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Emergent Economic Impact of Digital Information Networks

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by

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To my family...

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Abstract

Digital Information Networks (DINs) refer to information networks supported by telecommunication infrastructures and terminated by microprocessors. DINs provide a substrate for digital data flows. DINs enable the networking of individuals in the digital economy: an economy that uses digital products and services in any of the production, distribution and consumption stages. The key feature of DINs is that they enable interactive and flexible communication while reducing information transmission costs. This leads economic agents to be more productive within the economic environment that surrounds them.

A general recognition that DINs play an important economic role led to an increasing scientific interest in evaluating the economic importance of DINs. However, the announced impacts were not yet backed up with a factual evidence. Providing scientific grounding to this perception is an essential input to the development of telecommunication infrastructures related public and private policies.

Recent work has clarified how DINs impacts productivity of economic agents. Most remarkably, it hypothesized that an economic system influenced by DINs (a Digital Economic System (DES)) has the properties associated to a Complex Adaptive System (CAS): 1) it is composed of interacting agents; 2) some of the agents have individual and evolving goals; and 3) it exhibits unexpected emerging properties. Therefore, a DES requires a different type of analysis than the traditional approach used by economists based on evaluating the direct correlation of aggregated data on adoption or availability of DINs with macroeconomic productivity.

This MSc thesis donates to the study of DINs' economic impact by developing and testing a simulation model which can be used in further studies for the following purposes: a) to demonstrate evidences that a DES has the properties of a CAS; b) to demonstrate evidences of low correlation between DINs' adoption and macroeconomic productivity; c) to investigate new methods to increase the correlation between DINs' adoption and macroeconomic productivity. This model is designed with the help of Agents Based Modeling (ABM) which suits perfectly for simulating CASs.

From a scientific perspective, the novelty of this work lies in the investigation of the economic impact of DINs following a completely novel approach based on CAS, ABM and network theory. From an applied perspective, this work contributes to clarify utopian and dystopian views on DINs' effects on the economy, particularly aiming for policy makers and organizational managers.

Acknowledgements

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I would also like to thank all Computer Engineering department members for creating a very friendly atmosphere for students. I will definitely remember and miss all the social events organized by CE where we could talk with our professors informally and get to know fellow students closer.

My special thanks are addressed to my mother, my husband and my dear son. Their boundless support, patience and love was always encouraging me and giving me strength to move forward. Finally, I am thankful to all my friends who made my period of staying in the Netherlands exciting and joyful, who shared their culture, knowledge and experience with me

Zhanna Bazil
Delft, The Netherlands
September 14

Contents

List of Figures

Chapter 1

Introduction

Digital information networks (DINs) refer to information networks supported by telecommunication infrastructures and terminated by microprocessors. Broadly speaking, DINs serve three types of environments: fixed, mobile, and wireless. Examples of supporting technologies are cable, coaxial, and fiber (for fixed), GSM and UMTS (for mobile), and WiFi (for wireless).(see [25]). These data networks reduce interaction costs, expand information flow regardless of distance and nature (voice, video, data) and expand market boundaries. All of these factors influence positively the performance and productiveness of economic agents. By economic agent we refer to a unit of an economic system. A staff member or a consumer might be an example of an economic agent.

Investments in DINs take place throughout all sectors of economy, while there is no factual evidence that these investments are worthwhile. It is especially important nowadays, when most of the companies across all the sectors of economy suffered from worldwide economic crisis. In these conditions reasonable planning of expenditures on DINs becomes a problem of vital importance.

A significant number of studies attempted to prove that these expenditures have an effect on organizational as well as large scale productivity. The traditional approach followed by economists is to directly correlate aggregated (macro) data of economic productivity with adoption or availability of DINs. The results of these studies were ambiguous and contradictory which evidences that this approach is far from quantifying the real induced benefits. Lack of data and absence of a proper methodology in the traditional economic theory to evaluate effects of DINs were the main challenges faced by researchers.

1.1 Motivation

A new methodology is required to evaluate the macroeconomic value of DINs. To understand DINs' impact on economic processes and to be able to predict effects it is important to study the relationships and behaviors of individuals, because it is at this level that digital information network effects primarily happen. E.g. K.M.Carley stated in her article about the potential impact of communicating technologies: *understanding the impact of new technologies, particularly communication technologies, can only be done within a social context* (see [45]).

Recently a study was done, contributing to a valid theoretical ground to establish a correlation between DINs adoption and economic productivity on micro (e.g individual) as well as macro (e.g. sectoral) levels (see [51]). At the micro level a model labelled *Trans* was presented that identifies the *capabilities* of an economic agent somehow effected by DINs. These capabilities are proposed as the conceptual causal mechanisms linking DINs to micro economic productivity. Further, it proposes to study an economic system impacted by DINs (a Digital Economic System (DES)) as a Complex Adaptive System (CAS) which is characterized by the following properties: 1) it is composed of interacting agents; 2) some of the agents have individual and evolving goals; and 3) it exhibits unexpected emerging properties. Additionally, it proposed a new method to investigate the correlation between DINs adoption or availability and macroeconomic productivity.Apart from the proposals, no further investigation was done.

1.2 Goals and Contributions

This MSc thesis aims at *developing* and *testing* a simulation model which might be used in future studies to investigate the proposals made in [51] i.e. : a) to demonstrate evidences that a DES has the properties of a CAS; b) to demonstrate evidences of low correlation between DINs' adoption and macroeconomic productivity; c) to investigate new methods to increase the correlation between DINs' adoption and macroeconomic productivity.

This work is implemented using Agents Based Modeling (ABM)-type of simulations and Matlab for the analysis. The simulation model has the purpose of providing empirical data on how economic agents behave in a CAS under the influence of DINs adoption. Formation of emergent networks is observed using this model and further considered for the analysis.

Our final goal is to provide a novel direction and new estimation model for researchers interested in studying the impact of DINs.

1.3 Thesis Organization

The rest of the document is structured as follows: chapter 2 reviews state of the art and related challenges; chapter 3 includes the theoretical background which this work is based on; chapter 4 introduces the simulation model; chapter 5 presents the results of the sensitivity analysis; chapter 6 describes how the model should be further analyzed; and in chapter 7 we draw our conclusions and propose a future work.

Chapter 2

State of the art and challenges

This chapter represents state of the art overview and concludes the challenges that led to the IT productivity paradox best articulated by the Nobel laureate in economics Robert Solow: *we see computers everywhere except in the productivity statistics.*

2.1 State of the art

To give a more general overview of the state of the art, we reviewed also a number of studies on the economic impact of IT and ICT.DINs are also associated with these general terms although each of them has a different focus. [7] studied the potential impact of ICT and made a conclusion: *"at a macro level, the use of ICTs may be expected to enhance the productivity of the various factors of production and should be associated with increases in aggregate output. At a micro level, the use of these technologies should be associated with increases in firm and factor productivity".*

Most of the studies aiming at evaluating the benefits induced by IT and ICT adoption at the macroeconomic level have an empirical character. Mostly, they support their claims by correlating the availability of the technology or investments in it with macroeconomic indicators such as GDP and GNP (see [70], [50]). Usually, these studies rely on the statistics from several countries over a certain time period. However, they neglect the fact that *effectiveness* of utilization plays an important role. Depending on the *effectiveness* of implementation, the same amount of investments may lead to a success in one case and failure in another. Ignoring this lead to inappropriate estimation of economic effects caused by IT and ICT, inducing ambiguous and contradictory results.

The economic impact of DINs at the micro/organizational level has been investigated by an extensive number of studies. [15] surveyed over 150 studies, and they concluded that until early 1990s the link between DINs and productivity was inconclusive, but also that measuring it was impossible due to the lack of data and analytical methods. The literature with a fundamental character (e.g. [16]) is generally limited to complex purely verbal representations of the mechanisms leading DINs to productivity, making it hard to investigate the causal relations between assumptions at the organizational level and implications at sectoral/macro level. The studies aiming at establishing a microeconomic relation tend to rely on the analysis and correlation of data, not explaining thoroughly why these correlations should exist. Furthermore, they mostly discuss which econometrics methods to employ. Therefore, from the literature at the micro/organizational level it seems that no valid theoretical ground was yet established to derive sectoral/macro level economic impacts of DINs.

Alternative approaches for measuring IT productivity first appeared in literature in late 1990s. V.Grover et al. (see [32]) reviewed the earlier studies and concluded that the relationship between IT and productivity was unclear and confounded by methodological problems and intervening variables. Alternatively, they suggested that IT diffusion influences productivity primarily through its impact on process change and proposed a new methodology to assess perceived productivity which can lead to the market success depending on many contingency factors. According to this new methodology, the relationship between IT and perceived productivity changes must be mediated by the extent of perceived process change associated with IT diffusion. Several other studies claimed that productivity paradox could be solved only by understanding social and organizational changes caused by new information technologies on a firm-level (see [45], [64]). Our line of reasoning is coherent with these approaches for general IT.

2.2 Challenges

There are many challenges in the process of finding evidence of the economic value of DINs. Broadly speaking, these challenges can be summarized into four groups: 1) separability; 2) endogeneity; 3) causality; and 4) externality.

DINs do not act on economy by itself, but in conjunction with other IT (primarily consisting of computers and software) and associated organizational changes. Therefore, the separability of their effects is not an elementary task. Moreover, several other factors may affect productivity (e.g. price and availability of inputs, and macroeconomic context). Therefore, they should be endogenous in any evaluation.

The causality mechanisms that lead DINs to economic productivity implications necessarily involve human and social behaviors, because it is at this level that DINs have their primarily effect. Obviously, these are difficult to account, theoretically as well as empirically, particularly with the analytical tools traditionally used in economics. [30] pointed out that a fundamental difference between economics and sociology is that sociologists take it for granted that humans are socially embedded (see also [13]). Contrary to sociology, economic theory rests on the absence of social embeddedness. The consistency principle is one of the most stark evidences of the existence of social embeddedness (see [58]). Effectively, it states that humans tend to agree with those whom they share interests and social background (see [14]). DINs provide the network substrate to social economic actors, and therefore, to understand their impact on economic productivity, one must also be able to connect the dots from partially rational individual actors to systemic large scale economic patterns.

Externalities (also called spillover effects) refer to indirect effects of DINs that happen across economic actors, and therefore are difficult to quantify. [79] and [19] argue that externalities have the most significant economic impact, but that they are only realizable on the long term, as they may take time to disperse through an economy.

Chapter 3

Theoretical background

Recently a study was done, contributing to a valid theoretical ground to establish a correlation between DINs adoption and economic productivity on micro (e.g individual) as well as macro (e.g. sectoral) levels (see [51]). At the micro level a model labelled *Trans* was presented that identifies the *capabilities* of an economic agent somehow effected by DINs. These capabilities are proposed as the conceptual causal mechanisms linking DINs to micro economic productivity. Additionally, a proposition based on network theory was made to strengthen the correlation between DINs adoption and sectoral/macroeconomic productivity. In this chapter we transcript the content of [51] for clarifying the grounding for our work.

3.1 *Trans* model

3.1.1 Capabilities

Network externality can be defined as a change in productivity that an agent derives when the number of other agents using DINs changes. This allows, in principle, to separate the value of productivity in two distinct parts. One component, the autarky value is the productivity value if there are no other agents using DINs. The other component, the connection value, is the additional productivity value achieved when multiple other agents are using DINs. The latter value is the essence of DINs' externality effects. In a Trans model, digital economic agent is defined as follows: *Digital economic agent is any agent from an economic structure which may achieve an additional productivity value when multiple other agents are using DINs.* Examples of agents are workers, consumers and producers from any organization using DINs. Economic agent or simply agent is used to refer to digital economic agent. An agent explores personal and intrinsic capabilities to become more productive within his economic structure. For example, consumer A meets supplier B to acquire a production input at a lower price. The capability of A and B to meet each other will make both more productive. From a thorough literature review on the relation between information, digital infrastructures and productivity, [51] identified a set of capabilities of a productive economic agent, which are directly dependent on DINs. It hypothesized these capabilities to be generally applicable to agents across all economic sectors. *Capability* refers to a quality of the economic agent used for productive purposes and directly affected by DINs.

3.1.1.1 Sensitivity

According to a literature review done in [51] it was found that when the number of relationships between agents increased further than what they could retain, communication between them became difficult and at that time, the group broke into cliques. Moreover, prices in very large organizations were more volatile than in small ones, and proliferation of cliques resulted in additional overall volatility. Theoretically, in conditions of perfect information sensing one would expect prices to converge. From these observations, *sensitivity* was defined in [51] as *the capability of an economic agent to sense information from other agents*. High capacity communication infrastructures often directly influence sensitivity. DINs are expected to expand research and knowledge sharing capabilities. On the other hand, it may cultivate passivity, restrict imagination, and inhibit creativity.

3.1.1.2 Trustability

A risk-averse decision maker will pay premiums to insure against any arbitrary risk. While firms are traditionally assumed to be risk neutral, economists have increasingly recognized situations in which they may be risk averse instead (e.g. capital markets). Efficiency gains can be realized through information mechanisms that prevent poor transactions. *Trust* is one of them, providing the confidence that others will do the right thing despite a clear balance of incentives to the contrary. Therefore *trustability* was defined in [51] as the capability of an economic agent to have confidence that other agents will do the right thing despite a clear balance of incentives to the contrary. But trust does not always unambiguously improve productivity. Trust is advantageous in a stable situations, but leads to a lock in effect in the periods of changes.

3.1.1.3 Hierarchity

Another mechanism potentially useful to increase efficiency is a hierarchical structure. *Hierarchity* is defined in [51] as the capability of an economic agent to be ranked differently than other agents, according to given criteria, enabling it to act under different conditions. Within organizations, one has to balance the importance of global information favoring hierarchical centralization, with local information gathering enabling fast local organization adaptation, favoring decentralization. Productivity increases to the extent that distributing control optimally balances these factors in the light of complementarity and indispensability (see [16]). Information management theory then offers results on how to use DINs to explore [16] core insight (see [81]). One example is indispensable agents should exercise greater control. Also the communication between organizational structures becomes more efficient, with services being delivered by specialized providers (see [28]).

3.1.1.4 Normativity

Norms, being shared ideas about the proper way to behave, are one of the oldest arguments in social psychology (see [24]). They foster network effects by promoting economies of scale, and at the same time reduce information processing requirements by constraining potential interpretations (see [9]). On the long run, they can have negative effects, masking changes in the environment. *Normativity* is defined as the capability of an economic agent to share with other agents ideas about the proper way to behave. One important example of norms is loyalty systems (see [30]). DINs can displace individuals from conventional social contacts, and therefore affect their productivity (see [43]). Another negative example comes from intellectually free property rights (see [26]) e.g. unsupported open software can cause operational delays within organizational structures, and consequently inefficiencies in production. More positively, public measures have been established to promote cohesion and cultural diversity using digital communications (see [5]). [35] studied long run equilibrium patterns in coordination games in the presence of conventions.

3.1.1.5 Coordinativity

Coordination is "the act of managing interdependencies between activities performed to achieve a goal" (see [53]). It arises, effecting productivity, when the agent has to choose between actions, the order of the actions matters and/or the time at which the actions are carried out matters (see [20]). Therefore *coordinativity* is defined as the capability of an economic agent to manage interdependencies between activities with other agents to achieve a common goal. Coordinativity prevents conflicts, waste of efforts, and squandering resources, and assures focus, while trying to accomplish a common goal. The work of Kandori et al. (see [41]) and Young, 1993 ([92]) have triggered much interest in coordination games. Important research results concern the impact of different network structures in coordination (see [47]). In a survey performed by [38], 45 % of the respondents identified DINs as a driver to reorganize work practices. More specifically, online banking can be seen as a good example of an application of digital coordination (see [1]).

3.1.1.6 Cooperativity

Cooperation can be defined as acting together with a common purpose (see [37]). Sharing information helps agents aligning their individual incentives with outcomes. Assuming proper behavior, if absolute incentives are more advantageous over relative incentives, the agents cooperate. Both inter- and intra-organizational cooperation have been object of study since the work of [54]. Good examples are joint ventures. Therefore *cooperativity* is the capability of an economic agent to align his personal goals with individual goals from other agents for a common purpose. In practice, it is often hard to distinguish cooperativity from coordinativity. Conceptually, the key differences are two: (1) In coordinativity the agents share exactly the same goals, while in cooperativity the agents share only partially aligned goals; (2) And in coordinativity the relation between the agents is critically dependent on time, while in cooperativity the agents relate to each other typically offline. Although the experimental literature on cooperation is vast (see [47]), only a few papers consider the role of networks in this process (see e.g. [83]). Supply and demand matching with online trading is an important practical example of the importance of DINs for cooperativity (see [6]) and [49].

