ADDRESSING METHODICAL ASPECTS OF INTERDEPENDENT STANDARDIZATION DECISIONS

Complete Research

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Abstract

Standards and technologies (e.g. in the area of web services) will strongly change IT-based communication. However, the decision of an agent (e.g. a firm) to adopt a standard is accompanied by the risk that other agents do not adopt the standard as well. The interdependencies among the agents' standardization decisions due to positive network effects result in a coordination problem called "standardization problem". If each agent autonomously decides about the adoption of a standard based on incomplete information about the other agents (e.g. unknown cost structure), this problem is characterized by a decentralized decision structure and incomplete information. A well-known approach in this context is the Decentralized Standardization Model. Based on analysing methodical issues of this model, we propose a novel approach that explicitly and consistently takes into account the interdependencies among the adoption decisions by means of a system of inequalities. Game theoretical analyses reveal that this approach goes along with higher average net standardization benefits per agent as well as a lower fraction of incorrect individual agents' decisions than the Decentralized Standardization Model.

Keywords: Communication Standards, Network Effects, Standardization Problem, Decentralized Standardization Model.

1 Introduction

Communication and technology standards that enable a compatible information exchange between firms, business units, or individual information systems play an important role in times of global value chains. In this context, a standard represents a specified and established norm or rules of a technical system. Standards in the domain of web services or the semantic web may serve as examples. In literature, standardization which constitutes the process of establishing standards is widely studied using diffusion and adoption models. Diffusion models primarily focus on the macro level process of the dispersion of objects like information, products, innovations, and standards. Examples of diffusion models are the Exponential Diffusion Model, the Logistic Diffusion Model, and the Markov Representation of a diffusion process (e.g. Bass, 1969; Mahajan and Peterson, 1985; Rogers, 1995; Wejnert, 2002). In contrast, adoption models concentrate on the micro level of individual standardization decisions of agents (e.g. firms). Adoption models elaborate the question whether or not an individual agent establishes a new standard, for example. Davis et al. (1989) argue that aggregating micro level adoption decisions leads to diffusion processes on a macro level.

In the following, we focus on adoption models representing the decision behaviour of (potential) users of a new standard with respect to their cost and benefit. Such economic considerations have been discussed in many works referring first and foremost to the theory of positive network effects (e.g. Beck et al., 2008; Besen and Farrell, 1994; Farrell and Saloner, 1985, 1986, 1988; Katz and Shapiro, 1985; Liebowitz and Margolis, 1995; Matutes and Regibeau, 1988; Weitzel et al., 2003a, 2003c, 2006). Due to positive network effects, adopting a standard becomes basically more desirable if other agents adopt it as well. Hence, an agent’s cost-benefit position is inherently dependent on the decisions of the other agents. These interdependencies among the agents’ standardization decisions due to positive network effects result in a coordination problem referred to as the “standardization problem” (Besen and Farrell, 1994; Weitzel et al., 2006). This problem can be elaborated from a centralized or a decentralized perspective and decision structure. Depending on the decision structure and on whether or not information about the individual standardization costs and benefits of the other agents is known (complete vs. incomplete information), we can distinguish the problem statements in Table 1.

	Centralized decision structure	**Decentralized decision structure**
Complete information about the agents in the network	A central authority decides about the agents’ adoption of the new standard based on complete information.	Each individual agent autonomously decides about the adoption of the new standard based on complete information about the other agents in the network.
Incomplete information about the agents in the network	A central authority decides about the agents’ adoption of the new standard based on incomplete information (e.g. corporate headquarter vs. subsidiary firms).	Each individual agent autonomously decides about the adoption of the new standard based on incomplete information about the other agents in the network.

Table 1. Problem Statements in the Context of the Standardization Problem

Considering a centralized decision structure and complete information, the efficient standardization decisions are the ones that lead to the highest net standardization benefit for the entire network (Weitzel et al., 2003a). However, in many realistic decision situations (e.g. in case of different firms), all agents make their own autonomous decisions about the adoption (decentralized decision structure) and have to decide under uncertainty since they do not have complete information about the individual standardization costs and benefits of the other agents. Currently, this perspective becomes increasingly important to acquire a better understanding of the economics of IS standards and managerial implications (for a discussion of standardization decisions and efforts in firms cf. e.g. Block and Köllinger, 2007; Flügge, 2010; Techatassanasoontorn and Suo, 2011; Weitzel et al., 2006). Our problem context can be specified as follows:

> We focus on networks of autonomously deciding agents who have incomplete information about the individual standardization costs and benefits of the other agents in the network (cf. bottom right corner of Table 1). Thereby, we concentrate especially on methodical aspects of formal standardization models which represent the individual decision behaviour of the agents who have to decide under uncertainty whether or not to adopt a standard.

