem solving by harnessing the collective intelligence of distributed human agents.

Evolution: Emergence of Collective Intelligence

“A great belt of light, some ten feet wide, formed by thousands upon thousands of fireflies whose green phosphorescence bridges the shoulder-high grass” (Strogatz, 2003).

It is a phenomenon commonly seen in the mangroves of Malaysia where thousands of fireflies in rhythmically synchronise their flashes of lights. Who orchestrates the synchronous burst of flashes? Likewise, the beautifully synchronised choreographed performance of hundreds of birds in the sky prompts the same query: Who controls and steers the spontaneous formations of the flock? It is often concluded that a flock of birds or the fireflies are following-the-leader to create different formations in the sky or flash the light synchronously. Such choreographed collective behaviour is generally assumed to have the presence of a leader, practised or articulated plan, or even the presence of explicit communication for coordination amongst the members. Contrarily, Resnick postulates that this coordinated performance is a self-organised collective intelligence behaviour in which every bird takes decisions at a local level, relative to the actions of other birds in immediate local proximity(Resnick, 1994). In both scenarios, each firefly and bird are the followers and the leader at the same time, where single actions trigger more actions among other birds and fireflies based on simple rules without any explicit communication amongst them. Birds in the flock (Reynolds, 1987), the congregate of fireflies (Strogatz, 2003) and several other social animals/insects display self-organisation of global order from local interactions.

From the nucleus to the cosmos, at every scale, evolutionary self-organised behaviour prevails in nature. This phenomenon has intrigued and inspired researchers from various fields- from the world of cells(Olsen, 2011) to the studies of climate change(Livingstone, 2016). Hill building activities of termites randomly dumping mud(Deneubourg, Goss, Franks, & Pasteels, 1989), synchronisation of foraging ants through pheromones (Abraham, Grosan, & Ramos, 2006), Flock of birds or flash sync of fireflies are all the examples of evolutionary self-organised collective-intelligence behaviour. Self-organisation of collective-intelligence among social insects has prompted the curiosity amongst researchers to investigate the process of complex interaction produced by simple agents with limited cognitive ability. It represents the eusocial model of an integrated system design of convivial coexistence of diversity, governance and collective behaviour.

In 1959, the French entomologist Grassé closely studied the self-organised interaction of termites building a hill and found termites coordinate at the local level without any explicit communication between neighbouring agents. Subsequently, to explain the coordination paradox we proposed the term 'stigmergy' to elucidate this phenomenon (as cited in Theraulaz & Bonabeau, 1999). Stigmergy is an evolutionary process of adaptation among social animals in nature for collective survival. It leverages the innate survival instinct of each animal or agent in the absence or lack of direct communication and central planning(Susi & Ziemke, 2001; Theraulaz & Bonabeau, 1999).

1.1 Stigmergy: Signs to Self-Organisation

The etymology of 'Stigmergy' includes the combination of two Greek words - stigma (sign) and ergon (action)(Parunak, 2005). According to Grassé, 'actions' of anyone agent while working at the local level creates changes in the 'environment'(workspace) that act as 'sign'. The signs created that agent is sensed by other agents in the vicinity and subsequently leverage to shape the self-organised "reactions-action" loop (Theraulaz & Bonabeau, 1999). Stigmergy is an evolutionary framework of multi-agent self-organizing coordination mechanisms that emerge from the indirect communication sign-action feedback loop in the environment(Heylighen, 2015). Figure 1 is a schematic representation of the process of self-organisation of action-feedback loop in stigmergy, where actions of one agent leaves the sign in the environment that create change in the medium, this change act as the sign that communicates and provides feedback on the state of the work to other agents in the vicinity and triggers self-organised action loop.

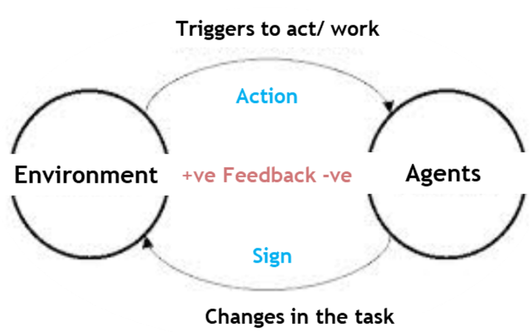


Figure 1 The process of self-organisation of an action-feedback loop in stigmergy.