3.1.1.7 Adoptativity

[59] state that firms improve their productivity by adopting technological and organizational solutions from the most innovative firms (see also [23] and [55]). Examples are informal associations (see [69]) and product advertisement (see [31]). Important dimensions to be accounted are the level of codification (see [87]) and the extent to which the knowledge fits in a set of interdependent elements (see [87]) and [76]). This leads to a definition of *adoptativity* as the capability of an economic agent to adopt knowledge from other agents. There is a vast literature studying *adoptativity* using network analysis. Many examples could be cited of the value of digital networks to exchange knowledge. A good example is e-learning between students (see [11]).

3.1.1.8 Creativity

Agents can increase their productivity by creating new knowledge by collaborating with other agents to address operational inefficiencies. Their motivation to collaborate comes from indivisibilities of their specialized knowledge (see [75]) and environmental changes. Organizations that best address crucial information gaps through their information network structures may be more able to create novel knowledge. Thus *creativity* is defined as the capability of an economic agent to create new knowledge, unknown to him before and to his collaborative agents. The relevance of DINs for collaborative research is well recognized (see [61]), and evidences have been found that organizations that use them more intensively, innovate more (see [46]). A trade-off exists between rate of information gathering and rate of environmental change (see [16]).

3.1.1.9 Selectivity

Selection is the process of scanning for the unknown or generating courses of action that improve on known alternatives (see [16]). For maximal productivity, the agent has to decide for a stopping point in an uncertain environment (see [22]), while keeping computational requirements within limits. *Selectivity* is defined as capability of an economic agent to scan information from other agents, generating courses of action that improve on known alternatives. The role of information networks has been extensively acknowledged in this process (see [85]). A practical proposal accounting the value of networks in the process of selection has been made in [67]. This framework has been used for interdependent information system project selection (see [42]). Online job hunting and Google.com are good example of selectivity using DINs.

3.1.1.10 Negotiability

Negotiability occurs when exchange happens between unfamiliar partners or when evaluating new courses of action. Negotiation grows in importance with the perception that potential downside effects of a wrong decision can be large and costly to reverse. Negotiability mechanisms include signaling (e.g. give guarantees to buy) and screening (e.g. give certificates to sell) (see [4] and [72]). Economic literature further distinguishes between one shot and repeated contracts (see [80]). [51] defines *negotiability* as the capability of an economic agent to bargain with other agents for inferior exchange costs. [48] developed a model in which the prices are determined by a bargaining process rather than an English auction. However, the precise influence of the network structure in negotiation processes has not been intensively studied yet (see [27] for some experimental work). Online stock trading activities are a good example of the importance of DINs for negotiability (see [93]).

3.1.2 Causal structure

In the previous section, we reviewed capabilities of the economic agent which were introduced in [51] that are somehow affected by DINs with implications for microeconomic productivity. In this section, the causal structure of the Trans model presented in [51] is observed. All the capabilities are grouped further into three layers (*sensit*, *jungit* and *intelligit*, see figure 3.1). Each layer has a unique character, making it possible to establish a dependency rule between them: the layers above are dependent on the layers below. [51] introduced a definition for *virtual information network* for better understanding of the particular character of each layer: *virtual information network is an information network in which meaningful information is exchanged in essence, but not in fact.*

The adjective *meaningful* refers to the information that is in practice used by the economic agents with a defined purpose, and not simply *raw* digital information (e.g. information supporting protocols for communication). The adjective virtual is used to denote activities that are realized or carried out using DIN infrastructures. Examples of these networks are email communications and photo exchange sessions. In a photo session the visual properties of a person in the photo are transmitted between agents, but in fact, the person in the photo does not travel physically.

DIN infrastructures provide a physical substrate for virtual information networks to emerge with minimum transmission costs in comparison with physical transportation networks (e.g. roads). With minimum transmission costs, virtual information networks make the economic systems alive and transient (see [8]).

Starting top-down, the first layer in the Trans causal structure is *intelligit*, followed by *jungit*, and finally *sensit*. From an economic perspective, the function of the agent is to choose and perform between alternative rational capabilities to navigate through the production space problem. These capabilities (adoptativity, creativity, selectivity, negotiability, coordinativity, and cooperativity), identified in the intelligit layer (meaning to think), give rise to productive transient virtual information networks, entitling its members to be in a higher state of productivity. The transiency of these networks relates to their typically short and dynamic existence. For instance, if a secretary from one organization has to organize a personnel meeting, she will initiate a digital session of coordination requesting and coordinating the schedules from all the involved parties. Thus, the coordinativity session is short and dynamic.

In an environment with limited access to information, agents tend to fall back to more or less institutionalized relationships of mutual acquaintance and recognition. The virtual information networks emerging from these relationships tend to be durable, entitling its members to credit, in the various senses of the word. The *jungit* layer encompasses the capabilities which enable an agent to establish these relationships (trustability, normativity and hierarchity). These are fundamental links between orthodox equilibrium economics and sociology, as has been pointed out by [29] when referring to social embeddedness of the economic actors. Jungit capabilities' effects in productivity might be positive or negative. On one hand, they might decrease transaction costs. But on the other hand, they might lead to lock in, group think, and redundancy. Extensive work has been done on the causal relation from jungit's to intelligit's capabilities. As an example, [35] studied long run equilibrium patterns in coordination games in the presence of norms.

Any model accounting for the relation between information and human productivity must inevitably contend with constraints on information sensing. The *sensit* layer accounts for these constraints, encompassing the previously described *sensitivity* capability. An agent might be sensible to information quality and quantity. Faced with overload or deterioration it refrains to more primitive mechanisms (e.g. reversion to first learned) (see [73]). On the other hand, additional or appealing information can make an agent more productive. Video conferencing among acquaintances is a good example in which sensitivity to the information can lead to better relationships between agents (see [86]). The relation between communication restriction (restricted sensitivity) and coordination performance has been intensively tested (see e.g. [56]).

3.2 Emergent networks

In this section, a proposition made in [51] based on network theory and extending Trans model to address sectoral/macro level productivity is revealed.

Networks are relational structures of economic and social life. [94] states that they should be considered only if the economic system can not be fully reduced to the constraints and choices made by the economic actors. If instead, the system can, a complete account of the relevant causal pathways may be rendered without attention to the networks. Networks really matter when aggregate micro-activity produces patterns not suggested by orthodox economic theory, particularly the rate and path towards equilibrium. More specifically, networks matter in a (complex and adaptive) system which exhibits the following three properties: 1) the system is composed of interacting agents; 2) at least some of the agents are capable of reacting in a systematic and timely way to changes in their environment in pursuit of built-in or evolved goals; 3) and the system exhibits emerging properties arising from the interaction between the agents that can not be deduced simply by aggregating the properties of the agents.

For a sectoral/macroeconomic system impacted by DINs, all these three prop-

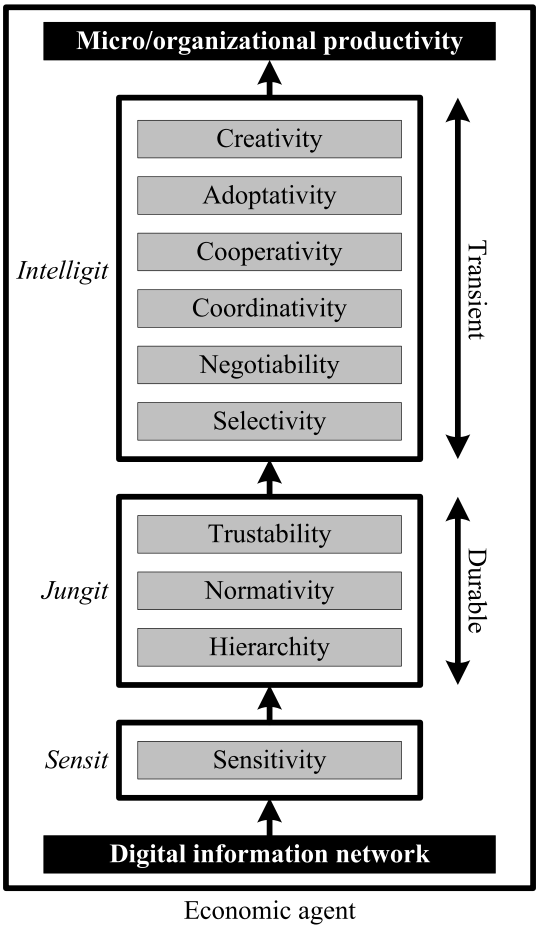


Figure 3.1: Trans causal structure

erties hold. Jungit's capabilities relate directly with the first property: the system is composed of interacting agents. Intelligit's capabilities relate directly with the second property: at least some of the agents are capable of reacting in a systematic and timely way to changes in their environment in pursuit of built-in or evolved goals. The third property (the system exhibits emerging properties) relates directly to the externality challenge, explained in the introduction of this paper. [79] and [19] have argued that the impact of DINs across economic agents is the most significant, but that it is only realizable on the long term, as they may take time to disperse through an economy.

Any effort to relate DINs with sectoral/macro level productivity has to take into account a characterization of the emergent virtual information networks, because their complexity and intermediate presence hampers any attempt to confidently establish a direct correlation between DINs and macro/sectoral level productivity. [51] proposes to use the topological properties of the emerging virtual information networks as this characterization, and use them as intermediate observations to correlate the adoption of DINs with sectoral/macro level productivity.

Topology specifies how items, called nodes, are interconnected or related to other nodes by links (see [82]). The interconnection pattern, is represented by a graph G^i, consisting of nodes and links, with i referring to the particular virtual information network under study. Each link in G^i can be further specified by a set of link weights. Broadly speaking, this analysis involves the following stages:

1. Analysis using simulations of the topological properties ($t_{k,i}$) of the virtual information networks emerging from digital information networks using K different metrics (e.g. the clustering coefficient).

2. Computation of a resume value (the T-*value*) of the topological properties of the virtual information networks. For the case of $i = 1$, a possible approach would be to use the T-value defined by a weighted, linear norm: $T = \sum_{k=1}^{K} w_k t_k$, where w and t are the $K \times 1$ weight and the topology vector, respectively.

3. Analysis of the correlation between digital information networks adoption and economic productivity, including an intermediate observation of the T-value.

Moreover, [51] states that simulating the system of virtual information network interactions enabled by DINs requires a modeling paradigm able to provide flexibility in the specification of the interaction structure. Moreover, the solution has to be found inductively, to account for uncertain emergent properties.

Agents Based Modeling (ABM) recommends itself as a very useful tool for this effort. In ABM, the modeler designs classes of *agents* (the basic components of the model), attributes these agents with certain functionality, instantiates a population of agents, assigns initial and boundary conditions, executes the simulation for a duration of time periods, and examines the final state of the model. Although no real agreement exists about the core question of exactly what an agent is, broadly it refers to bundled data and behavioral methods representing an entity constituting part of a computationally constructed world (see [78]).

The main purpose of ABM is to gain intuition on the two-way feedback between the micro and the macro structure of a CAS, which exhibits the following three properties: 1) the system is composed of interacting agents; 2) the system exhibits emerging properties from the interaction between the agents that can not be deduced simply by aggregating the properties of the agents; and 3) at least some of the agents are capable of reacting in a systematic and timely way to changes in their environment in pursuit of built-in or evolved goals.

3.3 Contribution

This thesis work aims at modelling a DES bared on a particular causal mechanism identified in the Trans model: DINs $\rightarrow$ trustability $\rightarrow$ coordinativity $\rightarrow$ productivity. *Trustability* belongs to the *Jungit* layer of the Trans model, and consequently it creates a base for *coordinativity* which is in the upper *Intelligit* layer. Coordinativity was studied by a considerable number of researchers and most of them provided an evidence that good coordination is one of the driving forces of productivity. The process of coordination enables agents to focus on the task being performed. The stronger is the coordinativity, the better is the performance and productivity.

Several studies concluded that coordination is highly dependent on the underlying interaction topology (see [39], [41], [60], [91]).

An approach that social and behavioral factors have a great influence on economy induced development of the conventional economic theory named agent-based computational economics.

A novel approach considering DES as a CAS and based on network theory might help to resolve productivity paradox and to investigate economic effects caused by DINs. This MSc thesis develops and tests a simulation model which can be used for the following purposes: a) to demonstrate evidences that a DES has the properties of a CAS; b) to demonstrate evidences of the low correlation between DINs' adoption and macroeconomic productivity; c) to investigate new methods to increase the correlation between DINs' adoption and macroeconomic productivity. Our model observes *emergent* economic impact of DINs. By the adjective *emergent* we mean effects appearing as a consequence of DINs adoption. As seen from the previous section, ABM recommends itself as a very useful tool for this effort.

C. Bruun (see [18]) claims that the ABM aproach in economics might resolve a number of paradoxes, since it does not separate micro and macro indicators, but states that a global effects *emerge* from the interaction of individuals. The network effect is crucial in such a system. Some studies even announce that advances in information technologies enable an increase of this effect making network of interactions more dynamic, uncertain and complex (see [90]).

In the next chapter we introduce our simulation model in more details.

Chapter 4

Simulation model

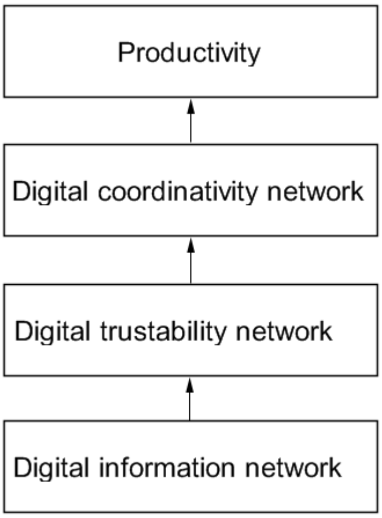


Figure 4.1: DES simulated in this work

In this chapter the simulation model is introduced. In order to investigate the problem addressed by this thesis, several assumptions were made, either logically or proposed by other studies.

This model simulates certain virtual information networks emerging from a DINs adoption (see figure 4.1). DINs provide a substrate for the networks of trust and coordination in our DES. The model aims at investigating how the DINs adoption changes interaction networks and what is the effect of these changes on productivity.

4.1 Digital information network

There are several models to forecast technology adoption, but review of the studies shows that the preference in the analysis of ICT adoption is given to the Bass diffusion model. For instance, diffusion of cellular phones [21], wireless communication [74], ICT [12] was analysed with the Bass diffusion model. The model represented by Bass assumes that the potential adopters are influenced both internally among members of the social system and externally. Recent studies mentioned

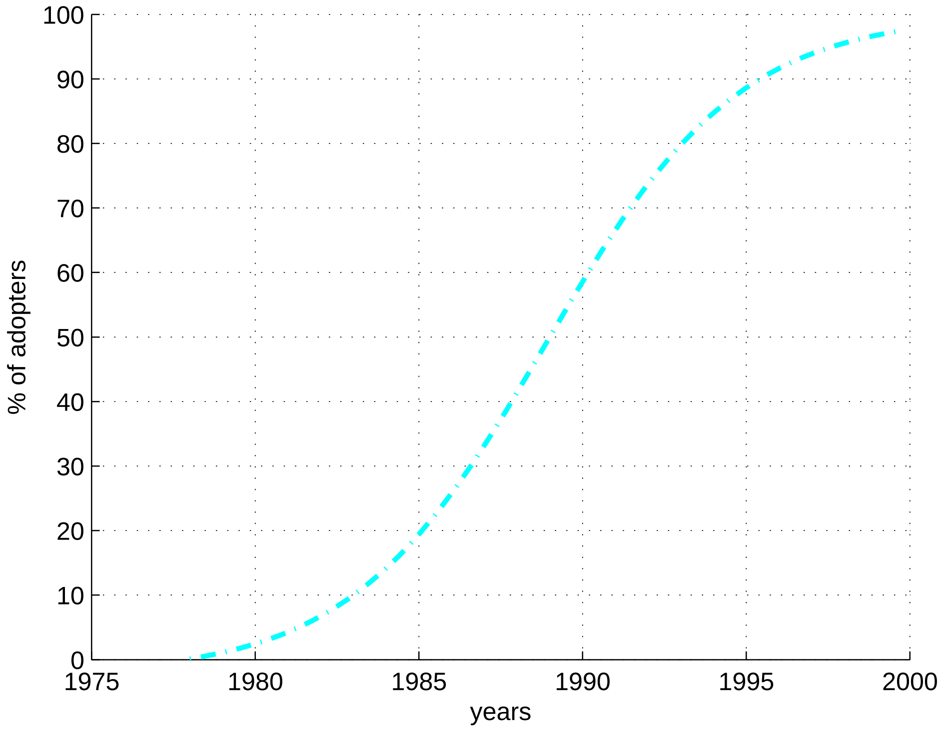


Figure 4.2: Illustration of the e-mail adoption

also additional factors not presented in the original Bass model, but influencing the results especially in large-scale studies (e.g. country development level and cultural effect). However, the main parameters are the coefficients of imitation and innovation.