Elaborating this problem context, several approaches in the field of economics have to be taken into account (e.g. Besen and Farrell, 1994; Farrell and Saloner, 1985, 1986, 1988; Katz and Shapiro, 1985; Liebowitz and Margolis, 1995; Matutes and Regibeau, 1988). Mostly, these works employ equilibrium analyses to explain phenomena like the start-up problem, market failure, and market instabilities. However, these approaches do not aim at a formal standardization model capturing all relevant IS-specific aspects and phenomena (Weitzel et al., 2006). Wendt et al. (2000), for instance, state that investigating network effects in such publications is done either on the basis of general macroeconomic aggregate demands, without, however, deriving the aggregation from individual agents' decision behaviour, or based on very restrictive assumptions regarding the micro-economical behaviour of agents. This means that network effects as a result of decentralized decisions of *individual* agents are not explicitly modelled. As opposed to a plethora of approaches in economics, the standardization decision of an individual agent is, however, not solely determined by the mere number of standardizing agents in the complete network, but rather by the concrete adoption decisions within the individual communication network. Thereby, the individual characteristics of each of the agents as well as of the communication relationships between these agents (e.g. cost structures, saving potentials, position in the network) have to be considered to receive meaningful results. As a part of the information is not known to all of the agents (in case of more than two agents), this results in a game with *incomplete* information (cf. section 2.1). As a further consequence, the decisions of other agents in the network are both unknown and uncertain.

Therefore, in the remainder of this paper, we focus on the so-called "Decentralized Standardization Model" (cf. e.g. Beck et al., 2008; Buxmann et al., 1999; Weitzel, 2004; Weitzel et al., 2003a, 2003b, 2006; Wendt et al., 2000), which has its roots in IS. In particular in their MIS Quarterly paper, Weitzel et al. (2006) elaborate the Decentralized Standardization Model which allows to "address the question of the conditions of particular diffusion behaviours by developing a formal standardization model that captures all fragmented phenomena in a unified approach" (Weitzel et al., 2006, p. 489). Many articles (e.g. Kauffman and Kumar, 2008; Lee and Mendelson, 2007; McIntyre and Subramaniam, 2009; Techatassanasoontorn and Suo, 2011; Venkatesh, 2006; Widjaja and Buxmann, 2009) refer to this model and discuss respective findings.

In this paper, we provide an in-depth analysis of the Decentralized Standardization Model from a game theoretical perspective (non-cooperative game). Each agent can decide for or against a standard whereas the resulting net benefit depends on the strategies chosen by the other agents. The model is based on game theoretical equilibrium analysis (Weitzel et al., 2006) to examine both the individual adoption behaviour and the resulting economic consequences. Specially, the model explicates whether or not an individual agent chooses the strategy to adopt a standard based on incomplete information regarding the cost structures of the other agents. First, we investigate *whether the Decentralized Standardization Model represents a decision behaviour of agents who act individually rational* (cf. Rapoport, 2001). Our analysis reveals some methodical shortcomings of this model. Hence, we employ analytical modelling (cf. Meredith et al., 1989) and develop an *adapted approach which constitutes a second contribution of this paper*. The adapted approach addresses the shortcomings by explicitly taking into account the interdependencies among the standardization decisions.

The remainder of the paper is structured as follows: In Section 2, we provide a detailed discussion of the Decentralized Standardization Model. Based on this, we identify important methodical shortcomings and conduct a game theoretical analysis by means of a simulation study to demonstrate the effects of these methodical shortcomings. To address these issues, in Section 3, we propose an adapted approach to represent the agents' individual decision behaviour. The evaluation of our approach is also based on game theoretical considerations and a simulation study. In the last section, we conclude with a critical summary of our findings and provide an outlook on future research.

2 Analysing the Decentralized Standardization Model

In the following, we provide an in-depth discussion of the Decentralized Standardization Model (regarding the details of this model we refer to Weitzel et al., 2006). Afterwards, from a game theoretical perspective, we elaborate on methodical shortcomings of this approach.

2.1 Discussion of the Decentralized Standardization Model

To analyse the decision behaviour of individual agents in communication networks, the Decentralized Standardization Model is based on a directed network (cf. e.g. Weitzel et al., 2006). In this network, each agent is represented by a node $i \in \{1, 2, \ldots, n\}$. The directed edges (i, j) (with $i, j \in \{1, 2, \ldots, n\}$, $i \neq j$) represent the information exchange between these agents. The weights $c_{ij} \in \mathbb{R}^+$ assigned to the edges (i, j) denote the individual information costs arising for agent i due to the information exchange with agent j using proprietary communication technologies. Initially, the Decentralized Standardization Model is based on a full-density network which implies that there is information exchange between each pair of agents i and j (with $i, j \in \{1, 2, \ldots, n\}$, $i \neq j$). However, this assumption can easily be relaxed in favour of any given network topology (cf. e.g. Westarp and Wendt, 2000).

If agent i adopts the new standard, this agent has the possibility to save information costs c_{ij}. It is important to note that the information costs c_{ij} can be saved if and only if both agents i and j standardize (the basic model is a one-standard model which can, however, be extended (cf. Weitzel et al., 2006)). Ex ante (i.e. before agent i decides whether or not to adopt the new standard) agent i does not know whether the other agents j will adopt the standard. The decision of agent i to adopt the standard goes along with standardization costs $K_i \in \mathbb{R}^+$ which have to be opposed to the potential cost savings c_{ij} (which does not necessarily mean that no costs occur in case of standardization, the information costs c_{ij} can rather also be interpreted as the potential savings along the respective edge).

Adopting a standard becomes more economically desirable if further agents adopt this standard as well. The interdependencies among the standardization decisions due to positive network effects result in a coordination problem called standardization problem (Besen and Farrell, 1994; Weitzel et al., 2006). In decentralized networks with autonomously deciding agents, this standardization problem arises for each single agent. Thereby, "given autonomous agents and the availability of a realistic information set, the decentralized standardization problem is mainly a problem of anticipating the standardization decisions of others" (Weitzel 2004, p. 54).