In this scenario, two or more agents (insects) interact indirectly when one modifies the environment and others respond to the modified environment. In other words, work done by one agent in the termite hill construction provides cues for the direction of work to be done by the following agencies. Thereby, stigmergy shapes complex systemic behaviour, with simple actions without the need of any centralised control, direct communication between the agents or memorising the actions of each agent (Heylighen, 2015). It provides appropriate distributed control for the emergence of self-regulatory collaboration between simple agents in nature, with limited memory capacity and intelligence.

Parunak explains, "the essence of stigmergy is the coordination of bounded agents embedded in a (potentially unbounded) environment, whose state they both sense (to guide their actions) and modify (as a result of their actions)"(Parunak, 2005). Stigmergic system exhibit the following characteristics that make it appropriate for channelizing collective intelligence and actions seamlessly:

- **Self-organization:** The global order of systemic behaviour emerges out of local actions loops where the output of each action acts as the reason for more input at the local level that continuously triggers and shapes the course of actions among distributed component. The actions of agents are self-organised until the task gets completed.
- **Decentralised action:** Stigmergy is a bottom-up approach to problem-solving where changes in the system are driven by the decisions of internally distributed components, without any explicit centralised command or communication.
- **Simplicity and robustness:** Robustness in this system arises from continuously interconnected simple rules and response actions that self-regulate errors of the system and optimize the local as well as the global resources (Parunak, 2005).
- **Optimised communication:** Agents in the stigmergic phenomenon work harmoniously based on the changing signs in the environment bypassing the need for direct communication between immediate neighbours or any other agent working in the distributed environment. Elliot elucidated that in this way the sign-based coordination optimises the need for communication within a distributed environment.
- **Feedback loop:** In the absence of explicit external control, feedback loops synergize local actions of the agents towards the global goal. Feedback loops in the stigmergic system are auto-generated in nature that self-regulates the coordinates actions towards the global goal.

Stigmergic phenomenon not just provides an explanation of the complex problems /systems emerging from networked interaction of diverse agents at the local level, but also provides a framework for designing emergent systems from simple coordinated goal-directed local actions. Stigmergic coordination is prevalent in nature among social insects, but it is equally ubiquitous in "computational or non-computational" coordination among humans (Parunak, 2005), emergence of soft trails is one of the simple examples where footfall in a deserted place change the environment and act as cues for a new person looking for a reliable path. Wikipedia is another example of stigmergy in the digital environment among human agents where incomplete text act as a sign and trigger actions to complete the text among other authors(Rezgui & Crowston, 2017). The output of authors triggers the need for the input among many other authors with knowledge of the content to complete the article creating a self-organized action-feedback loop. Here the webpage act as the environment and text act as the sign. Google page rank is another example of stigmergy where user activity on a webpage act as 'digital pheromones'(Parunak, 2005) creates the ranking of the pages for others with similar interests creating a self-organized system with simple actions. Looking at the mechanism and the increasing application of stigmergy in digital environment Heylighen envisioned the potential of stigmergy for harnessing the collective intelligence of human agents for the emergence of a "global brain"(Heylighen, 2007). Collective Intelligence has been envisioned as the instrument of the prosperity of mankind (Bonabeau, 2009; Malone & Bernstein, 2015).