J.T.C. Teng et al. (see [77]) studied diffusion of information technology innovations and provided a table of Bass curve coefficients for 19 IT innovations such as e-mail, LAN, teleconferencing, etc. Cumulative adopter distribution of the Bass model used in above mentioned study is given below:

$$N(t) = m\frac{1 - exp(-t(a+b))}{1 + \frac{b}{a}exp(-t(a+b))} \tag{4.1}$$

Where:
$N(t)$ - number of potential adopters that has adopted the innovation at time t
m - maximum number of potential adopters
a - coefficient of innovation
b - coefficient of imitation

Since e-mail communication is absolutely dependent on DINs and is related more than other IT innovations to DINs, we present the e-mail adoption distribution for illustrative purposes (see figure 4.2) and we use the same coefficients in our simulation model: $a = 0.0008$ and $b = 0.3303$.

The DIN is formed under the influence of the dynamically changing number of adopters. We assume the topology of the DIN to be a full mesh, meaning that once a node gets a connection, it can communicate directly with any other node

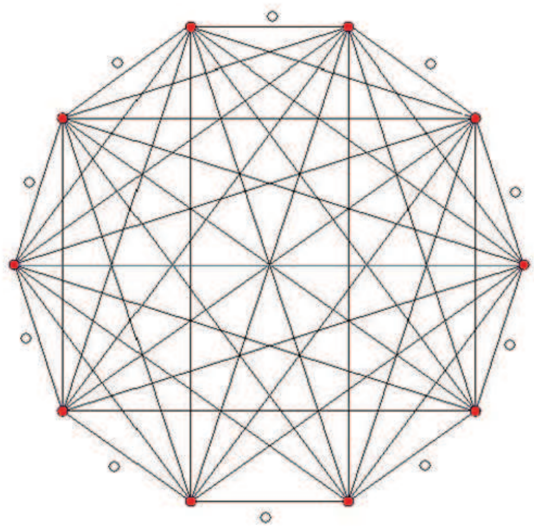


Figure 4.3: Digital information network

in that network. However, the nodes that have not adopted DIN are not able to communicate and thus do not have any links in all the networks represented in the simulation model (see figure 4.3). Adopters are represented by red nodes in Figure 4.3 and form a full mesh network, while non-adopters (white nodes at figure 4.3) stay disconnected in this network. The DIN provides a substrate for the digital trustability and digital coordinativity networks.

4.2 Digital trustability network

Xianchen Guo et al. (see [33]) claim that trust networks possess small-world and scale-free network properties: high clustering, short average path length and scale-free link distribution.

The trustability network is modelled in this work as the small world network proposed by Watts and Strogatz (see [84]). According to the Watts and Strogatz model, the small world network is evolved from a ring network by rewiring each edge with a given probability. If the probability of rewiring equals zero, this process leaves the ring undisturbed. If p = 1 every edge will be randomly wired, creating a random graph, but in between intermediate graphs emerge. Our literature review showed that only a few studies investigated the parameter values of these type of trust networks. In the sensitivity analysis we tested the impact of different values of these parameters.

Digital trustability network is formed as a result of the intersection of the trustability network simulated as a small-world network and the DIN modelled as described in previous section. The digital trustability network in our work consists of nodes, which trust other nodes in a social network and have digital links with each other. For instance, if a pair of nodes have a link in a trustability network but one of the nodes hasn't adopted the DIN, this node stays disconnected in the digital trustability network.

Figure 4.5 depicts the formation of the digital trustability network. As we can

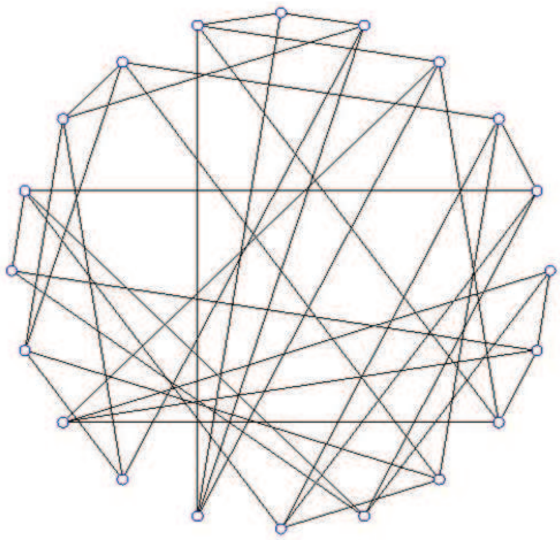


Figure 4.4: Small world network

see from the figure 4.5, digital information network is the network where all the adopters (red nodes) are connected with each other in the full-mesh manner, while non-adopters are disconnected. The real trustability network is a network of interpersonal trust ties, where agents may have trust links independently weather they adopted DIN or not. Red nodes represent adopters in figure 4.5 while blank nodes display non-adopters. Digital trustability network is formed by intersection of digital information network and real trustability network. As we can see, non-adopters do not have any links with others in digital trustability network since they have not adopted the technology yet.

4.3 Digital coordinativity network

Coordination games are used widely nowadays to simulate individual's behavior during the decision making process either in real interaction networks or in simulation models. In coordination games, agents try to conform to what their neighbors do. The *graph coloring problem* is a good representation of coordination games in networks. A number of studies investigating coordination mechanisms in the networks of interpersonal communication used graph coloring games (see [44], [17], [62]). [44] states: *the graph coloring problem is a natural abstraction of many human and organizational problems in which it is desirable or necessary to distinguish one's behavior from that of neighboring parties.*

In our work coordination process will be modelled by simulating the graph coloring game in the digital trustability network. We will use in our simulation the graph coloring game as it was proposed by Olson & Carley (see [62]). Every node chooses a color at the first step. The number of colors available is defined during the experiment. After each iteration every node can see the direct neighbors and learn from that. The nodes are rewarded based on the number of neighbors who have chosen the same color.

Chen and Khoroshilov studied three learning algorithms: a simple reinforce-

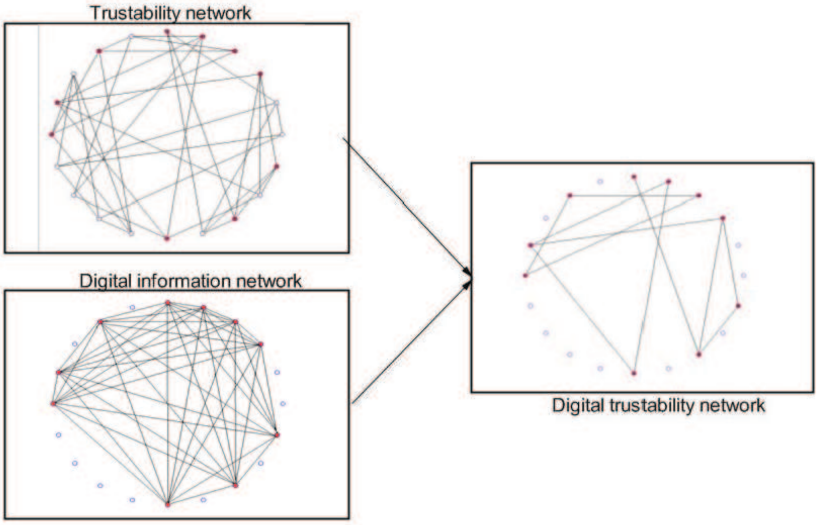


Figure 4.5: Digital trustability network formation

ment learning model, a modified experience-weighted attraction learning model, and a payoff-assessment learning model in their work [89]. They found out that *"the learning models which incorporate more optimization, such as the payoff-assessment learning model and the experience-weighted attraction learning model, make better predictions under the serial mechanism and the coordination games"*. In our work all nodes follow the payoff-assessment learning algorithm as was proposed by Sarin and Vahid (see [68]). At each stage, the player chooses the strategy that he assesses to give him the highest payoff and updates his assessment adaptively.

According to the model, each agent makes an assessment of a possible payoff $u_j(n)$ in case of choosing color j. We suppose that coordinating with one node gives a payoff $= 1$. Thus the actual payoff received after each round, $\pi_j(n)$, equals to the number of neighboring nodes who have chosen the same color at the previous step. At the next step, the assessment is updated for the same strategy based on the actual payoff received and the assessment at the previous stage:

$$u_j(n+1) = (1-\lambda)u_j(n) + \lambda\pi_j(n) \tag{4.2}$$

Where:

λ - learning parameter ($0 < \lambda < 1$)

u_j - assessed payoff

π_j - actual payoff received from the previous step

The learning parameter is applicable only for the chosen color j, for the remaining colors other than j, the assessment is done based on the current situation. The parameter λ determines how fast the assessment adapts to the observed payoffs. The larger is λ, the stronger is the influence of observed payoffs on assessments.

During the graph coloring experiment underlying topology will remain unchanged. Each experiment will be simulated for a certain number of iterations after which the simulation will terminate. The sufficient number of rounds will be defined during the sensitivity analysis presented in chapter 5. A simple example of the graph coloring mechanism is depicted at 4.7(a).

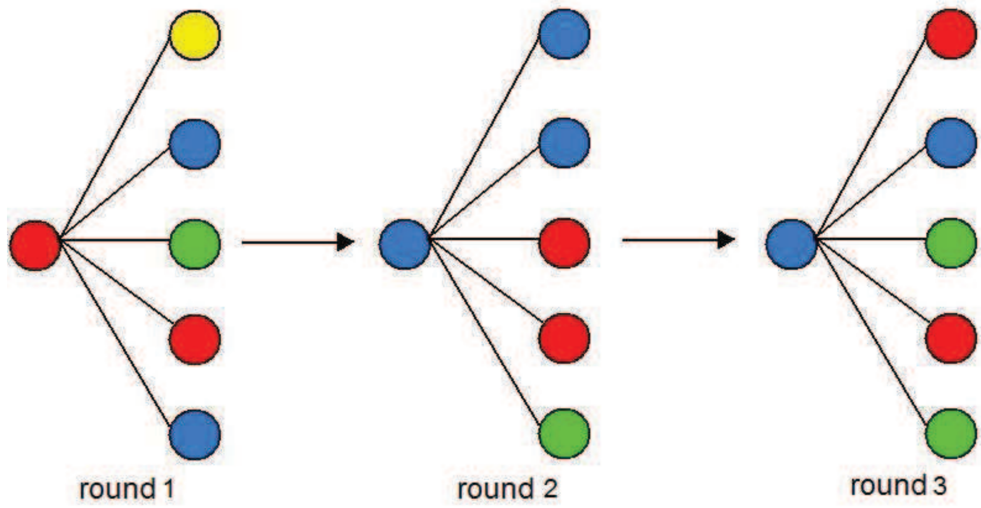


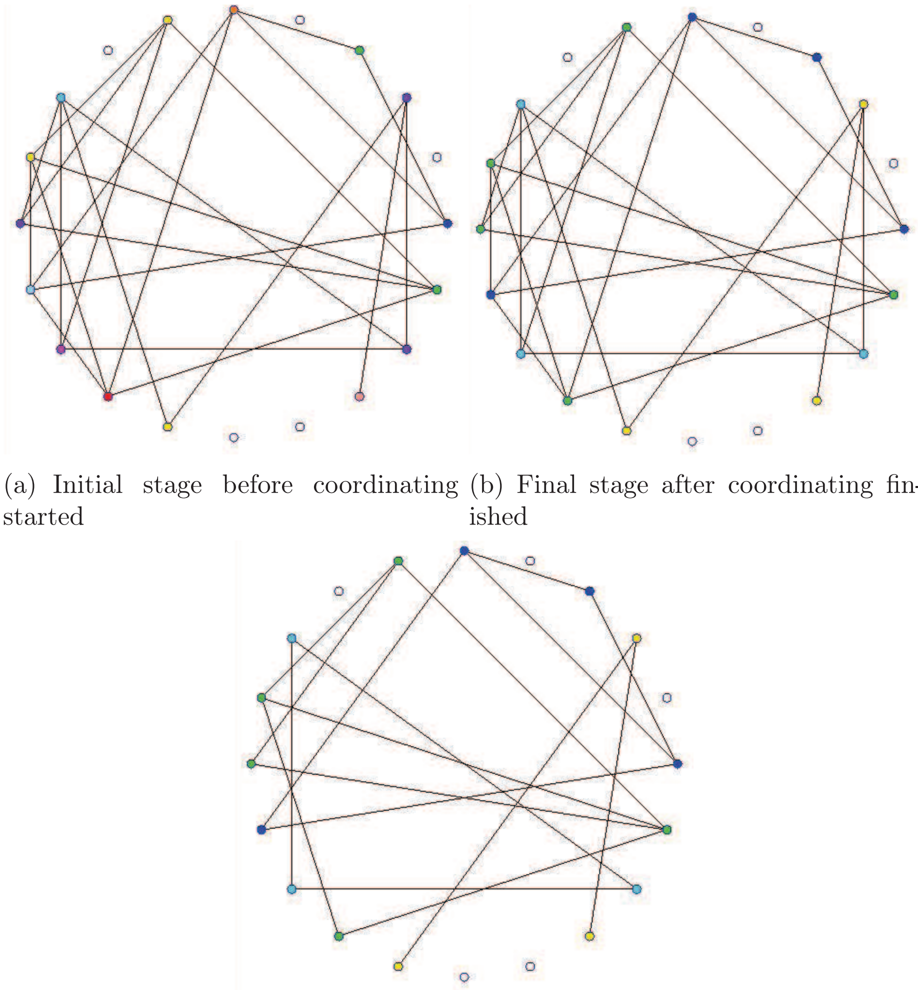
Figure 4.6: Graph coloring algorithm

Table 4.1: Payoff assessment of a graph coloring mechanism depicted at 4.7(a), $\lambda = 0.5$

Color	Payoff assessment at round 1	Payoff assessment at round 2	Payoff assessment at round 3
red	$u_1 = \lambda\pi = 0.5 * 1 = 0.5$	$u_2 = \lambda\pi = 0.5 * 2 = 1$	$u_3 = \lambda\pi = 0.5*2 = 1$
blue	$u_1 = \lambda\pi = 0.5 *2 = 1$	$u_2 = (1-\lambda)u_1 + \lambda\pi = 0.5*1 + 0.5*2 = 1.5$	$u_3 = (1-\lambda)u_2 + \lambda\pi = 1.25$
green	$\lambda\pi = 0.5 *1 = 0.5$	$u_2 = \lambda\pi = 0.5 *1 = 0.5$	$u_3 = \lambda\pi = 0.5*2 = 1$
yellow	$\lambda\pi = 0.5 *1 = 0.5$	$u_2 = \lambda\pi = 0$	$u_3 = \lambda\pi = 0$

At the first round an agent does not have an experience, thus assesses the state of the world only by the current situation choosing the color observed from the majority of neighbors. At the second round an agent makes new assessments applying learning from the experience for the chosen color. However, learning from the previous step is availabe only for the adopted strategy, i.e. is implied for the blue color in this example. Other colors' payoffs are assessed only by the immediate observations. This assessment method expresses the decision making process very naturally, because in the real social networks agents (i.e. people) tend to learn from adopting a certain strategy. If a chosen strategy was successful and met the expectations, this increases the chances of this strategy to be taken by agent again.