Regarding the information set available for the autonomous agents, in the Decentralized Standardization Model it is assumed that each agent i knows the following (Weitzel et al., 2006): (1) the standardization costs K_j of all agents j in the network; (2) the information costs c_{ij} and c_{ji} directly associated with agent i (i.e. c_{ij} and c_{ji} $\forall j \neq i$); and (3) the number of agents in the network n. In contrast, agent i does not know the information costs c_{jk} between two other agents j and k (with $j \neq k$ and $j, k \neq i$). Weitzel et al. (2006, p. 494) emphasize that this information set is realistic and refer to empirical research that "shows that these data are, in fact, usually available to the deciders." In addition, in the Decentralized Standardization Model neither a notification of the unknown information costs and standardization decisions of all agents nor coordination mechanisms like "cheap talk" (cf. Farrell, 1987) are considered.

Due to incomplete information regarding the information costs of the other agents in the network, each agent i has to decide under uncertainty whether or not to adopt the standard. In the Decentralized Standardization Model, this decision behaviour of each agent i is modelled as follows: In a first step, agent i determines the probabilities p_{ij} with which agent i supposes that the other agents j ($j \neq i$) in the network will adopt the standard. On this basis agent i decides based on the expected value $E(S_i)$ of the savings in communication costs (cf. Term (1)). Hence, each agent i adopts the new standard if and only if the expected value $E(S_i)$ – i.e. the difference between the agent's expected savings in information costs c_{ij} and the standardization costs K_i – is positive.

$$E(S_i) = \sum_{\substack{j=1 \\ j \neq i}}^{n} c_{ij} \cdot p_{ij} - K_i \tag{1}$$

Term (1) reveals that determining the probabilities p_{ij} constitutes the core of the decentralized decision behaviour since these probabilities p_{ij} are the only variables which are unknown to agent i. To determine the probabilities p_{ij} that other agents j (with $j \neq i$) will adopt the standard from the perspective of agent i, in the Decentralized Standardization Model the following quotient is proposed:

$$p_{ij} = \max\left[\frac{\sum_{k=1;\, k\neq j}^{n} c_{jk} \cdot p_{jk} - K_j}{\sum_{k=1;\, k\neq j}^{n} c_{jk} \cdot p_{jk}};\, 0\right] \tag{2}$$

The numerator describes – from the perspective of agent i – the expected savings $E(S_j)$ in communication costs through standardization for agent j. This means that agent i anticipates the expected savings for agent j to determine the probability p_{ij} that agent j will adopt the standard. The denominator contains the expected savings in information costs of agent j. Hence, the quotient represents the expected net benefits (expected gross benefits minus costs) divided by the expected gross benefits of standardization for agent j. Using this denominator, Term (2) is normalized to values for the probability p_{ij} which are less or equal to one. The higher the standardization costs K_j – ceteris paribus – are, the smaller is the probability p_{ij} that agent j adopts the standard and vice versa. If the quotient is negative (i.e. the standardization costs are higher than the expected gross standardization benefits), the maximum function ensures that no probabilities smaller than zero are determined.

Agent i, however, does not know the probabilities p_{jk} which are part of Term (2) (i.e., the probabilities with which agent j supposes that the other agents k will adopt the standard). In the Decentralized Standardization Model, it is therefore assumed that $p_{jk} = 1$ holds for all agents j and k (with $j \neq k$ and $j, k \neq i$) to determine p_{ij}. This means when determining the probability p_{ij} it is assumed that all other agents k will adopt the standard with certainty (i.e. the maximum savings in communication costs and thus the best case scenario are assumed). Hence, it is expected that through standardization agent j can save all information costs c_{jk}. As agent i does not know these costs c_{jk}, it is further assumed that agent i takes the known information costs c_{ji} as representative for the unknown information costs c_{jk} of agent j (with $j \neq k$ and $j, k \neq i$). On this basis, Term (2) to determine the probability p_{ij} in the Decentralized Standardization Model can be denoted as follows (cf. Weitzel et al., 2006):

$$p_{ij} = \max\left[\frac{c_{ji} \cdot (n-1) - K_j}{c_{ji} \cdot (n-1)};\, 0\right] \tag{3}$$

The numerator represents the expected net standardization benefit for agent j, if all other agents adopt the standard. The denominator normalizes the values for the probability p_{ij} to less or equal to one. If the quotient results in a value less or equal to zero (i.e. $c_{ji} \cdot (n - 1) - K_j \leq 0$), then $p_{ij} = 0$ holds.

Using Term (3) to determine the probabilities p_{ij} with which agent i supposes that the other agents j

will adopt the standard, it is possible for agent i to calculate the expected value $E(S_i)$ of the savings in communication costs through standardization (cf. Term (1)). This leads to the decision of each agent i in the Decentralized Standardization Model (agent i adopts the standard if and only if $E(S_i) > 0$ holds).

2.2 Methodical Shortcomings of the Decentralized Standardization Model

The Decentralized Standardization Model constitutes a well-known and important approach to explicate the decision behaviour of agents in decentralized networks with incomplete information (cf. Terms (1)-(3)) and provides a formal basis to explain and discuss economic aspects of standard diffusion. Nevertheless, there are some methodical shortcomings which are discussed in the following.