Collective intelligence can be defined as the "intelligence that emerges from the synergy of individual creative efforts when a cognitive task takes place"(Kaur & Shah, 2018; Salminen, 2012). For example in the case of Foldit (Cooper et al., 2011) a multiplayer game, where an online community of players (non-researcher) solved long-existing(scientific community) complex problem of protein fold with simple gamified actions. It provides a possible course of envisioning the real potential of collective intelligence and the emergence of the global brain(Chandrasekharan & Nersessian, 2015; Heylighen, 2002; Lewis & Bergin, 2016). In Foldit, youngsters with no formal education of protein structure helped scientists working in research of protein folding for more than 10 years, in solving a problem in merely 10 days (Chandrasekharan & Nersessian, 2015). Ushahidi is yet another example of stigmergy where the emergence of collective intelligence that proved efficient in coordinating simple actions of distributed agents in emergency condition for collective survival(Marsden, 2013, 2015). Stigmergy has been envisioned as an intelligent mechanism of harnessing decentralised information/ knowledge production (Heylighen, 2015). Heylighen explained, "the World-Wide Web is merely a collective memory or shared workspace into a true Global Brain for humanity, that would be able to efficiently solve any problem, however complex"(Heylighen, 2007). In past decade collective intelligence (CI) has emerged as a potent instrument for the resolution of the complex problems of the interdependent and interconnected world (Brabham, 2008; Elia & Margherita, 2018; Malone & Bernstein, 2015; Murty, Paulini, & Maher, 2012; Rosenberg, 2016).

In this research, we aim to present the study the framework of stigmergy in modelling the collective intelligence of human agents in complex problem-solving. To study the phenomenon of stigmergy among human agents, we have designed the game as a research tool for studying holistic aspects of self-organised complex problem-solving. In this paper, we aim to present the potential of stigmergy as a system design framework for modelling self-organised complex problem solving by harnessing the collective intelligence of distributed human agents.

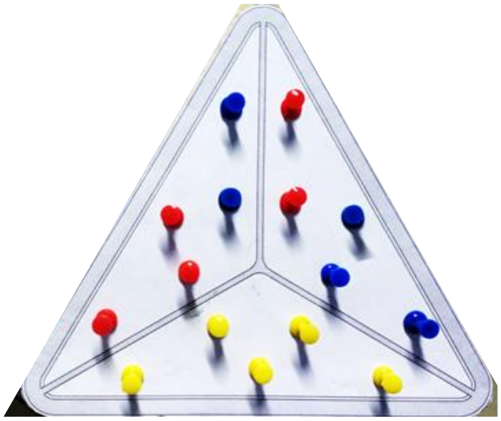
Stigmergy among Human: Complexity of Coordination

Harnessing collective actions for complex problem solving among human agents and the insects fundamentally differ as insects are inherently cooperative with the basic need for collective survival. Whereas human agents have highly complex needs structure and cognitive capability that may work for or work against the coordinated action towards a common goal. The literature on stigmergy also concentrates on social insects who at the individual level are incapable of surviving alone; with altruist cooperation, they collectively strengthen the entire community to adapt and recover from various external disturbances(Bonabeau, Theraulaz, Deneubourg, Aron, & Camazine, 1997; Theraulaz & Bonabeau, 1999). On the other hand, stigmergy among human agents is a choice and not a preservation principle or a default programmed value. Largely in literature, cases of pure cooperation are studied and analysed as stigmergic interaction among human agents, who are intrinsically motivated to work for a collective goal such as Wikipedia, open software development, open universities and so on. Limiting the attention to cooperative scenarios alone have impeded our understanding of the selfish interest of agents in solving a collective problem(Tummolini, Mirolli, & Castelfranchi, 2009). A common good dilemma arises in such situations where an agent with selfish interest does not cooperate for a common goal and damages /exploits the common resources(Hardin, 1968; Lange & Visser, 1999). Agents sharing a limited resource condition either defect or over-consume the resource for selfish benefits (short term) that affects the entire group negatively giving rise to social dilemmas. It is generally known as the "tragedy of commons"(Delaney, Sophister, & Curran, 1992; Hardin, 1968; Hekkert, 2009). Hence, humans, unlike social insects, cannot be assumed to be altruist agents, rather their real behaviour in decision making