As soon as graph coloring mechanism is finished we start coordinativity network formation process. All the edges connecting two different colors are removed meaning that there is no coordination between two agents since they hold different colors. Consequently, coordinativity network consists of several clusters, where each cluster contains nodes of the same color (see figure 4.7(c)).



(a) Initial stage before coordinating started (b) Final stage after coordinating finished

(c) Final coordinativity network

Figure 4.7: Coordinativity network formation

4.4 Productivity

Productivity is a function of overall coordinativity in our model and holds values in range (0,1). It is worthwhile to mention that productivity does not hold an absolute value in our work:

$$P = \frac{N_0 - N_{fin}}{N_0} \tag{4.3}$$

Where:
N_0 - initial number of colors in the network
N_{fin} -final number of colors in the network after finishing graph coloring game

4.5 Agents Based Modeling toolkit

Several researchers interested in ABM, made a comparison of the most well-known ABM toolkits such as Swarm, Repast and NetLogo [88], [65], [63]. According to

D.A. Robertson (see [65]), NetLogo is easy to install and operate and is basically the perfect environment for implementation of simple models. However, extending these simple models and adding more functionality is a complicated task in NetLogo.

Swarm is an alternative toolkit, which can handle simulation of complex systems, but the main disadvantage of this environment is that it was written originally in Objective C that led to a number of incompatibility issues of Java Swarm (current version of Swarm), difficulty of debugging run-time errors and slow execution speed (see [63]).

Both [65] and [63] name Repast as a most convenient and complete toolkit for ABM studies since it comprises useful Swarm functions and additional capabilities such as resetting and restarting models from graphical interface. Another advantage to mention is a good execution time compared to the other platforms.

Considering all cons and pros we made a preference in favor of Repast mainly because this toolkit includes many classes for network functions and is advantageous in comparison with others as stated above.

4.6 Building model with Repast Symphony

The simulation model was built with the help of free and open source ABM toolkit named Repast Symphony (Repast S). This last version of Repast allows users to build simulation models by using pure Java, Groovy coding or visual editor. The last technique is created by building flowcharts of agent's behavior(see Figure 4.8). After saving a diagram it is automatically compiled into a usable Groovy code which can be loaded immediately into the Repast runtime and executed.

Repast S is expected to use two major types of settings, namely, model and scenario descriptors, to glue or bond models together. Model descriptors define what can be in a model, such as the allowed agent types, permitted agent relationships, and watching information. Scenario descriptors define what actually is in a model, such as agent data sources, visualizations, and logging. Model and scenario descriptors are stored in XML files.

We used visual editor for creating our agent class and describing its' behaviors, but we found coding in Java more flexible for developing visual representation of agents and a context file. Context is an important data structure in a Repast S. It creates an abstract environment where agents exist at a given point in the simulation. Moreover, it provides the basic infrastructure to define a population and the interactions of that population without actually providing the implementations. Our context file describes populating the model with a number of nodes and forming small world trustability network. Further it produces digital trustability network where only those nodes who have already adopted digital information network can have links and hence communicate with each other.

Agent class describes scheduled behaviors such as initialization, coloring, coordinativity network formation and calculating the results. Initialization step assigns random color for each adopter in the digital trustability network. Coloring behavior is scheduled right after initializing step is finished. It defines graph coloring algorithm followed by each agent. As was mentioned before, this step is continuously

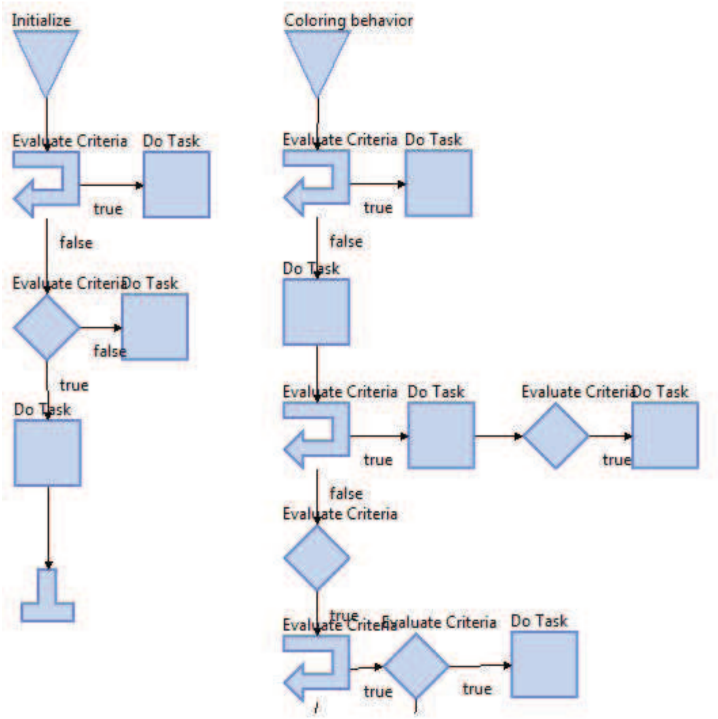


Figure 4.8: Coding with visual editor

repeated unless stable results are achieved. Next step in the schedule is coordinativity network formation which is achieved by removing redundant edges connecting different colors. Finally, productivity is calculated and all the results (including adjacency matrix) are written to the text file which can be loaded afterwards to Matlab for further analysis.

For a graphical implementation of our model we developed a node style class by using Java coding. This class encodes how colors should be displayed and under what conditions they should be changed. However, running program in a batch mode is more convenient for a big number of experiments. Batch mode sweeps through the values assigned in a parameter file as many times as user defined, but does not include graphical representation.

Chapter 5

Sensitivity analysis

This chapter presents results of the sensitivity analysis of the simulation model. Sensitivity analysis aims at investigating how the designed parameters of the simulation model influence productivity. It has also a purpose to define which parameters are important to make the model sufficiently useful and valid. Each parameter was tested in order to identify if it influences an output of the model, i.e. the productivity value. During the experiments a tested parameter is varied, while the rest of the parameters have fixed values.

Table 5.1: Table of parameters

Parameter name	Description	Details
N_n	Population size	Number of nodes in a physical trustability network
N_a	Number of adopters	Number of nodes in a digital trustability network. Defined according to the Bass diffusion formula
N_0	Number of colors	Initial number of colors in the network
λ	Learning parameter	Parameter used in a payoff assessment
N_{rounds}	Number of rounds	Number of times a coloring game is repeated by agents
D	Neighborhood degree	Neighborhood degree is a parameter given to a small world network generator and specifying an average number of neighbors for each node in a real trustability network
β	Beta	Probability value with which links are rewired during the small world network formation according to Watts and Strogatz algorithm
P	Productivity	Productivity is an output parameter

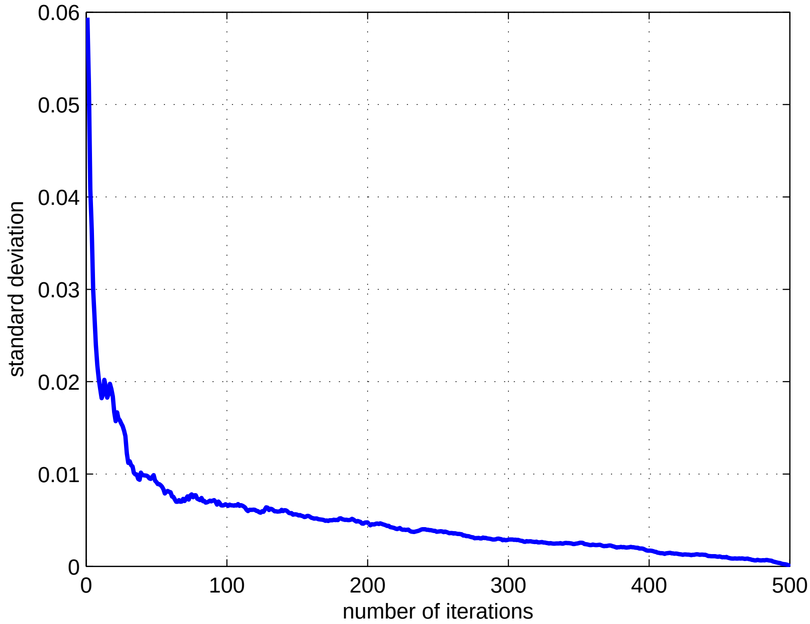


Figure 5.1: Number of iterations: deviation analysis

5.1 Number of iterations

We start by investigation how many iterations we need for each experiment in order to get reliable results. One experiment was repeated a certain number of iterations and then standard deviation of the obtained results was compared. Figure 5.1 displays this comparison: number of iterations is indicated by X-axis whereas Y-axis expresses the standard deviation value. As we can see, deviation from the mean value tends to decrease while number of iterations increases. However, it drops down rapidly unless the value of one hundred iterations is reached. Further it improves slightly. Since each iteration takes several minutes and there is a considerable amount of experiments to be done for sensitivity analysis we assumed that repeating each experiment a hundred times would provide acceptable and reliable enough results.

5.2 Learning parameter (λ)

In the payoff assessment model developed by R.Sarin and F.Vahid(see [68]), the learning parameter λ determines how fast the assessments adapt to the observed payoff. They claim that the bigger is λ, the stronger is the influence of the observed payoffs on assessments.

We did a set of experiments to find out how this assessment policy effects productivity. Figure 5.2 depicts the dependency of productivity on the learning parameter λ. Results showed that without learning (λ=0) agents do not coordinate at all, meaning that learning parameter absence is associated with no observations of the state of the world. Moreover, the highest productivity is achieved when coordina-

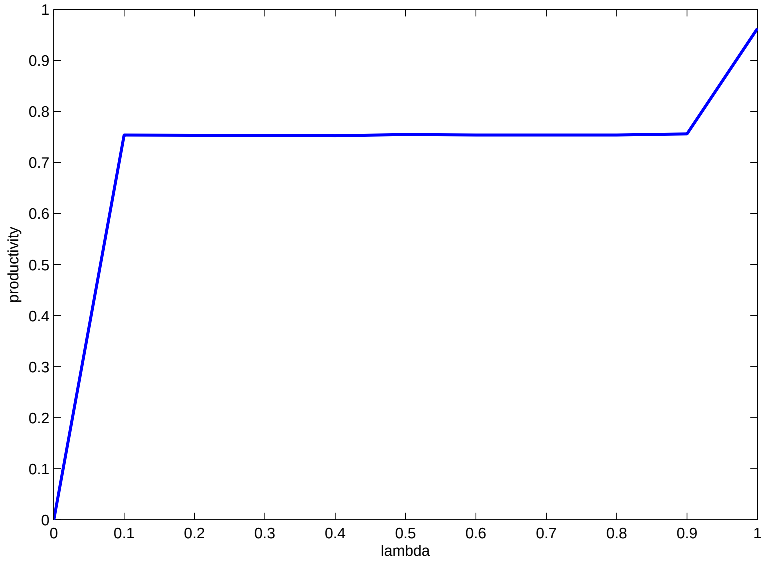


Figure 5.2: Correlation of λ and Productivity

tion is fully relied on the learning experience (λ=1). Thus we conclude that learning has a positive impact on productivity. However, absolute values of λ-s in the range [0.1;0.9] do not affect productivity very much.

As far as λ is characterized as a parameter influencing the adaptation of experience to the observed state of the world, our further experiment aims at investigating how fast is stable productivity value reached for different λ-s. Figure (5.3) depicts that smaller values of λ requires more time to achieve stable results, meaning that more rounds are needed to reach equilibrium. At the same time, raising λ values allows to decrease number of rounds of graph coloring game without affecting productivity(see figure 5.3)[1]. As we can see at figure 5.3, even 100 number of rounds is not enough to reach a stable productivity value when $\lambda = 0.1$, while around 50 rounds is needed in case $\lambda = 0.5$ and 30 rounds in case $\lambda = 0.9$. Therefore, we conclude that λ does not affect the productivity value directly, but influences how fast agents adapt to the observed payoffs and reaches equilibrium.

5.3 Number of nodes and adoption (N_n and N_a)

In the following experiment, we first tried to investigate how the population size, i.e. number of nodes in a physical trustability network, influences the productivity trend during the adoption period. Three productivity trends for a different population sizes and consequently different number of adopters for each case at the same moment of the adoption period are represented at the figure 5.4(a). The other parameters remain fixed during the experiment. We can observe from the figure 5.4(a)

[1]for a better visualization curves for all λs in the range [0.1;0.9]are plotted separately at Figures B.1 - B.9in Appendix

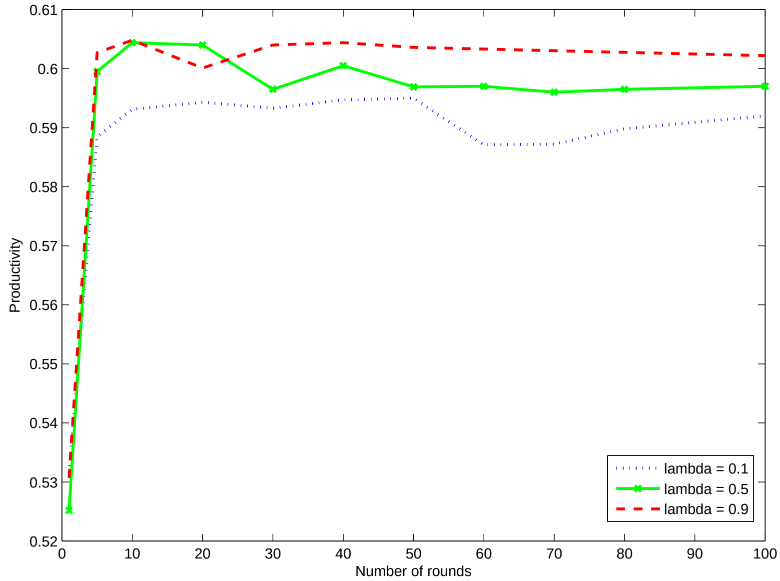


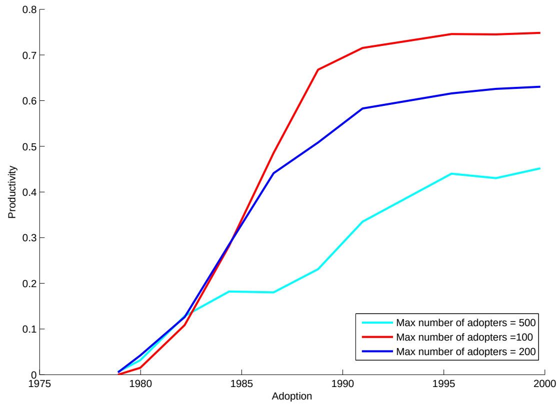
Figure 5.3: Number of rounds for different λ values

that the productivity value tends to increase along the adoption period for any population size. This fact leads us to the conclusion that bigger number of adopters results in a better productivity. Nevertheless, productivity varies for different population sizes even in case they are at the same adoption period. The greater is the difference between population sizes, the more significant productivity mismatch is observed especially at the later adoption stages.

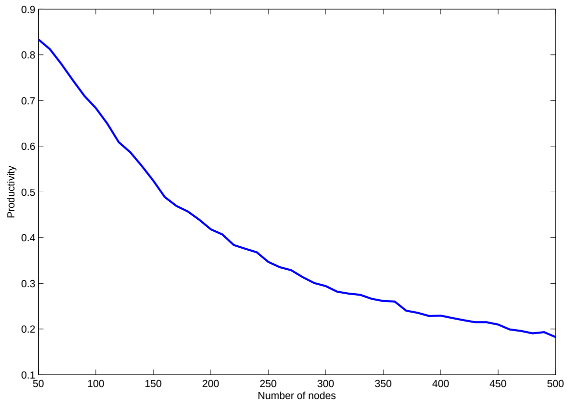
In order to investigate these dependencies, we moved to another experiment which might shed more light upon this situation. At this step, we investigated how population size impacts productivity while keeping the number of adopters fixed, as well as other parameters. The curve revealing this dependency is depicted at figure 5.4(b). It is easily noticeable that productivity value is declining steadily along the population size growth. An intuitive explanation we can provide lies in the fact that bigger population size results in a smaller probability that adopters are linked to each other, while the probability that adopter is linked to a non-adopter grows. This in turn implies that the digital trustability network is most likely to be fragmented into small groups of adopters. Linkage absence makes coordinating between these small groups impossible. And vice versa, the smaller size of physical trustability network results in a more dense digital trustability network for the same amount of adopters leading to a higher connectivity, and therefore higher productivity.