1) In the Decentralized Standardization Model, it is assumed that all other agents k (with $k \neq j$) will adopt the standard with certainty (i.e. with probability $p_{jk} = 1$) when agent i determines the probability p_{ij} that agent j will standardize (cf. Term (3)). However, this assumption does not consistently reflect the interdependencies among the standardization decisions due to network effects, which are a major characteristic of the standardization problem. In the Decentralized Standardization Model, on the one hand, it is assumed that agent i uses a probability of $p_{jk} = 1$ that agent k adopts the standard when determining p_{ij}. On the other hand, it is assumed that agent i also determines the probability p_{ik} that agent k adopts the standard using Term (3), which may obviously contradict $p_{jk} = 1$. In this respect, the interdependencies among the standardization decisions are not consistently considered. It may even be argued that the other agents are rather modelled as rigid states of nature than as players trying to optimize their individual payoffs.

2) The Decentralized Standardization Model assumes risk-neutral agents i who standardize if and only if the *expected value* $E(S_i)$ of the savings in communication costs is positive (cf. Term (1)). Term (3) which defines how to determine the probabilities p_{ij} and thus constitutes the core of the decentralized decision behaviour, however, is not consistent with the assumption of risk-neutral agents. Term (3) of the Decentralized Standardization Model results in a value of zero for the probability p_{ij} if and only if $c_{ji} \cdot (n - 1) - K_j \leq 0$ holds. In this context, as discussed above, by using the factor $(n - 1)$ it is assumed that all other agents k (with $k \neq j$) adopt the standard with certainty (i.e. all information costs can be saved due to the fact that $p_{jk} = 1$ holds). Therefore, Term (3) to determine the probabilities p_{ij} bases on a best case scenario (i.e. what are the *maximum savings* in communication costs for agent j?) and does not account for the uncertainty regarding the standardization decisions of the other agents (i.e. what are the *expected savings* in communication costs for agent j?). A risk-neutral decision maker, however, would rely on expected values instead.

3) The denominator of the quotient in Term (3) represents the savings in information costs. This way, in the Decentralized Standardization Model it is ensured that the values for the probabilities p_{ij} are normalized to values which are less or equal to one. As a consequence, Term (3) results in a value of $p_{ij} = 1$ if and only if the standardization costs are zero and/or the savings in information costs approach infinity. Apart from these special cases, $p_{ij} < 1$ holds. Even if the expected savings in information costs are twice as large compared to the standardization costs, for example, Term (3) results in a value of only $p_{ij} = 0.5$. This aspect is also not consistent with the assumption of a risk-neutral decision maker who would already adopt a standard if the expected savings in information costs are greater than the standardization costs.

To demonstrate the effects of these methodical shortcomings, a game theoretical analysis of the Decentralized Standardization Model can be conducted. In this context, each agent or player, respectively, can basically choose between the strategies *standardization* and *no standardization*. The net standardization benefits can be interpreted as the payoff of a player's strategy that depends on the strategies chosen by the other players. Rational players will try to optimize their individual payoffs taking account of the strategies of the other players when choosing their strategy. This concept of individual rationality leads to one or more Nash equilibria (Rapoport, 2001).

In the Decentralized Standardization Model, the uncertainty of agent *i* with regard to the decision behaviour of the other agents *j* is represented by the probabilities p_{ij} (cf. Terms (2) and (3)). Due to the fact that the model is explicitly grounded on a game theoretical foundation (cf. Weitzel et al., 2006, p. 496ff.), the approach ought to represent rational decision behaviour. Otherwise, all findings and explanations founded on this major approach would have to be reconsidered carefully.

In addition to the Decentralized Standardization Model, two trivial alternative decision behaviours are included in the analysis (for a detailed definition cf. e.g. Weitzel et al., 2006): (1) *never standardize* which means that an agent never (i.e. under no circumstances) adopts the standard; and (2) *always standardize* which means that an agent always (i.e. in any decision situation) adopts the standard.

To conduct the game theoretical analysis based on payoff matrices, many articles (e.g. Weitzel et al. 2006) proposed and ran simulation studies. A simulation study is necessary due to the complexity of the Decentralized Standardization Model in case of more than two agents and incomplete information that does not allow for promising analyses of closed-form expressions. This is underlined by the fact that the solution of the relatively simple standardization problem for a centralized decision structure and complete information cannot be represented in closed-form either (Domschke and Wagner, 2005). Modelling the standardization problem focused here as a Bayesian game was explicitly requested by Farrell and Saloner (1988, p. 250) as "desirable extension" of their two-player game in 1988, even though it has not yet been realised. Moreover, it would be necessary, to extend such a comparatively simple two player-game to a N-player game (with N>2) taking into account the following additional aspects: the individual characteristics of each single agent (e.g. cost structure) including his communication relationships (note that in a two-player game it is for agent *i* not necessary to consider information costs c_{jk} between two other agents) and the network effects as the result of concrete decentralized decisions of individual agents (note that this is not trivial for more than two players). To sum up: an adequate modelling of the problem would result in an extremely complex Bayesian game whose analytical investigation or even solution would be anything but promising. Thus, a simulation study has to be carried out (methodically we refer to Bertrand and Fransoo, 2002), which is consistent with prior works in this research strand. For instance, according to Beck et al. (2008, p. 416) "interdependencies between micro level phenomena (individual adoption) and macro level phenomena (network effects) imply complex system behavior". Against this background, they suggest the use of simulation studies to cope with this challenge (Beck et al., 2008). In addition, using a simulation study to analyse the Decentralized Standardization Model is consistent with prior research (cf. e.g. Buxmann, 1996; Buxmann et al., 1999; Weitzel et al., 2003a, 2006; Weitzel, 2004). To ensure both comparability and objectivity, the parameterization of our simulation study follows the one by Weitzel et al. (2006):