requires to be investigated in stigmergic interactions. Therefore, this study also proposes to study the nature of negotiation amongst selfish agents, and its effect on the level of stigmergy achieved in an environment. Furthermore, human stigmergy is defined as cognitive stigmergy where agents with higher cognitive capabilities interact and evaluate possible scenarios at the local level to resolve local concerns, but the process continues to be associated with the metaphor of social insects coordinating simple actions. Hence, stigmergic tasks for human Agents are designed with a low cognitive load and altruist coordination where human agents respond to local stimuli with limited stimulus-response action to achieve global coordination (Christensen, 2013; Lewis & Marsh, 2016; Susi & Ziemke, 2001). Klyubin et al. (2004) believe that "complex processing at the level of individual agents would destroy the naturally emergent behaviour of stigmergy" (Klyubin, Polani, & Nehaniv, 2004). Therefore, even after decades of research, we are only able to attempt altruist model human stigmergy in simple altruist model designs.
This study explores such fundamental questions related to the role self-interest vs community benefit on stigmergy within a collective problem-solving task. As they are identified as some of the common threats for collective problem-solving in real-world scenario among human agents. This includes the behaviour of human agents in a closed or open system (resources closed or open for exchange or negotiation), with or without the knowledge of the global goal (awareness of the effect of resolving local problems at the systemic level).

Game as research tool

Studying Stigmergy has been a methodological challenge in every discipline given the complexity and scale of the phenomena. Moreover, our 'centralized mindset'(Resnick, 2009) itself has raised significant difficulties in perceiving and accepting distributed actions around us. Stigmergy is one such inherently complex phenomenon that requires attention at micro and macro behaviour of agent and the system. To address this challenge, we have adopted 'Game' as a research tool to control, observe, and analyse the distributed actions of the agents, in Stigmergic interaction for collective problem-solving. Game simulation in research is "design-based research"(Barab & Squire, 2004), where the purpose of the simulation is to assess the actions or problem-solving strategies of the players as well as to comprehend how and why the designed system works (or fails) in a given context. Games, in general, are self-organized systems(Bell, 1975; Coutinho, Galvão, De Abreu Batista, Moraes, & Fraga, 2015)) with simple rules of interaction and goal to trigger continuous interdependent action loops of agents. Using the game as a research tool provides an appropriate medium to explore self-organizing social scenarios whereas action research framework offers a framework for systematic inquiry of emerging stigmergic development. Game as a research tool bridges the limitation of lab experiments and natural setting observation by recreating real-world scenarios, often with the goal to observe specific behaviours within controlled gamified environments(Gentry, Tice, Robertson, & Gentry, 1984). In this study, the characteristics of stigmergy itself have shaped the basic structure of the gamified research tool. The stigmergy game (collective survival) is a non-zero-sum board game as shown in figure 2, with symmetrical negotiation design of crop optimization at the global level wherein the agents at distributed environment optimize resources at the local level with coordinated actions using virtual feedback, thereby leading to a global optimization.



Task cycle	Price YELLOW	Price BLUE	Price RED	Price Field 1	Price Field 2	Price Field 3
`1	1.6	1.6	1.6	6.4	6.4	6.4
2	1.4	1.4	1.4	9.8	9.8	9.8
3	1.8	1.6	2	15	15.6	18.4
4	1.6	1.4	1.8	11.2	12.4	15.2
`5	2	1.6	1.8	17.2	14.6	17.2
`6	1.8	1.4	1	14.2	6.6	10.2
`7	1.6	1.2	1.4	10	9.2	10.6
`8	2	1.6	1.8	17.2	14.6	17.2
`9	2.2	2.2	2.2	24.2	24.2	24.2
`10	1.8	2	2.2	17.2	21.6	21.6
`11	2	2	2	22	22	16

Figure 2 Collective survival board game and Asset Evaluator (real time digital feedback)

The game “collective survival” is a simulation tool developed for this research with the various operational variable to control the cognitive level of the task, to control the motivation of the agents (selfish interest, the reason for cooperation), control interdependence among agents, and so forth. The board game mirrors real-world interactions, where Agents (players in this case, from here on expressed with a capital ‘A’) resolve the problem of distributed resource optimisation in the form of a board (fields) and pegs (crops with different colours) with real-time digital feedback through *Asset Evaluator*. In this research, the author has conducted 19 final and 6 trial games among 75 participants where each game on an average took 40 minutes (in total 13 hours of gameplay recording) excluding the time of instructions. In this research, the results are derived based on 60000 action codes derived based on the systemic outcome at every action cycle and an individual participant level for analysing each action condition and decision made by the agent in the collective problem-solving the task.