Figure 5.5 depicts digital trustability network with N_a=10 formed from the real trustability network with a population size N_n= 20 (see 5.5(a)) and N_n=50 (see 5.5(b)). As seen from the picture, the smaller N_n leads to a more dense network in comparison with a network with higher N_n.

According to the obtained results we conclude that inversely proportional correlation exists between these two variables. Consequently, larger amount of adopters in a network with fixed population size has higher probability that adopters will



(a) Productivity at different population size with corresponding number of adopters



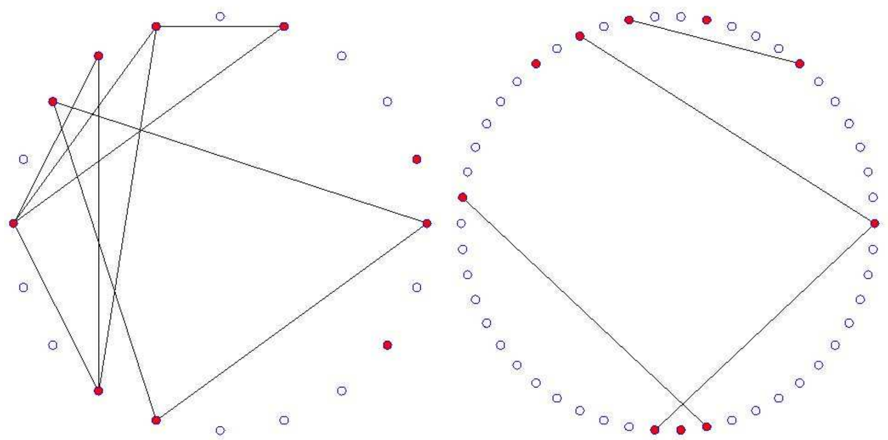
(b) Productivity at different population size with fixed number of adopters

Figure 5.4: Population size vs productivity

stay connected in the digital trustability network and thus will be able to coordinate. This leads to a better productivity along the adoption period. (see figure 5.4(a)).

5.4 Number of colors(N_0)

Next experiment estimates the dependency of productivity on the initial number of colors provided for the simulation model. As follows from the Figure 5.6, productivity tends to go up with an increasing number of colors. This comes from the fact that productivy is estimated as a ratio $P = \frac{N0-N_{fin}}{N_0}$. For instance, if a number of agents reduces initial number of colors N_0=20 to a final number of colors N_{fin} to 5, it is more productive (P=0.75), than decreasing N_0=10 to N_{fin}=3 where P=0.7. Growth of the productivity value in this case does not mean that bigger number of colors has no affect on coordinating process, because final number of colors is increasing as well. But the ratio of the these two values tends to raise. However,



(a) Population size=20 (b) Population size=50

Figure 5.5: Digital trustability network formed from the real trustability network with different population sizes

rapid increase of productivity is observed only when small values N_0 are applied. Productivity growth slows down with a bigger N_0 values and becomes stable when a saturation point is reached. Starting from this point productivity does not improve meaning that the ratio $P = \frac{N0-N_{fin}}{N_0}$ remains the same.

5.5 Degree (D)

Real trustability network is modelled as a small world network as was mentioned before in 4.4. In our simulation model we used Repast's constructor class for generating the small word network. This constructor builds a small world network as was proposed by Watts and Strogatz [84] and requires two arguments to define a small world network namely the probability of rewiring the network (β) and the local neighborhood size i.e. degree (D). This subsection revises if there is any influence of the D value on P.

Figure 5.7 depicts the productivity value change during the adoption period in the networks with different D. As we can see from this graph, P is higher in the networks with a greater D. Obviously, bigger neighbourhood size leads to a better knowledge about the state of the world for agents , thus making coordinating easier and more productive. Moreover, this experiment proves the fact that increasing the number of adopters does not always lead to a higher productivity. Looking at the figure 5.7 we see that $P \approx 0.65$ at the time step 4 in case $D = 14$. As we might expect, at the next time step the P value should raise because of the increased number of adopters. This will be the case if the degree D remains unchanged. However, a sudden degree drop leads to a decrease in productivity: in case D becomes 6, the P will become ≈ 0.55. This example evidences that direct correlation of the DIN adoption with productivity is inefficient without topological analysis of the interaction network.

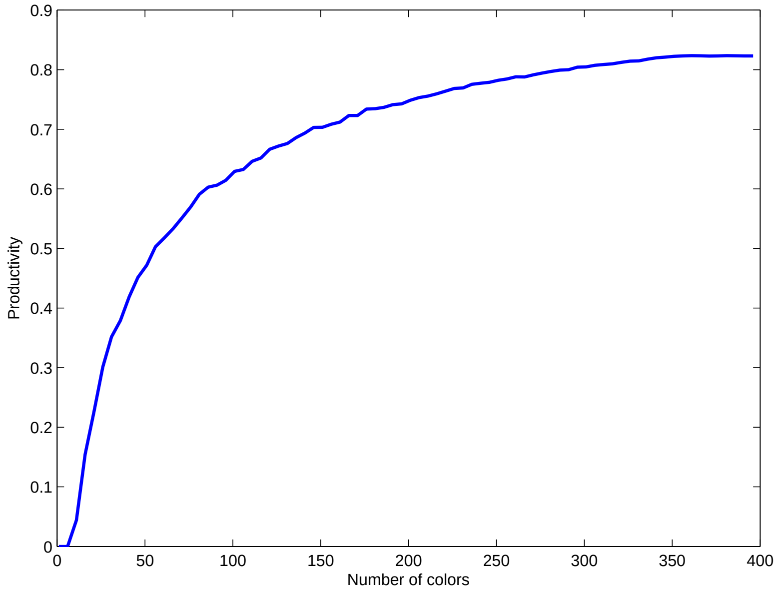


Figure 5.6: Number of colors vs Productivity

5.6 Beta (β)

Another parameter passed to a small world network generator is β. This parameter sets the probability of rewiring links in a k-ring network in order to obtain small world network. Our next simulation experiment aims at investigating the correlation between β and P. We observed the productivity change during the adoption period in the same manner as we did for a previous experiment. All the parameters remained unchanged for different β values. Each curve represents productivity change in time for variable βs on the Figure 5.8. As follows from the graph, productivity is not dependent on β, curves stay almost unchanged for all β values.

5.7 Conclusions

Sensitivity analysis was done to explore the dependency of the productivity on the input parameters of the simulation model. Based on the results of the sensitivity analysis we conclude that productivity growth is directly proportional to the number of adopters, while inversely proportional to the population size. But we have to emphasize here that productivity is strongly correlated with productivity, only in case other parameters remain unchanged. Variations in the other parameters may lead to unexpected results. Degree is another parameter influencing positively productivity: higher degree leads to a higher productivity. Moreover, sudden drops of the degree may decrease the productivity even if the number of adopters is increased. Therefore, we conclude that productivity is essentially sensitive to these parameters. This observation demonstrates that productivity is dependent on the several parameters. All of them have to be considered in the analysis of the macroeconomic effect caused by DINs adoption. Another conclusion we made from our observations

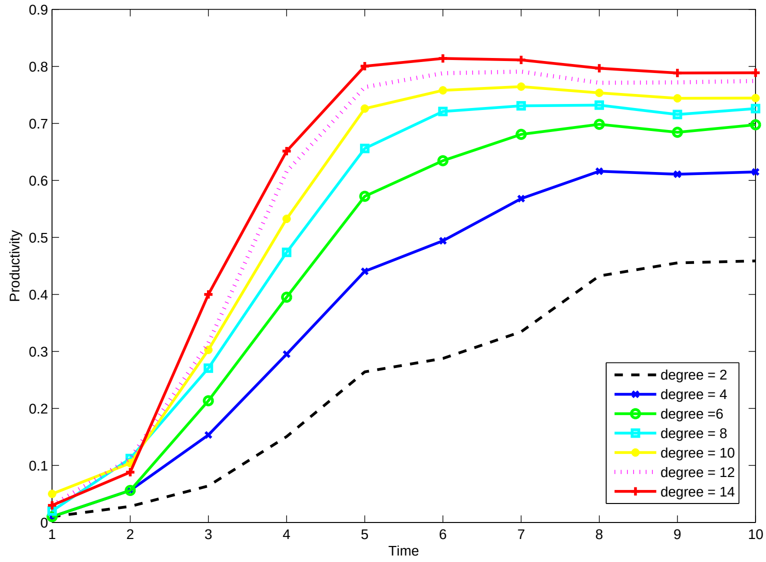


Figure 5.7: Degree vs Productivity

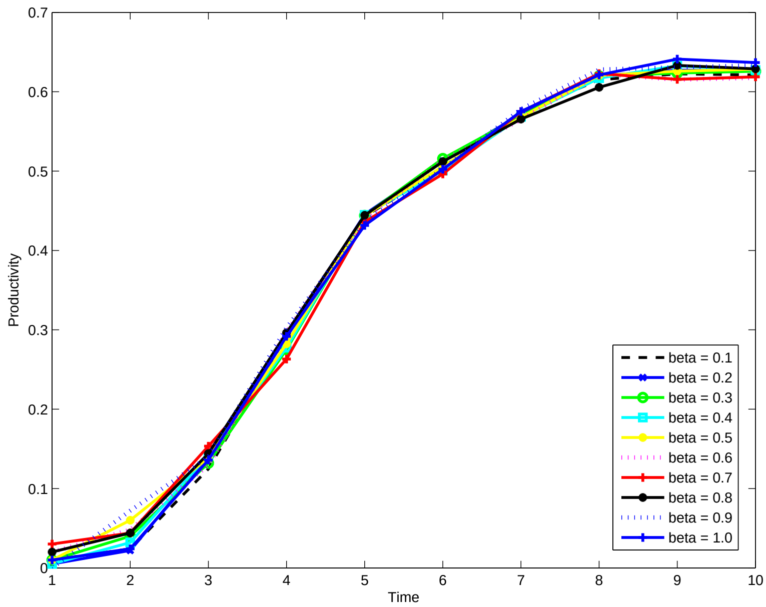


Figure 5.8: Beta vs Productivity

is that incrementing number of colors raises productivity unless the saturation point is reached. Besides, we found out that there is a number of parameters, which productivity value is insensitive to: rewiring probability β and learning parameter λ. However, λ defines how fast agents reach equilibrium.

Chapter 6

Model analysis proposal

In this chapter we lay down our proposals to address the three motivations to develop our model: a) demonstrating evidences that a DES has the properties of a CAS; b) demonstrating evidences of the low correlation between DINs' adoption and macroeconomic productivity; c) investigating new methods to increase the correlation between DINs' adoption and macroeconomic productivity.

6.1 CAS properties and DES

A CAS portrays the economy not as a deterministic, predictable, and mechanistic, but as process dependent, organic, and always evolving. As the elements of CAS react, the aggregate changes; as the aggregate changes, elements react anew. This is the main reason a CAS is difficult to estimate and control. However, agents are learning, thus the mechanisms that mediate these systems are much more alike than surface observations would suggest. Further, we review the properties of a CAS.

Emergency

Each agent in a CAS has individual goals and tries to reach them through the interaction with other agents and by observing the state of the world. These individual behaviors compose an overall behavior influencing the output of the system. However, an overall behavior cannot be simply derived from the actions of the parts. Emergency is a property of a CAS meaning that the overall behavior and consequently a system's outcome emerges from the interactions of the parts (see [36]).

Evolving structure

CAS has a dynamic *evolving structure*. Agents change, reorganize and adapt themselves to the problems posed by their surroundings in a CAS. They do not memorize all possible states of the world and all the phases they pass through, but rather observe current situation, adapt for it, learn and make appropriate decisions. Any changes in the surroundings triggers re-estimation followed by adaption for a new situation (see [36]).

Unpredictability

Without understanding how the system's configuration gives rise to its' aggregate behavior, it is difficult to understand how a small change to that configuration will affect the system's aggregate behavior. In a traditional systems, small changes to the configuration tend to result in proportionally small changes in a collective behavior. In a CAS small changes can cause either negligible or significant impact on the collective behavior (see [66]).

Phase transition
Change of some parameters may enforce agents to change abruptly their behavior or to assess the situation in a different way. If number of agents impacted by a change of a certain parameter is small, it does not usually affect collective behavior. Otherwise, it may cause significant modifications, which may lead to changes in a collective behavior and thus in output. This property is known as a *phase transition* associated with a collective behavior transition (see [57]).

Self-organizing
There is no hierarchy of command and control in a CAS. There is no planning or managing, but there is a constant re-organising to find the best fit with the environment. The system is continually self organising through the process of emergence and feedback.

In order to demonstrate evidences that a DES behaves as a CAS, we propose to observe if above-mentioned properties appear in the simulation model.

6.2 Low correlation evidences

Our literature review has shown the evidence that existent methods of correlating macroeconomic productivity and DINs availability/adoption are inefficient and unclear. We propose to use the traditional correlation analysis with our simulation model in order to demonstrate low correlation between DINs' adoption and macroeconomic productivity and to confirm the need of more advanced methods to strengthen this correlation.

A. Bedia (see [7]) reviewed a set of studies that examine the effect of communication technologies on economic outputs. He states that most of macroeconomic studies that try to evaluate the benefits of DINs relate measures of the availability of DINs to measures of national aggregate activity, such as GDP. Studies in this genre usually rely on panel data (information from several countries over a certain time period) and utilize an empirical framework motivated by a production function, such as:

$$Y_{it} = f(K_{it}, L_{it}, I_{it}, A_{it}) \tag{6.1}$$

Where for country i and time period t, Y, K, L and I are GDP, capital, labor, and a measure of DIN infrastructure, respectively, and A is an overall efficiency factor which captures the level of technology. Differentiating (6.1), yields a growth-accounting equation:

$$\dot{Y}/Y = \eta_1(\dot{K}/K) + \eta_2(\dot{L}/L) + \eta_3(\dot{I}/I) + \eta_4(\dot{A}/A) \quad (6.2)$$

where η represents the income share of an input (elasticities in the regression context) and the product $\eta_4(\dot{A}/A)$ represents multifactor productivity (the productivity residual in a regression context). Empirical specifications of (6.1) and (6.2) may be used as a basis for analyzing the effects of DINs on the level and growth of GDP, respectively. (see [7]).

As we can see, the traditional approach does not take into account the externality effect of DIN and other network effects investigated in our simulation model. Therefore, we expect that the traditional approach does not allow to establish strong correlation between DINs adoption and productivity, leading us to the conclusion that new methods are required to strengthen this link.

6.3 New correlation method

In this section we describe with more details how to address new method of correlating DINs adoption and productivity. Topological metrics proposed for the analysis are revealed in the subsection 6.3.1. A correlation method for estimating the economic effect of DINs via intermediate observations is proposed in the subsection 6.3.2.

6.3.1 Topological metrics

Various sets of topological metrics were proposed in recent years to characterize real-world networks. Network topology analysis involving different topological metrics helps to understand and forecast an overall performance of a network since values for a particular graph metric may capture a graph's resilience to failure or its routing efficiency (see [52]).

To perform such analysis one has to decide which set to choose from an increasing number of proposed metrics in order to measure important graph properties. A.Jamakovic et al.(see [3]) performed correlation analysis of 14 topological metrics and showed an evidence that some metrics are either fully related to other topological metrics or significantly limited in the range of their possible values. However, they distinguished four groups based on existing correlation between metrics: 1) *Distance cluster* comprising average node distance, average node eccentricity, average node and link betweenness; 2) *Degree cluster* including average degree, average node coreness and clustering coefficient; 3) *Intra-connectedness cluster* consisting of link density, rich club coefficient, algebraic connectivity; and 4) *Inter-connectedness cluster* with average neighbor degree and assortativity coefficient.