Networks are generated using approximately (i.e. only positive values of the random variables are used) normally distributed random values for the information costs (c_{ij}~$ND(\mu(c_{ij}), \sigma(c_{ij}))$) and standardization costs (K_i~$ND(\mu(K_i), \sigma(K_i))$). The expected value of the standardization costs $\mu(K_i)$ is systematically increased from $\mu(K_i) = 0$ to $\mu(K_i) = 50{,}000$ by increments of 250, while $\mu(c_{ij}) = 1{,}000$, $\sigma(c_{ij}) = 200$, and $\sigma(K_i) = 1{,}000$ as well as the number of agents with $n = 35$ remain constant. Before systematically increasing the parameter $\mu(K_i)$, the simulation process is repeated 50 times. For each generated network depending on the agents' decision behaviour the single standardization decisions can be determined easily. Based on all agents' standardization decisions their *ex post* standardization benefits can be calculated as well.

Table 2 illustrates the results of the simulation study in the form of a payoff matrix. Over all simulation runs, the payoff matrix contains the average net standardization benefits (payoffs) per agent resulting *ex post*. The payoff matrix considers the decision behaviours *never standardize*, *always standardize*, and *decide according to the Decentralized Standardization Model* (short: *Decentralized Model*). The rows refer to the decision behaviour of any given agent in the network (without loss of generality agent 1). The columns refer to the decision behaviours of the other agents in the network (here, agents 2-35). As represented by the columns, we assume that besides agent 1 all other agents 2-35 decide according to the same decision behaviour (i.e. *never standardize*, *always standardize*, or *Decentralized Model*). This is due to the fact that in case a rational decision behaviour exists the rational agents 2-35 would decide according to exactly this same decision behaviour. Here, it is important to note that this does not necessarily mean that agents 2-35 come – in case of the decision behaviour *Decentralized Model* – to the same standardization decisions because the agents' individual characteristics (e.g. their standardization costs) and information (e.g. with respect to the other agents' information costs) may differ. For each combination of the decision behaviours of agent 1 and agents 2-35, the payoffs for agent 1 are denoted in the top left and those for agents 2-35 in the bottom right corner of the cells. In such a payoff matrix a decision behaviour of autonomous agents who act individually rational is characterized by a Nash equilibrium (i.e. ceteris paribus no player can benefit from a change).

The payoff matrix illustrates that the game has a Nash equilibrium if all agents decide according to the decision behaviour *always standardize*[1]. This Nash equilibrium results in the highest payoffs of 8,979 per agent for both agent 1 (row maximum) and agents 2-35 (column maximum) and is indeed Pareto optimal. Hence, from a game theoretical perspective an agent should *not* decide according to the Decentralized Standardization Model (i.e. according to the decision behaviour *Decentralized Model*) – in fact, in this situation under uncertainty (due to unknown information costs) it would be rational to decide according to the decision behaviour *always standardize*. Thereby, no agent has an incentive to unilaterally change his decision behaviour (i.e. to choose *never standardize* or *Decentralized Model* instead) or to hypothesize that other agents may decide differently.

			Decision behaviour of agents 2-35					
			Never standardize		*Always standardize*		*Decentralized Model*	
			agent 1	agents 2-35	agent 1	agents 2-35	agent 1	agents 2-35
Decision behaviour of agent 1	*Never standardize*	agent 1	0		0		0	
		agents 2-35		0		7,979		8,007
	Always standardize	agent 1	-25,015		**8,979**		-13,675	
		agents 2-35		0		**8,979**		8,340
	Decentralized Model	agent 1	-2,745		8,551		8,332	
		agents 2-35		0		8,311		8,332

Table 2. Payoff Matrix

To sum up: The game theoretical analysis based on a simulation study (the parameterization follows the one by Weitzel et al., 2006) reveals that the Decentralized Standardization Model does not represent rational decision behaviour.

3 An Adapted Approach taking into Account the Interdependencies among the Standardization Decisions

In the following, we address the shortcomings of the Decentralized Standardization Model and propose an adapted approach. Afterwards, we provide a game theoretical analysis.

[1] There is another Nash equilibrium if all agents decide according to the decision behaviour *Decentralized Model*. This Nash equilibrium, however, is not Pareto efficient.

3.1 Developing an Adapted Approach

The interdependencies among the agents' standardization decisions represent the fundamental characteristic of the standardization problem. To take these interdependencies into account when modelling an agent's decentralized decision behaviour, the other agents have to be modelled as players with their individual decision behaviour trying to optimize their own individual payoffs. This means, based on the information set available, each player has to determine the probabilities that the other agents in the network adopt the standard.