Conclusion

The findings of this study put forth the potential of stigmergy in resolving real-world complex systemic problems by harnessing the collective actions of human agents with selfish interest. Harnessing collective actions and intelligence of agents at the distributed locations is the possible way of resolving complex problems where the centralised approach has a limitation. It provides ample opportunities for a system designer to alter services, structure, and behaviour of the user for long term adaptation towards systemic goal. Grounded in the overall results from all the stigmergy game simulation, we strongly conclude that designing stigmergy is possible for real-world problem-solving with the virtual trigger to mediate interactions, communications, connect actions for a feedback mechanism. The primary structure of stigmergic negotiation is dependent on rules of distributed control between agent-agents and agent-resource interaction. Systemic interactions are inter-dependent on the common resources that are either getting built, utilised, accessed, consumed or optimised by the coordinated actions of multiple Agents. Therefore, the rules for interaction between Agents to control resources are strongly affected by the accrued benefit perceived by the Agents for every move to negotiate. The perceived or real benefit could range between two distinct poles of ‘collective good’, where the Agent is motivated to act voluntarily to optimise the resources for the prosperity of the whole community, or else a ‘selfish benefit’ where Agents are motivated to optimise the resource solely for their own gain. This study also revealed, in a system where agents are unaware of a common global goal, they cooperate with other agents to achieve own benefit. In such interaction, cooperation emerges to accomplish own selfish goal. Such interaction can be described as selfish cooperation. In such system tit for tat, strategy controls the selfish exploitation of resources and creates an environment for mutually beneficial negotiation. Prolonged tit for tat negotiation converged and emerged into a stable and optimized system. In this system, errors made by agents are self-adjusted by the interconnected agents' negotiation for self or mutual benefit. Selfish cooperation is the backbone of stigmergy in a system with the local goal alone.

- In a system where agents are aware of both the explicit global goal (the reason for cooperation) and the selfish local goal, global goal induces cooperative instinct in some agents but does not remove "free rider" agents taking advantage of the cooperative interaction to fulfil their own selfish interest. Competition emerges even in a system where agents are aware of the condition of collective prosperity and tend to work towards own short-term goal. Tit for tat again emerged as a strategy to control the selfish exploitation of shared resources from free-riders and to maintain optimization of the local as well as system state. A stigmergic system design control with both the local and global goal is no different from a system with the local goal alone and requires similar control over agents with selfish interest. This is because human agents are both inherently cooperative and selfish as well, in a condition where some agents cooperate and work towards the common goal of the system, few agents with selfish interests tend to exploit the system by not cooperating with each other and working only towards own local benefits. Selfish agents do not contribute to system welfare and take undue advantage of the cooperative behaviour of other agents in the collective system.

The game scenario strongly demonstrates a tit for tat strategy to control conflict or exploitation (free riders) and induces "selfish cooperation" among agents. Here, the success of stigmergy relies upon the efficient indirect communication, the design of the interconnected task and its control over negotiation, further backed by transparent rules and clear feedback mechanism.
Stigmergy provides an extensive framework to address complex systemic concerns from local actions. The main reason for its success is the fact that stigmergy is the amalgamation of appropriate selection of agents, artefacts and the actions within the boundary of the complex system, using simple, transparent rules, information, goal-directed feedback, and action loops of the agents in an interconnected task. The user is an active agent in the designing of an alternative solution to the existing local problem. It provides ample opportunities for a systemic designer to alter services structure and behaviour of the user for long-term adaptation towards systemic goal. The advancement of the cyber-physical system provides an appropriate platform for harnessing collective actions using the complex cognitive capability of human agents by generating more precise real-world data mapping and coordination of local actions to resolve complex problems. In the coming decade, evolved and sophisticated stigmergy system in various domains for scientific collaboration, e-governance, addressing global sustainability goals will be designed to solve complex problems.