In [17] clustering coefficient, nodal degree and average path length were proposed for establishing correlation between interaction topology and coordination effectiveness. But according to the study presented in [3], clustering coefficient and average node degree are significantly correlated, and thus bring redundancy. Therefore, we propose to use only one metric out of each cluster for analyzing the topology of coordinativity network: *average degree*, *average node distance*, *connectivity* and *as-*

sortativity.

Average degree

The degree of a node d_j in a graph $G(N, L)$, where N denotes number of nodes and L number of links, equals the number of its neighboring nodes and $0 < d_j < N - 1$. The average degree of a graph is defined as $d_a = \frac{1}{N}\sum_{j=1}^{N} d_j$. Sometimes networks are classified as dense if d_a is high or as sparse if d_a is small (see [82]).

Average node distance

Node distance, or hopcount, specifies the number of hops on the path between a source and a destination. The average hopcount in a network is the average value of the hopcount between all possible source-destination node pairs (see [34]).

Connectivity

A graph G is connected if there is a path between each pair of nodes and disconnected otherwise. The second smallest eigenvalue of the Laplacian matrix is called the algebraic connectivity. The algebraic connectivity plays a special role in many graph theory related problems. The most important is its application to the overall connectivity of a graph: the larger the algebraic connectivity is, the more difficult it is to cut a graph into independent components. Two other connectivity measures are directly related to the algebraic connectivity: 1) the link connectivity is the minimal number of links whose removal would disconnect a graph, 2) the node connectivity is defined analogously (nodes together with adjacent links are removed). The latter two connectivity measures provide worst case bound on the robustness to node and link failures (see [3])

Assortativity

The degree correlation, k_{nn}, is a mapping between a node degree k and the mean degree of nearest neighbors of those nodes of degree k. Its distribution is often characterized by the assortativity (r), which is defined as the Pearson correlation coefficient of the degrees of either nodes which is connected by a link. It is expressed as follows:

$$r = \frac{\langle k_i k_j \rangle - \langle k_i \rangle \langle k_j \rangle}{\sqrt{(\langle {k_i}^2 \rangle - \langle k_i \rangle^2)((\langle {k_j}^2 \rangle - \langle k_j \rangle^2)}} \tag{6.3}$$

where k_i and k_j are degrees of the nodes located at either end of a link and the $\langle \cdot \rangle$ notation represents the average over all links ([2]).

If a network's assorativity is negative, a hub tends to be connected to non-hubs, and vice versa. When r $>$ 0, we the network has an assortative mixing pattern, and when r $<$ 0, disassortative mixing. Assortative networks tend to have nodes that are connected to nodes with similar degree and dissimilar in dissassortative networks respectively (see [2], [3]).

For enabling topological analysis we included additional functionality to our simulation model: the calculation of the adjacency matrix of the digital coordinativity network. Adjacency matrix is an N x N matrix (N is number of nodes in the network) consisting of 0-s and 1-s, where 1 refers to the existence of a link between pair of nodes, while 0 stands for the absence of a link, respectively. Calculated adjacency matrix is written to the file which further might be passed to a MATLAB for evaluating topological metrics.

6.3.2 Correlation

Figure 6.1 shows an adjusted for our study mediating effects model correlating digital information network diffusion with productivity. This model was first mentioned in [32] for studying the relationship between IT and perceived productivity improvement mediated by the extent of perceived process change associated with IT. We propose to use the topological properties of the digital coordinativity network as the mediator in our model.

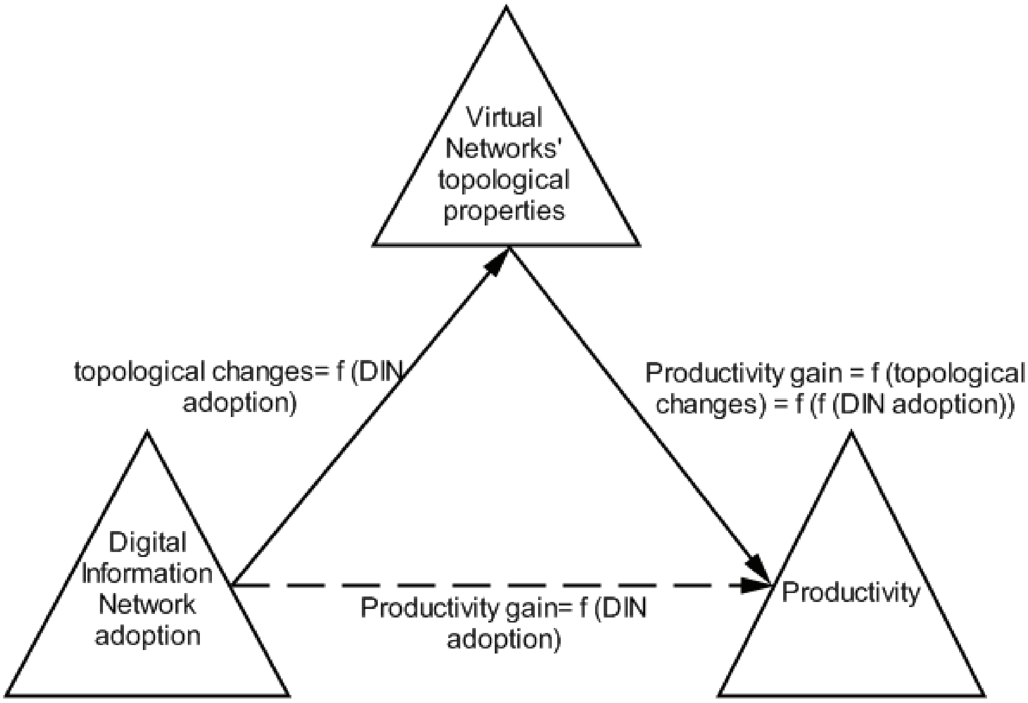


Figure 6.1: Correlation scheme

This model represents a hypothesized causal chain in which DIN adoption affects Virtual networks' topological properties that, in turn, affects productivity. In order to demonstrate the existence of mediation in the process, the following properties should be observed: 1) an independent variable (DIN adoption in our case) should affect the outcome variable (Productivity); 2) each variable in the causal chain affects the variable that follows in the chain (DIN adoption → Topological properties, Topological properties → Productivity); 3) the independent variable exerts no effect upon the outcome when the mediating variables are controlled (see [40]).

The most widely used method to assess mediation was described by Baron and Kenny (see [10]). An independent variable is denoted as X, outcome as Y and mediator as M in their model. Baron and Kenny proposed a four step approach in which several regression analyses are conducted and significance of the coefficients is examined at each step:

1. Conduct a simple regression analysis with X predicting Y to test the direct path $X \rightarrow$ alone:

$$Y = B_0 + B_1 X + e \tag{6.4}$$

   Where:

$$B_0 = \bar{Y} - B_1 \bar{X} \tag{6.5}$$

$$B_1 = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sum (X - \bar{X})^2} \tag{6.6}$$

$$e = Y - \hat{Y} \tag{6.7}$$

2. Conduct a simple regression analysis with X predicting M (i.e. mediator) to test for path $X \rightarrow M$,

$$M = B_0 + B_1 X + e \tag{6.8}$$

3. Conduct a simple regression analysis with M predicting Y to test the significance of the path $M \rightarrow Y$,

$$Y = B_0 + B_1 M + e \tag{6.9}$$

4. Conduct a multiple regression analysis with X and M predicting Y:

$$Y = B_0 + B_1 X + B_2 M + e \tag{6.10}$$

Further, the indirect effect can be calculated as was approached by M. Sobel (see [71]). This calculation involves partial regression coefficient B_2 obtained from 6.10 and simple regression coefficient B_1 obtained from 6.8 :

$$B_{indirect} = (B_2)(B_1) \tag{6.11}$$

We propose to use described above methods for mediation analysis of our model.

Chapter 7

Conclusions and future work

In this section we draw some conclusions and propose future work to be done. Further improvements are required, both in the methodological approach in general, and in the simulation model as well.

7.1 Conclusions

Diffusion of DINs to all sectors of economy led to a formation of new *digital* economy in which information is a critical resource. This raised an interest in studying an economic impact of DINs for researchers, as well as for public decision makers responsible for telecommunication infrastructures aiming at justifying investments in more advanced forms of infrastructure, and for organizational managers aiming at higher productivity gains. The state of the art review has shown that traditional economic tools are insufficient to establish strong correlation between DINs adoption and large-scale productivity. A new methodology is required to strengthen the link between DINs and macroeconomic productivity.

However, a new approach was recently proposed to evaluate DINs' macro- and microeconomic effects .This approach proposes studying agent's capabilities to investigate DIN's impacts at the microeconomic level, and emergent virtual information networks at the macroeconomic level. Our main contribution to this approach is the elaboration and testing of the simulation model. This simulation model has a purpose to investigate the proposals made in [51] i.e. : a) to demonstrate evidences that a DES has the properties of a CAS; b) to demonstrate evidences of low correlation between DINs' adoption and macroeconomic productivity; c) to investigate new methods to increase the correlation between DINs' adoption and macroeconomic productivity.

Our model considers the formation of the virtual information networks emerged from the DINs adoption. We assume that DINs provide a substrate for the digital information flows in the networks of trust and coordination networks. The model aims at investigating how the DINs adoption changes interaction networks and what is the effect of these changes on productivity.

Sensitivity analysis examined a number of input parameters and their impact on productivity. Based on the results of the sensitivity analysis we conclude that productivity growth is directly proportional to the number of adopters, while inversely proportional to the population size. Moreover, an increased number of colors raises productivity unless the saturation point is reached. Degree is another parameter influencing positively productivity: higher degree leads to a higher productivity. Besides, there is a number of parameters which have very small correlation with productivity: rewiring probability β and learning parameter λ. However, λ defines how fast the reliable productivity results can be achieved.

7.2 Future work

Testing the developed simulation model demonstrated the impact of several parameters on productivity. However, in order to understand *why* these parameters cause a change in productivity, one has to observe changes in the structure of the interaction network which leads to changes in overall behavior ,and hence, productivity. As an intermediate analysis, [51] proposed to study the topological properties of the emergent networks. We suggest applying this method to our simulation model in further studies for establishing a correlation between DINs adoption and macroeconomic productivity taking into account all the above mentioned parameters. We propose to observe *average degree, average node distance, connectivity and assortativity* of the digital coordinativity network and conduct mediation analysis for establishing a correlation via intermediate observations of topological properties of the emerged networks. Results of the mediation analysis will prompt the conclusion if the intermediate observations of topological properties are effective for evaluating DINs macroeconomic productivity.