The major idea of the adapted approach is to explicitly consider the probabilities p_{jk} (with $k \neq j$) when agent i determines the probability p_{ij} that another agent j in the network standardizes. But how can agent i calculate these probabilities p_{jk}? In this context, when modelling the agents' decentralized decision behaviour, we act as follows (without loss of generality, we take the perspective of agent i):

When determining the probability p_{ij} that agent j adopts the standard, agent i takes the probabilities p_{ik}, which are determinable based on the information set available, as representative for the probabilities p_{jk}. This means, that the probability with which agent i supposes that agent k will adopt the standard is taken as representative for the probability p_{jk} with which agent j supposes that agent k will adopt the standard. The reason is that the probability p_{ik} is the best-known information when determining the unknown probability p_{jk} from the perspective of agent i. Moreover, by using the probability p_{ik} the interdependencies of the standardization decisions can be taken into account as well, since for determining the probability p_{ik} all other probabilities p_{ij} (with $i \neq j \neq k$) need to be considered, too (for details cf. Term (5)). From the perspective of agent i the expected value $E^i(S_j)$ of the savings in communication costs through standardization of agent j can be expressed as denoted in Term (4) (for $c_{jk} = c_{ji}$ as proposed by Buxmann et al., 1999; König et al., 1999; Weitzel et al., 2003a, 2003b, 2003c).

$$E^i(S_j) = \sum_{k=1;\, k \neq j}^{n} c_{ji} \cdot p_{ik} - K_j \tag{4}$$

As above (cf. Term (1)), a risk-neutral agent i decides based on the expected value $E(S_i) = \sum_{j=1;\, j \neq i}^{n} c_{ij} \cdot p_{ij} - K_i$ of his individual savings in communication costs. To be able to calculate the expected value $E(S_i)$, it is necessary for agent i to determine the probabilities p_{ij} for all other agents j in the network. As each agent j is assumed to be risk-neutral as well, the decision of agent j solely depends on the expected value $E(S_j)$ of his savings in communication costs. This means that agent j will adopt the standard if and only if the expected value $E(S_j)$ of his savings is positive. Hence, it is consistent for agent i to derive the probability p_{ij} based on the expected value $E^i(S_j)$ of the savings in communication costs for agent j (cf. Term (4)).

The same argumentation holds when deriving the probabilities p_{ik} for all other agents k (with $k \neq j$ and $k \neq i$). Summing up, for agent i this results in a system of n inequalities. Each inequality refers to the expected value of the savings in communication costs for a certain agent in the network and contains the (n - 1) probabilities that the respective other agents will adopt the standard. Thus, the interdependencies of the standardization decisions are represented by a system of n inequalities, ensuring that each determined decision has its impact on all other decisions. The inequalities take account of the fact that the agents do not standardize in case of negative expected savings in communication costs (cf. right hand side of the inequalities). Using the indicator function $1_{\{p_{ij} > 0\}}(p_{ij})$ ensures that the standardization costs for agent j (with $j \neq i$) occur if and only if agent j standardizes (cf. inequalities 2 to n). The system of inequalities is defined as follows:

$$
\begin{array}{lll}
E(S_i) & = \sum_{k=1;\, k\neq i}^{n} c_{ik} \cdot p_{ik} - K_i & \geq 0 \\
E^i(S_1) & = \sum_{k=1;\, k\neq 1}^{n} c_{1i} \cdot p_{ik} - 1_{\{p_{i1}>0\}}(p_{i1}) \cdot K_1 & \geq 0 \\
\ldots & \ldots & \ldots \\
E^i(S_{(i-1)}) & = \sum_{k=1;\, k\neq (i-1)}^{n} c_{(i-1)i} \cdot p_{ik} - 1_{\{p_{i(i-1)}>0\}}(p_{i(i-1)}) \cdot K_{(i-1)} & \geq 0 \\
E^i(S_{(i+1)}) & = \sum_{k=1;\, k\neq (i+1)}^{n} c_{(i+1)i} \cdot p_{ik} - 1_{\{p_{i(i+1)}>0\}}(p_{i(i+1)}) \cdot K_{(i+1)} & \geq 0 \\
\ldots & \ldots & \ldots \\
E^n(S_n) & = \sum_{k=1;\, k\neq n}^{n} c_{ni} \cdot p_{ik} - 1_{\{p_{in}>0\}}(p_{in}) \cdot K_n & \geq 0
\end{array}
\quad (5)
$$

The system of inequalities explicitly and consistently takes into account the interdependencies among the standardization decisions of the n agents. On this basis, it is possible for agent i to make his decision based on the expected value $E(S_i)$ of his savings in communication costs. In this respect, agent i adopts the standard if and only if the system of inequalities has a solution for $p_{ij} \in [0; 1]$. Term (5) may have multiple solutions. Each solution refers to a situation where agent i adopts the standard while all agents are characterized by non-negative expected savings. To determine the decision of agent i, it is not necessary to find the solution which refers to the situation where the number of agents who are positive towards the standard is maximal. Indeed, this solution reflects the actual result from the perspective of agent i as network effects are positive and each agent aims at maximizing his expected savings (the inequalities only ensure non-negativity). However, due to the characteristics of positive network effects it is clear that given any solution of Term (5) all agents adopting the standard in the respective situation also standardize in the solution reflecting this actual result from the perspective of agent i. A solution of the system of inequalities is characterized by two aspects: On the one hand, it is ensured that adopting the standard goes along with a positive expected value $E(S_i)$ of the savings in communication costs for agent i (cf. first inequality not including the indicator function). On the other hand, none of the other agents j (with $j \neq i$) in the network expects negative savings in communication costs $E^i(S_j)$ due to an adoption of the standard (cf. inequalities 2 to n including the indicator function).

The adapted approach addresses the shortcomings of the Decentralized Standardization Model:

1) It is no longer assumed that all other agents k (with $k \neq j$ and $k \neq i$) will adopt the standard with certainty (i.e. with probability $p_{jk} = 1$) when agent i determines the probability p_{ij} that agent j will standardize. Rather, this assumption is avoided and the interdependencies of the standardization decisions are taken into account in an explicit and consistent way by a system of inequalities.