References

Abraham, A., Grosan, C., & Ramos, V. (2006). *Stigmergic Optimization (Studies in Computational Intelligence)*. Berlin, Heidelberg.: Springer.

Barab, S., & Squire, K. (2004). Design-Based Research: Putting a Stake in the Ground. *Journal of the Learning Sciences*, *1*(13), 1–14. https://doi.org/10.1207/s15327809jls1301

Bell, D. c. (1975). Simulation Games : Three Research Paradigm. *Simulation & Games*, pp.271-287.

Bonabeau, E. (2009). Decisions 2.0: The Power of Collective Intelligence, (50211).

Bonabeau, E., Theraulaz, G., Deneubourg, J. L., Aron, S., & Camazine, S. (1997). Self-organization in social insects. *Trends in Ecology and Evolution*, *12*(5), 188–193. https://doi.org/10.1016/S0169-5347(97)01048-3

Brabham, D. C. (2008). Crowdsourcing as a model for problem solving: An introduction and cases. *Convergence*, *14*(1), 75–90. https://doi.org/10.1177/1354856507084420

Chandrasekharan, S., & Nersessian, N. J. (2015). Building Cognition: The Construction of Computational Representations for Scientific Discovery. *Cognitive Science*, *39*(8), 1727–1763. https://doi.org/10.1111/cogs.12203

Christensen, L. R. (2013). Stigmergy in human practice: Coordination in construction work. *Cognitive Systems Research*, *21*, 40–51. https://doi.org/10.1016/j.cogsys.2012.06.004

Cooper, S., Khatib, F., Makedon, I., Lu, H., Barbero, J., Baker, D., … Popović, Z. (2011). Analysis of Social Gameplay Macros in the Foldit Cookbook Categories and Subject Descriptors. In *In Proceedings of the 6th International Conference on Foundations of Digital Games .* (pp. 9–14). Bordeaux, France: ACM.

Coutinho, L. R., Galvão, V. M., De Abreu Batista, A., Moraes, B. R. S., & Fraga, M. R. M. (2015). Organizational gameplay: The player as designer of character organizations. *International Journal of Computer Games Technology*, *2015*. https://doi.org/10.1155/2015/731031

Delaney, L., Sophister, J., & Curran, D. (1992). Public Goods and the Prisoners Dilemma : Experimental Evidence, 15–22.

Deneubourg, J. L., Goss, S., Franks, N., & Pasteels, J. M. (1989). The blind leading the blind: Modeling chemically mediated army ant raid patterns. *Journal of Insect Behavior*, *2*(5), 719–725. https://doi.org/10.1007/BF01065789

Elia, G., & Margherita, A. (2018). Can we solve wicked problems? A conceptual framework and a collective intelligence system to support problem analysis and solution design for complex social issues. *Technological Forecasting and Social Change*, (October 2017), 0–1. https://doi.org/10.1016/j.techfore.2018.03.010

Gentry, J., Tice, T., Robertson, C., & Gentry, M. (1984). Simulation Gaming as A Means Of Researching Substantive Issues: Another Look. *Developments in Business Simulation & Experiential Exercises*, *11*, 261–266.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, *162*(3859), 1243–1248.

Hekkert, P. (2009). A clash of concerns : Applying Design Thinking to Social Dilemmas. *Design Engineering*, 393–403.

Heylighen, F. (2002). The Global Brain as a New Utopia, 1–11.

Heylighen, F. (2007). Accelerating Socio-Technological Evolution: from ephemeralization and stigmergy to the global brain, (1), 1–26.

Heylighen, F. (2015). Stigmergy as a Universal Coordination Mechanism : components , varieties and applications. *Human Stigmergy: Theoretical Developments and New Applications (Studies in Applied Philosophy, Epistemology and Rational Ethics*, 1–43.