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Appendix A

Source code

A.1 Adopter agent

```
/**
 *
 * This file was automatically generated by the Repast
    Simphony Agent Editor.
 * Please see http://repast.sourceforge.net/ for details.
 *
 */

/**
 *
 * Set the package name.
 *
 */
package zhanna

/**
 *
 * Import the needed packages.
 *
 */
import java.io.*
import java.math.*
import java.util.*
import javax.measure.unit.*
import org.jscience.mathematics.number.*
import org.jscience.mathematics.vector.*
import org.jscience.physics.amount.*
import repast.simphony.adaptation.neural.*
import repast.simphony.adaptation.regression.*
import repast.simphony.context.*
import repast.simphony.context.space.continuous.*
```

```
import repast.simphony.context.space.gis.*
import repast.simphony.context.space.graph.*
import repast.simphony.context.space.grid.*
import repast.simphony.engine.environment.*
import repast.simphony.engine.schedule.*
import repast.simphony.engine.watcher.*
import repast.simphony.groovy.math.*
import repast.simphony.integration.*
import repast.simphony.matlab.link.*
import repast.simphony.query.*
import repast.simphony.query.space.continuous.*
import repast.simphony.query.space.gis.*
import repast.simphony.query.space.graph.*
import repast.simphony.query.space.grid.*
import repast.simphony.query.space.projection.*
import repast.simphony.parameter.*
import repast.simphony.random.*
import repast.simphony.space.continuous.*
import repast.simphony.space.gis.*
import repast.simphony.space.graph.*
import repast.simphony.space.grid.*
import repast.simphony.space.projection.*
import repast.simphony.ui.probe.*
import repast.simphony.util.*
import simphony.util.messages.*
import static java.lang.Math.*
import static repast.simphony.essentials.RepastEssentials.*

/**
 *
 * This is an agent.
 *
 */
public class Adopter {

    /**
     *
     * This is an agent property.
     * @field color
     *
     */
    @Parameter (displayName = "color", usageName = "color")
    public int getColor() {
        return color
    }
    public void setColor(int newValue) {
```

```
        color = newValue
    }
    public int color = 0

    /**
     *
     * This is an agent property.
     * @field color_array
     *
     */
    @Parameter (displayName = "color_array", usageName = "
       color_array")
    public int[] getColor_array() {
        return color_array
    }
    public void setColor_array(int[] newValue) {
        color_array = newValue
    }
    public int[] color_array = new int[GetParameter("maxCol
       ")]

    /**
     *
     * This is an agent property.
     * @field id
     *
     */
    @Parameter (displayName = "id", usageName = "id")
    public int getId() {
        return id
    }
    public void setId(int newValue) {
        id = newValue
    }
    public int id = agentIDCounter%GetParameter("
       initialNumNode")

    /**
     *
     * This is an agent property.
     * @field maxCol
     *
     */
    @Parameter (displayName = "maxCol", usageName = "maxCol
       ")
    public int getMaxCol() {
```

```
        return maxCol
    }
    public void setMaxCol(int newValue) {
        maxCol = newValue
    }
    public int maxCol = GetParameter("maxCol")

    /**
     *
     * This is an agent property.
     * @field counter
     *
     */
    @Parameter (displayName = "counter", usageName = "
       counter")
    public int[] getCounter() {
        return counter
    }
    public void setCounter(int[] newValue) {
        counter = newValue
    }
    public int[] counter = new int[GetParameter("maxCol")]

    /**
     *
     * This is an agent property.
     * @field max
     *
     */
    @Parameter (displayName = "max counter", usageName = "
       max")
    public double getMax() {
        return max
    }
    public void setMax(double newValue) {
        max = newValue
    }
    public double max = 0

    /**
     *
     * This is an agent property.
     * @field max_i
     *
     */
    @Parameter (displayName = "index_of_max_counter",
```

```
   usageName = "max_i")
public int getMax_i() {
    return max_i
}
public void setMax_i(int newValue) {
    max_i = newValue
}
public int max_i = 0

/**
 *
 * This is an agent property.
 * @field change
 *
 */
@Parameter (displayName = "change_color", usageName = "
   change")
public boolean getChange() {
    return change
}
public void setChange(boolean newValue) {
    change = newValue
}
public boolean change = false

/**
 *
 * This is an agent property.
 * @field u
 *
 */
@Parameter (displayName = "u", usageName = "u")
public double[] getU() {
    return u
}
public void setU(double[] newValue) {
    u = newValue
}
public double[] u = new double[GetParameter("maxCol")]

/**
 *
 * This is an agent property.
 * @field neighbor_col
 *
 */
```

```
    @Parameter (displayName = "neighbor_col", usageName = "
       neighbor_col")
    public int getNeighbor_col() {
        return neighbor_col
    }
    public void setNeighbor_col(int newValue) {
        neighbor_col = newValue
    }
    public int neighbor_col = 0

    /**
     *
     * This is an agent property.
     * @field finnumcolors
     *
     */
    @Parameter (displayName = "finnumcolors", usageName = "
       finnumcolors")
    public int getFinnumcolors() {
        return finnumcolors
    }
    public void setFinnumcolors(int newValue) {
        finnumcolors = newValue
    }
    public int finnumcolors = 0

    /**
     *
     * This is an agent property.
     * @field productivity
     *
     */
    @Parameter (displayName = "productivity", usageName = "
       productivity")
    public double getProductivity() {
        return productivity
    }
    public void setProductivity(double newValue) {
        productivity = newValue
    }
    public double productivity = 0

    /**
     *
     * This is an agent property.
     * @field min
```

```
 *
 */
@Parameter (displayName = "min", usageName = "min")
public int getMin() {
    return min
}
public void setMin(int newValue) {
    min = newValue
}
public int min = 0

/**
 *
 * This is an agent property.
 * @field matrix
 *
 */
@Parameter (displayName = "matrix", usageName = "matrix
   ")
public int[][] getMatrix() {
    return matrix
}
public void setMatrix(int[][] newValue) {
    matrix = newValue
}
public int[][] matrix = new int[GetParameter("
   numAdopters")][GetParameter("numAdopters")]

/**
 *
 * This value is used to automatically generate agent
    identifiers.
 * @field serialVersionUID
 *
 */
private static final long serialVersionUID = 1L

/**
 *
 * This value is used to automatically generate agent
    identifiers.
 * @field agentIDCounter
 *
 */
protected static long agentIDCounter = 1
```

```
/**
 *
 * This value is the agent's identifier.
 * @field agentID
 *
 */
protected String agentID = "Adopter " + (agentIDCounter
   ++)

/**
 *
 * This is the step behavior.
 * @method initialize
 *
 */
public void initialize() {

    // Note the simulation time.
    def time = GetTickCountInTimeUnits()


    // This is a loop.
    for (j in 0..(GetParameter("numAdopters")-1)) {


        // This is a loop.
        for (i in 0..(GetParameter("numAdopters")-1)) {

            // This is a task.
            matrix[i][j]=0

        }


    }


    // This is a loop.
    for (i in 0..(GetParameter("maxCol")-1)) {

        // This is a task.
        u[i]=0
        color_array[i]=0

    }
```

```
        // This is an agent decision.
        if (id<GetParameter("maxCol")) {

            // This is a task.
            setColor(id)

        } else  {

            // This is a task.
            Random generator= new Random()
             int rand = generator.nextInt(maxCol)
            setColor(rand)

        }
        // End the method.
        return

    }

    /**
     *
     * This is the step behavior.
     * @method step
     *
     */
    @ScheduledMethod(
        start = 200d,
        interval = 8d,
        shuffle = true
    )
    public void step() {

        // Note the simulation time.
        def time = GetTickCountInTimeUnits()


        // This is a loop.
        for (i in 0..(maxCol-1) ) {

            // This is a task.
            counter[i]=0

        }

        // This is a task.
```

```
Network network = FindNetwork("zhanna/SmallNetwork")
Iterator neighbors = new NetworkAdjacent(network,
   this).query().iterator()
setMax_i(color)
setMax(0)
setMin(color)

// This is a loop.
while (neighbors.hasNext()) {

    // This is a task.
    Adopter neighbor=neighbors.next()
    counter[neighbor.getColor()]++

    // This is an agent decision.
    if (neighbor.getColor()<min) {

        // This is a task.
        setMin((neighbor.getColor()-1))

    } else {


    }

}


// This is an agent decision.
if (id<GetParameter("numAdopters")) {


    // This is a loop.
    for (i in 0..(maxCol-1)) {


        // This is an agent decision.
        if (color==i) {

            // This is a task.
            u[i]=(1-GetParameter("lambda"))*u[i]+
               GetParameter("lambda")*counter[i]

        } else {

            // This is a task.
```

```
                u[i]=GetParameter("lambda")* counter[i]

            }

        }


        // This is a loop.
        for (i in 0..(maxCol-1)) {


            // This is an agent decision.
            if (u[i]>max) {

                // This is a task.
                setMax(u[i])
                setMax_i(i)

            } else {


            }

        }


        // This is an agent decision.
        if (max_i !=color) {

            // This is a task.
            setColor(max_i)
            setChange(true)

        } else {


        }

    } else {


    }
    // End the method.
    return

}
```

```
/**
 *
 * This is the step behavior.
 * @method step1
 *
 */
@ScheduledMethod(
    start = 501d,
    shuffle = true
)
public void step1() {

    // Note the simulation time.
    def time = GetTickCountInTimeUnits()

    // This is a task.
    Network network = FindNetwork("zhanna/SmallNetwork")
    Iterator neighbors = new NetworkAdjacent(network,
       this).query().iterator()

    // This is a loop.
    while (neighbors.hasNext()) {

        // This is a task.
        Adopter neighbor=neighbors.next()
        setNeighbor_col(neighbor.getColor())

        // This is an agent decision.
        if (color != neighbor_col) {

            // This is a task.
            RepastEdge removedEdge = RemoveEdge("zhanna/
               SmallNetwork", this, neighbor)

        } else {


        }

    }

    // End the method.
    return

}
```

```
/**
 *
 * This is the step behavior.
 * @method step2
 *
 */
@ScheduledMethod(
    start = 520d,
    shuffle = true
)
public void step2() {

    // Note the simulation time.
    def time = GetTickCountInTimeUnits()

    // This is a task.
    Network network = FindNetwork("zhanna/SmallNetwork")
    Iterable iterable=(Iterable<Adopter>) network.
       getNodes()
    Iterator iterator=iterable.iterator()

    // This is a loop.
    while (iterator.hasNext()) {

        // This is a task.
        Adopter agent=iterator.next()

        // This is an agent decision.
        if (agent.getId()<GetParameter("numAdopters")) {

            // This is a task.
            Iterator neighbors = new NetworkAdjacent(
               network, agent).query().iterator()

            // This is a loop.
            while (neighbors.hasNext()) {

                // This is a task.
                Adopter neighbor=neighbors.next()
                matrix[agent.getId()][neighbor.getId()
                   ]=1

            }
```

```
            } else {


            }

        }

        // End the method.
        return

    }

    /**
     *
     * This is the step behavior.
     * @method step3
     *
     */
    @ScheduledMethod(
        start = 550d,
        pick = 1l,
        shuffle = true
    )
    public void step3() {

        // Note the simulation time.
        def time = GetTickCountInTimeUnits()

        // This is a task.
        Network network = FindNetwork("zhanna/SmallNetwork")
        Iterable iterable=(Iterable<Adopter>) network.
           getNodes()
        Iterator iterator=iterable.iterator()

        // This is a loop.
        while (iterator.hasNext()) {

            // This is a task.
            Adopter agent=iterator.next()

            // This is an agent decision.
            if (agent.getId()<GetParameter("numAdopters")) {

                // This is a task.
                color_array[agent.getColor()]=agent.getColor
                   ()+1
```

```
        } else {


        }

    }


    // This is a loop.
    for (i in 0..(GetParameter("maxCol")-1)) {


        // This is an agent decision.
        if (color_array[i]!=0) {

            // This is a task.
            finnumcolors++

        } else {


        }

    }

    // This is a task.
    FileOutputStream output = new FileOutputStream("C:/
       Users/zhanna/Documents/MATLAB/adjacency.txt",true
       )

    // This is a loop.
    for (i in 0..(GetParameter("numAdopters")-1)) {


        // This is a loop.
        for (j in 0..(GetParameter("numAdopters")-1)) {

            // This is a task.
            new PrintStream(output).print(matrix[i][j]+"
                ")

        }

        // This is a task.
        new PrintStream(output).print(";")
```

```
        }


        // This is an agent decision.
        if (GetParameter("maxCol")>GetParameter("numAdopters
            ")) {

            // This is a task.
            setProductivity((GetParameter("numAdopters")-
                finnumcolors)/(GetParameter("numAdopters")))
            FileOutputStream output_1 = new FileOutputStream
                ("C:/Users/zhanna/Documents/MATLAB/
                productivity.txt",true)
            new PrintStream(output_1).println(productivity)
            new PrintStream(output).println()

        } else {

            // This is a task.
            setProductivity((GetParameter("maxCol")-
                finnumcolors)/(GetParameter("maxCol")))
            FileOutputStream output_1 = new FileOutputStream
                ("C:/Users/zhanna/Documents/MATLAB/
                productivity.txt",true)
            new PrintStream(output_1).println(productivity)
            new PrintStream(output).println()

        }
        // End the method.
        return

    }

    /**
     *
     * This is the step behavior.
     * @method step4
     *
     */
    @ScheduledMethod(
        start = 90d,
        shuffle = true
    )
    public def step4() {
```

```
        // Define the return value variable.
        def returnValue

        // Note the simulation time.
        def time = GetTickCountInTimeUnits()


        // This is an agent decision.
        if (id>=GetParameter("numAdopters")) {

            // This is a task.
            Network network = FindNetwork("zhanna/
               SmallNetwork")
            Iterator neighbors = new NetworkAdjacent(network
               , this).query().iterator()

            // This is a loop.
            while (neighbors.hasNext()) {

                // This is a task.
                Adopter neighbor=neighbors.next()
                RepastEdge removedEdge = RemoveEdge("zhanna/
                   SmallNetwork", this, neighbor)

            }


        } else {


        }
        // Return the results.
        return returnValue

    }

    /**
     *
     * This method provides a human-readable name for the
        agent.
     * @method toString
     *
     */
    @ProbeID()
    public String toString() {
```

```
        // Define the return value variable.
        def returnValue

        // Note the simulation time.
        def time = GetTickCountInTimeUnits()

        // Set the default agent identifier.
        returnValue = this.agentID
        // Return the results.
        return returnValue

    }


}
```

A.2 Model context

```
package zhanna;
import java.awt.Color;
import java.util.Iterator;
import java.util.List;
import java.io.*;
import java.math.*;
import java.util.*;
import repast.simphony.context.*;
import repast.simphony.engine.environment.*;
import repast.simphony.engine.schedule.*;
import repast.simphony.engine.watcher.*;
import repast.simphony.groovy.math.*;
import repast.simphony.integration.*;
import repast.simphony.matlab.link.*;
import repast.simphony.query.*;
import repast.simphony.parameter.*;
import repast.simphony.random.*;
import repast.simphony.space.continuous.*;
import repast.simphony.space.gis.*;
import repast.simphony.space.graph.*;
import repast.simphony.space.grid.*;
import repast.simphony.space.projection.*;
import repast.simphony.ui.probe.*;
import repast.simphony.util.*;
import simphony.util.messages.*;
import static java.lang.Math.*;
import static repast.simphony.essentials.RepastEssentials.*;
import repast.simphony.util.collections.IndexedIterable;
```

```
import java.lang.String;
import repast.simphony.context.Context;
import repast.simphony.context.space.graph.NetworkBuilder;
import repast.simphony.context.space.graph.
   NetworkFactoryFinder;
import repast.simphony.context.space.graph.NetworkGenerator;
import repast.simphony.context.space.graph.
   WattsBetaSmallWorldGenerator;
import repast.simphony.dataLoader.ContextBuilder;
import zhanna.Adopter;
import  repast.simphony.parameter.Parameters;
import repast.simphony.engine.environment.RunEnvironment;


public class ModelContext implements ContextBuilder<Adopter>
    {

        /**
         * Builds and returns a context. Building a
      * context consists of filling it with
         * agents, adding projects and so forth.
      * When this is called for the master context
         * the system will pass in a created context based
      * on information given in the
         * model.score file. When called for subcontexts,
      * each subcontext that was added
         * when the master context was built will be passed
            in.
         *
         * @param context
         * @return the built context.
         */
        public Context build(Context<Adopter> context) {

                Parameters p = RunEnvironment.getInstance().
                   getParameters();
                int numnodes = (Integer)p.getValue("
                   initialNumNode");
                int numadopters=(Integer)p.getValue("
                   numAdopters");
                int maxCol=(Integer)p.getValue("maxCol");

                 long free = Runtime.getRuntime().freeMemory
                    ();
         System.out.println( " free start" +free );
```

```
            for (int i = 0; i < numnodes; i++) {
                    Adopter a = new Adopter();
                a.initialize();
                context.add(a);
            }

        NetworkGenerator gen= new
           WattsBetaSmallWorldGenerator(1.0,4, false);
    NetworkBuilder builder = new NetworkBuilder("
       SmallNetwork",context, false);
    builder.setGenerator(gen);
    Network socialNetwork = builder.buildNetwork();

    boolean [] adopter_array;
    adopter_array= new boolean[numnodes];
            for(int i=0; i<numnodes;i++){
                    adopter_array[i]= false;
            }
            for (int i=0; i<numadopters;i++){
                    adopter_array[i]= true;
            }


         if (RunEnvironment.getInstance().isBatch()){

                    double endAt = (Double)p.getValue("
                       runlength");
                    RunEnvironment.getInstance().endAt(
                       endAt);
            }


            return context;


        }



}
```

A.3 Display method

```
package zhanna;
import java.awt.Color;
import java.awt.Paint;
```

```
import java.awt.Stroke;
import java.lang.reflect.Array;
import java.util.*;
import java.io.OutputStream;
import java.io.FileOutputStream;
import java.io.PrintStream;
import  repast.simphony.parameter.Parameters;
import repast.simphony.engine.environment.RunEnvironment;
import zhanna.Adopter;
import repast.simphony.engine.environment.RunEnvironment;
import repast.simphony.visualization.visualization2D.style.
   DefaultStyle2D;
import repast.simphony.valueLayer.ValueLayer;
import repast.simphony.visualization.visualization2D.style.
   ValueLayerStyle;

public class NodeStyle2D_edited extends DefaultStyle2D {

        @Override
        public Paint getPaint(Object o){

                Parameters p = RunEnvironment.getInstance().
                   getParameters();
                int initialNumNode = (Integer)p.getValue("
                   initialNumNode");
                int numAdopters=(Integer)p.getValue("
                   numAdopters");
                int max_col=(Integer)p.getValue("maxCol");
           Adopter adopter = (Adopter) o;


           int  number_of_colors;


           Color[] c_arr = new Color [max_col];{

                        for (int i=0;i<max_col;i++){
                                if(i==0){
                                        c_arr[i]=new Color
                                           (255,0,0);
                                }
                                else if (i==1){
                                        c_arr[i]= new Color
                                           (0,255,0);
                                }
                                else if(i==2){
```

```
                                c_arr[2]= new Color
                                    (0,0,255);
                        }
                        else if(i==3){
                                c_arr[i]= new Color
                                    (255,255,0);
                        }
                        else if(i==4){
                                c_arr[i]= new Color
                                    (0,255,255);
                        }
                        else if(i==5){
                                c_arr[i]= new Color
                                    (255,0,255);
                                }
                        else if(i==6){
                                c_arr[i]= new Color
                                    (255,135,0);
                        }
                        else if(i==7){
                                c_arr[i]= new Color
                                    (138,43,226);
                                }
                        else if(i==8){
                                c_arr[i]= new Color
                                    (142,229,238);
                        }
                        else if(i==9){
                                 c_arr[i]= new Color
                                    (255,160,122);
                        }
                        else{
                         int red=(25*i+i)%255;
                int green=(125*i+i)%255;
                int blue=(45*i+i)%255;
                c_arr[i]=new Color(red, green, blue
                    );

                        }
                }



        int col_id= adopter.getColor();
```

```
            Color m= c_arr[col_id];
            int r= m.getRed();
            int g= m.getGreen();
            int b= m.getBlue();

                                int id= adopter.getId();
                                System.out.println(id);
                                System.out.println(col_id);

                        boolean change= adopter.getChange();

                        if (id>= numAdopters )
                                return Color.white;
                        else if (change==false){
                Color col = c_arr[col_id];
                    return col;
                        }
                    else{
                 Color changed_col= c_arr[adopter.getMax_i()
                    ];
                 return changed_col;



                    }

                    }


                }
        // Don't paint the outline of the shape.
        public Stroke getStroke(Object Adopter){
                return stroke;
        }
}
```

A.4 Batch parameters file example

```
<?xml version="1.0"?>
<sweep runs="50">
<parameter name="initialNumNode" type="constant"
   constant_type="number" value="200"/>
<parameter name="numAdopters" type="list" value_type="int"
   values="2 5 15 32 60 96 133 180 190 195"/>
<parameter name="maxCol" type="constant" constant_type="
   number" value="50"/>
```

```
<parameter name="lambda" type="constant" constant_type="
    number" value="0.5"/>
<parameter name="runlength" type="constant" constant_type="
    number" value="551.01"/>
</sweep>
```