2) When determining the probabilities p_{ij} according to the Decentralized Standardization Model, it is assumed that all other agents k (with $k \neq j$ and $k \neq i$) will adopt the standard. As a consequence, the agents' decision behaviour is based on a best case scenario (see above). This is not consistent with the assumption of risk-neutral agents. In the adapted approach this shortcoming can be avoided. The system of inequalities consistently takes into account that all agents base their decisions solely on the expected value of their individual savings (and not on maximum savings).

3) In the Decentralized Standardization Model, the savings in communication costs are divided by the savings in information costs in order to normalize the values for the probabilities p_{ij} to less or equal to one (cf. Terms (2) and (3)). This normalization is not consistent with the assumption of risk-

neutral agents and may result in a distortion of the determined probabilities. Deciding according to the adapted approach avoids this shortcoming. It is characterized by a consistent use of probabilities and considers solely the expected value of the savings in communication costs when determining the probabilities (cf. Term (5)). This is consistent with the assumption of risk-neutral agents.

3.2 Game Theoretical Analysis of the Adapted Approach

In the following, we provide a game theoretical analysis of our approach. For this purpose, we included the decision behaviour according to the adapted approach in the simulation study described above (parameterization follows Weitzel et al., 2006). To cope with the system of inequalities - which constitutes the core of the decision behaviour according to the adapted approach – we implemented a Java application and used routines of the mathematics software *Mathematica*™. In addition, we conducted several test procedures like Structured Walk-through, Unit testing, and Extreme value testing to verify the implemented application and the results of the simulation study.

Table 3 shows the results of the extended simulation study as a payoff matrix. Unlike Table 2, it also includes *decide according to the adapted approach* (short: *Adapted Model*). Again, the rows refer to any given agent in the network (without loss of generality agent 1), and the columns to the other 34 agents in the network (here, agents 2-35). The payoffs for agent 1 are denoted in the top left and those for agents 2-35 in the bottom right corner of the respective cells.

			Decision behaviour of agents 2-35							
			Never standardize		*Always standardize*		*Decentralized Model*		*Adapted Model*	
			agent 1	agents 2-35	agent 1	agents 2-35	agent 1	agents 2-35	agent 1	agents 2-35
Decision behaviour of agent 1	*Never standardize*	agent 1	0		0		0		0	
		agents 2-35		0		7,979		8,007		9,542
	Always standardize	agent 1	-25,015		8,979		-13,675		-8,664	
		agents 2-35		0		8,979		8,340		10,022
	Decentralized Model	agent 1	-2,745		8,551		8,332		8,551	
		agents 2-35		0		8,311		8,332		9,874
	Adapted Model	agent 1	-5,835		10,561		5,505		**10,005**	
		agents 2-35		0		8,462		8,340		**10,005**

Table 3. Extended Payoff Matrix

The extended payoff matrix shows that - considering these decision behaviours – a Nash equilibrium is constituted when all agents choose to decide according to the adapted approach. The Nash equilibrium results in payoffs of 10,005 per agent. Thereby, nobody has an incentive to unilaterally change his decision behaviour or to hypothesize that other agents may decide differently since this would lead to a reduction in the payoffs (cf. other rows for agent 1).

The payoff matrices contain average net standardization benefits per agent over all simulation runs. In the following, we take a deeper look at the agents' *individual standardization decisions*. To evaluate different solutions in the context of a decentralized decision structure and *incomplete* information, the (optimal) solution for a decentralized decision structure and *complete* information can serve as a sound reference base (cf. Table 1; Heinrich et al., 2011). Indeed, the solution for a decentralized decision structure and complete information would occur in case of incomplete information as well, if – despite incomplete information – each agent could perfectly anticipate the standardization decisions of the others. Figure 1 focusses on the fractions of individual agents' incorrect decisions with respect to the solution for a decentralized decision structure and complete information. The single charts compare the fractions of individual agents' incorrect decisions for the *Adapted Model* with those for the other decision behaviours depending on the expected value of the standardization costs $\mu(K_i)$ which is systematically increased from 0 to 50,000 (cf. parameterization of the simulation study).

The analysis reveals that, with respect to the solution for a decentralized decision structure and complete information (reference base), deciding according to the adapted approach leads to significantly fewer individual agents' incorrect decisions as opposed to the other decision behaviours. The fractions of incorrect individual decisions over all simulation runs are as follows: *never standardize*: 62%; *always standardize*: 38%; *Decentralized Model*: 28%; and *Adapted Model*: 14%. It is particularly remarkable that referring to this reference base deciding according to the adapted approach strictly dominates the decision behaviours *Decentralized Model* and *never standardize* in the sense that for all 351,750 standardization decisions in the simulation study not a single agent is worse off when deciding according to *Adapted Model*.