Kaur, R., & Shah, R. (2018). Collective intelligence : Scale development and validation. *Journal of Human Behavior in the Social Environment*, (00), \. https://doi.org/10.1080/10911359.2018.1432438

Klyubin, A. S., Polani, D., & Nehaniv, C. L. (2004). Tracking information flow through the environment: Simple cases of stigmergy. *Proceedings of the Ninth International Conference on the Simulation and Synthesis of Living Systems (ALIFE 2004), MIT Press*, 563–568.

Lange, P. A. M. Van, & Visser, K. (1999). Locomotion in Social Dilemmas : How People Adapt to Cooperative , Tit-for-Tat , and Noncooperative Partners, *77*(4), 762–773.

Lewis, T. G., & Bergin, R. (2016). Imitation and novelty in product development. *Cognitive Systems Research*, *38*, 23–30. https://doi.org/10.1016/j.cogsys.2015.12.004

Lewis, T. G., & Marsh, L. (2016). Human stigmergy: Theoretical developments and new applications. *Cognitive Systems Research*, *38*, 1–3. https://doi.org/10.1016/j.cogsys.2015.12.001

Livingstone, R. M. (2016). Models for Understanding Collective Intelligence on Wikipedia. *Social Science Computer Review*, *34*(4), 497–508. https://doi.org/10.1177/0894439315591136

Malone, T. W., & Bernstein, M. S. (2015). *Handbook of Collective Intelligence*. MIT Press.

Marsden, J. (2013). Stigmergic self-organization and the improvisation of Ushahidi. *Cognitive Systems Research*, *21*, 52–64. https://doi.org/10.1016/j.cogsys.2012.06.005

Marsden, J. (2015). *Developing a framework for stigmergic human collaboration with technology tools: Cases in emergency response*. *ProQuest Dissertations and Theses*. Doctor of Philosophy (PhD) Dissertation, Syracuse University.

Murty, P., Paulini, M., & Maher, M. Lou. (2012). Collective Intelligence and Design Thinking. *Design Thinking Research Symposium 8*, (or CI), 309–316.

Olsen, M. M. (2011). Variations on stigmergic communication to improve artificial intelligence and biological modeling. *ProQuest Dissertations and Theses*, *3482652*, 152.

Parunak. (2005). *A Survey of Environments and Mechanisms for Human-Human Stigmergy*. *International workshop on environments for multi-agent systems*. Berlin, Heidelberg.: Springer.

Resnick, M. (1994). Learning About Life, *241*, 229–241.

Resnick, M. (2009). Beyond the Centralized Mindset. *THE JOURNAL OF THE LEARNING SCIENCES*, (March 2015), 37–41. https://doi.org/10.1207/s15327809jls0501

Rezgui, A., & Crowston, K. (2017). Stigmergic Coordination in Wikipedia Amira. *CEUR Workshop Proceedings*, *1828*, 53–59. https://doi.org/10.1145/1235

Rosenberg, L. (2016). Artificial Swarm Intelligence , a Human-in-the-loop approach to A . I . *Proceedings of the 30th Conference on Artificial Intelligence (AAAI 2016)*, 4381–4382.

Salminen, J. (2012). Collective Intelligence in Humans : a Literature Review. *Arxiv Preprint ArXiv12043401*, *abs/1204.3*, 1–8.

Strogatz, S. (2003). *SYNC : The emerging science of spontaneous order*. Hyperion,.

Susi, T., & Ziemke, T. (2001). Social cognition, artefacts, and stigmergy: A comparative analysis of theoretical frameworks for the understanding of artefact-mediated collaborative activity. *Cognitive Systems Research*, *2*(4), 273–290. https://doi.org/10.1016/S1389-0417(01)00053-5

Theraulaz, G., & Bonabeau, E. (1999). A brief history of stigmergy. *Artificial Life*, *5*(2), 97–116. https://doi.org/10.1162/106454699568700

Tummolini, L., Mirolli, M., & Castelfranchi, C. (2009). Stigmergic Cues and their Uses in Coordination: An Evolutionary Approach. *Agents, Simulation and Applications*, 243–265.