Appendix B

Additional figures

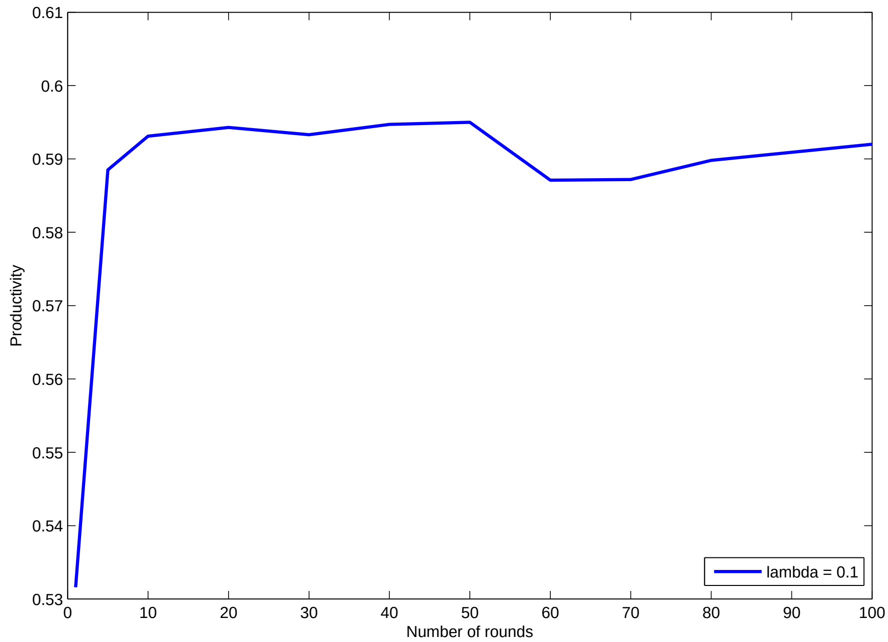

Figure B.1: Number of rounds for $\lambda = 0.1$

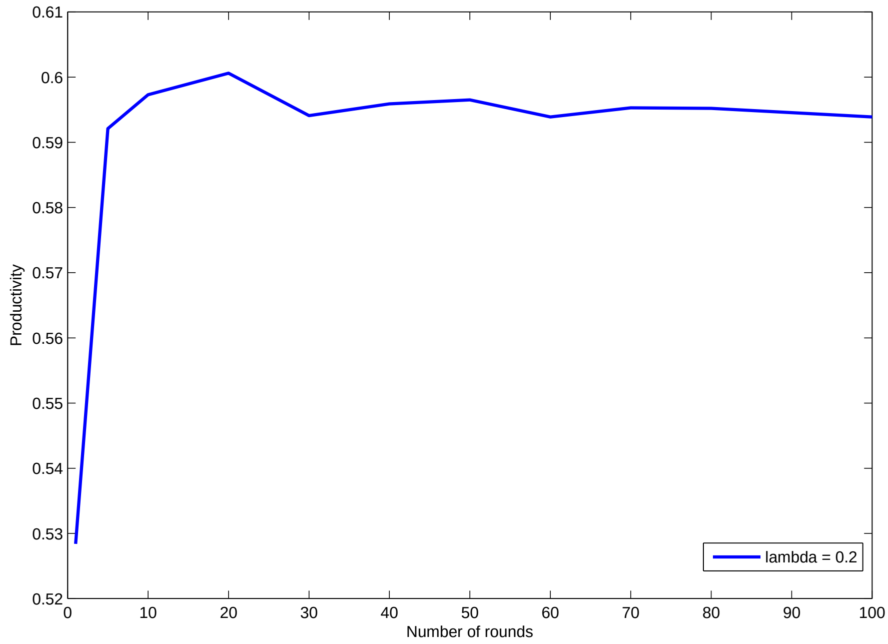

Figure B.2: Number of rounds for $\lambda = 0.2$

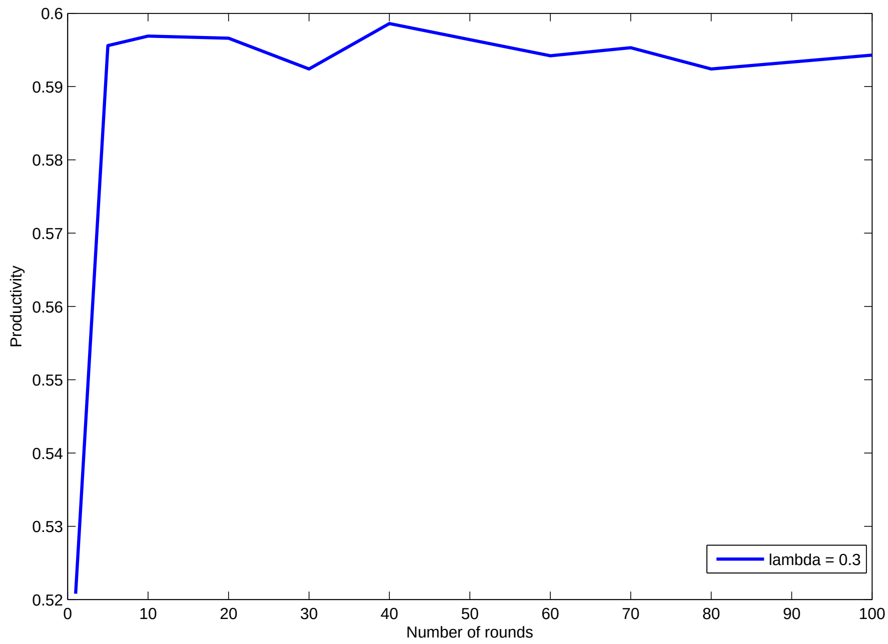

Figure B.3: Number of rounds for $\lambda = 0.3$

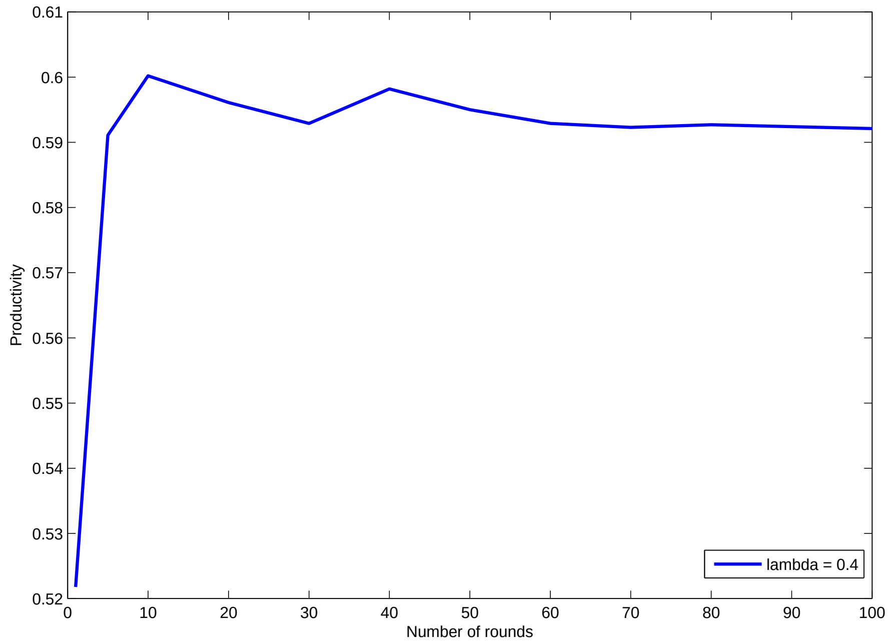

Figure B.4: Number of rounds for $\lambda = 0.4$

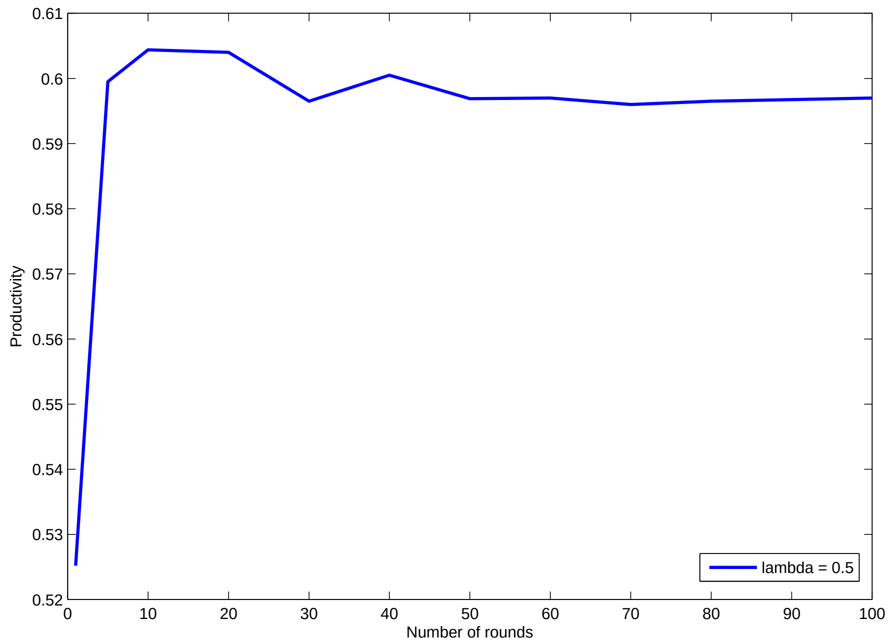

Figure B.5: Number of rounds for $\lambda = 0.5$

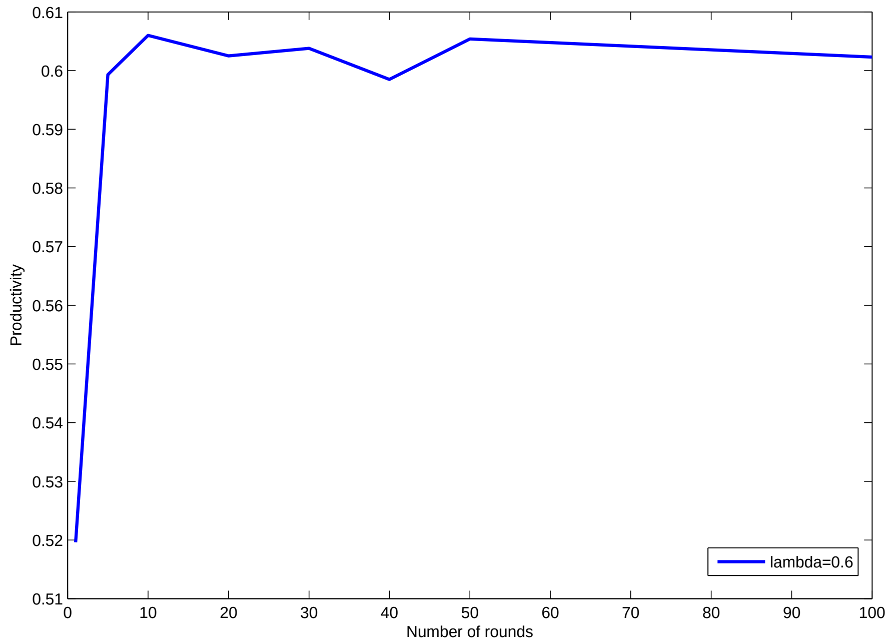

Figure B.6: Number of rounds for $\lambda = 0.6$

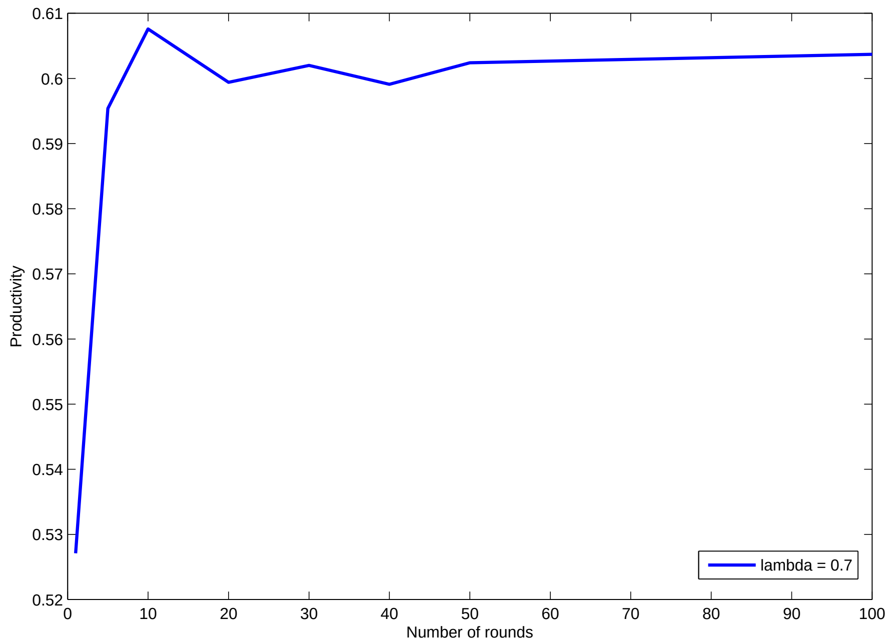

Figure B.7: Number of rounds for $\lambda = 0.7$

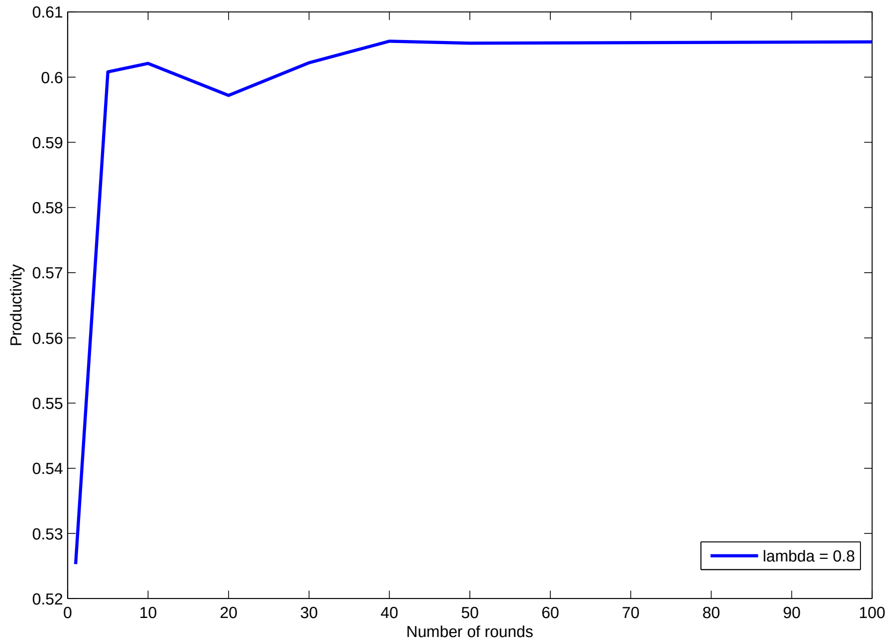

Figure B.8: Number of rounds for $\lambda = 0.8$

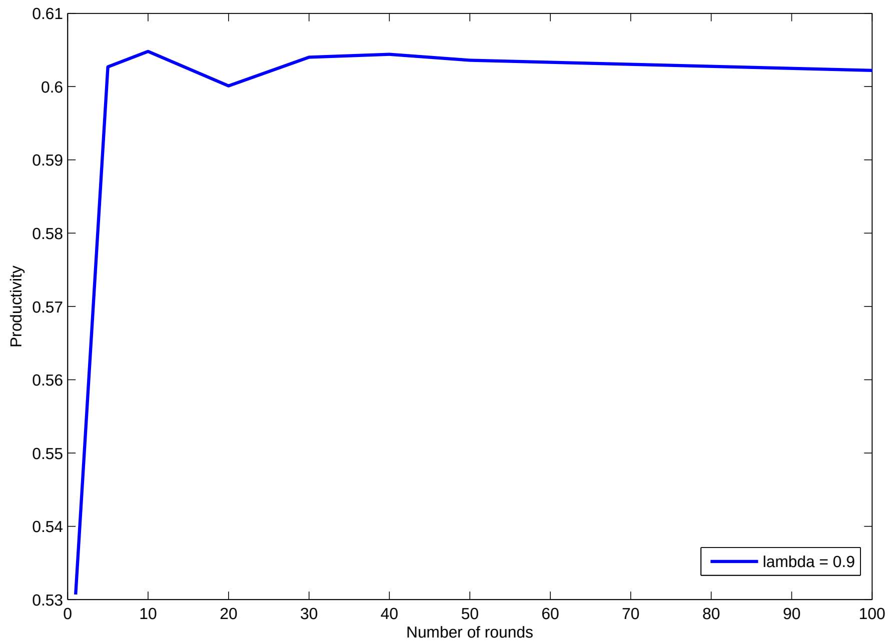

Figure B.9: Number of rounds for $\lambda = 0.9$