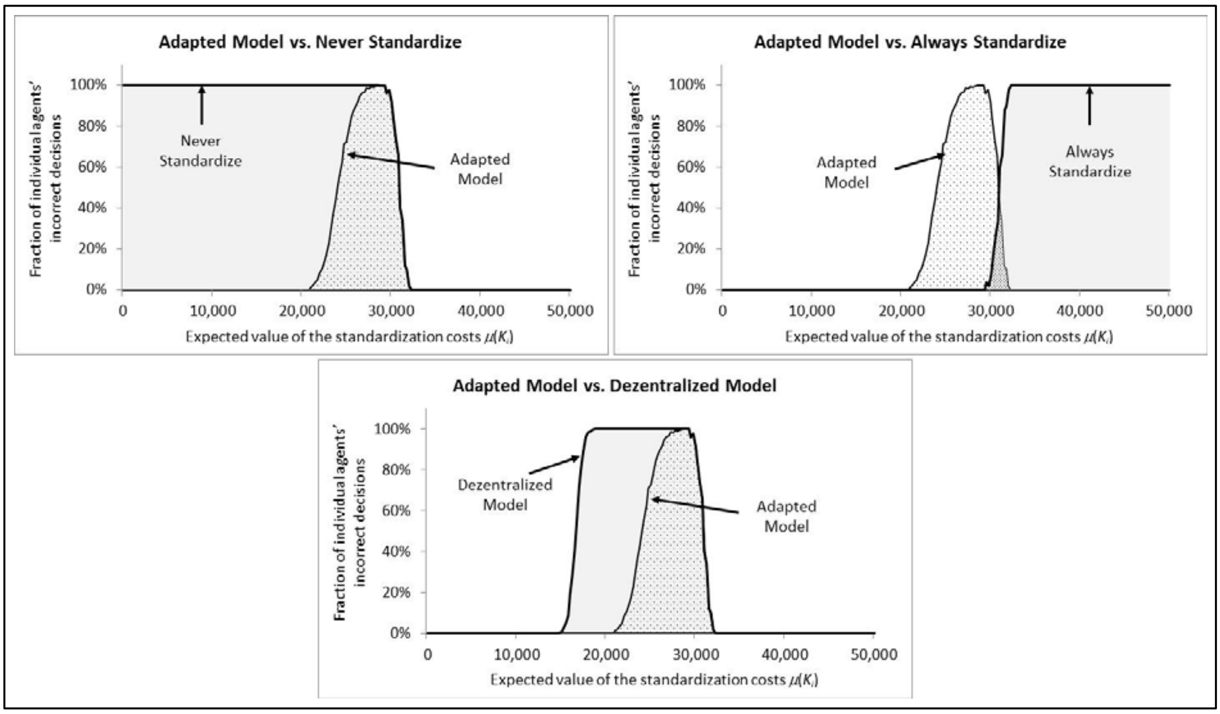

Figure 1. Fraction of Individual Agents' Incorrect Decisions with respect to the Solution for a Decentralized Decision Structure and Complete Information

Another interesting aspect refers to the so-called "standardization gap" which is defined as the difference in network-wide savings between the solution for a centralized decision structure and complete information and the solution for a decentralized decision structure and incomplete information (cf. e.g. Lee and Mendelson, 2007). In literature, the standardization gap is used to quantify inefficiencies in decision making in terms of "network effect benefits as yet unexploited" (Weitzel et al., 2006, p. 498). Here, the simulation study reveals that compared to the Decentralized Standardization Model deciding according to the adapted approach leads to a significantly smaller standardization gap: Actually, the average standardization gap observed over all simulation runs is about 55,473 instead of 115,199 (in case of the Decentralized Standardization Model) which constitutes a reduction of more than 50%.

To sum up: The simulation study (the parameterization follows Weitzel et al., 2006) reveals that it is rational and helps to reduce inefficiencies to explicitly take into account the interdependencies among the standardization decisions and decide according to the adapted approach.

4 Conclusion, Limitations and Further Research

In this paper, we focus on the standardization problem for a decentralized decision structure and incomplete information. We concentrated on methodical aspects of standardization models representing the individual decision behaviour of agents who have to decide under uncertainty. The interdependencies among the agents' standardization decisions are the fundamental characteristic of both the standardization problem and the network theory. Therefore, we investigated how to take these interdependencies into account when modelling the individual decision behaviour of the agents and developed an adapted approach. The results can be summarized as follows:

1) Compared to the well-known Decentralized Standardization Model, respective discussions (e.g. Kauffman and Kumar, 2008; Lee and Mendelson, 2007; McIntyre and Subramaniam, 2009; Techatassanasoontorn and Suo, 2011; Venkatesh, 2006; Widjaja and Buxmann, 2009) and approaches in the field of economics (e.g. Farrell and Saloner, 1985, 1986), our approach explicitly and consistently takes into account the interdependencies among the standardization decisions of the agents in the network. Methodically, our approach is based on a system of inequalities. This way, several restrictive assumptions and methodical shortcomings of the Decentralized Standardization Model are avoided.
2) A game theoretical analysis based on a simulation study revealed that our approach goes along with the highest average net standardization benefits per agent. Furthermore, it is remarkable that referring to the fractions of incorrect individual agents' decisions (cf. Figure 1) the proposed adapted approach strictly dominates the Decentralized Standardization Model.
3) In our paper, we mainly focus on methodical aspects of the standardization problem. On the one hand, our approach constitutes a theoretical contribution which can serve as a basis for further scientific analyses to get a better understanding of the economics of IS standards. On the other hand, the approach may also be apt to make decision makers and managers more aware of the fact that (1) standardization decisions are *inherently* interdependent and that (2) the interdependencies among the agents' standardization decisions have to be adequately taken into account to reduce inefficiencies. In this respect, especially the system of inequalities may be valuable which – according to empirical research – bases on a realistic information set available to the agents (e.g. firms) in practice: It demonstrates what happens to the decision of an agent in case other agents will or will not adopt a standard. This may constitute a starting point for fruitful discussions about the interdependencies of standardization decisions. Moreover, analyses show that deciding according to the adapted approach (i.e. based on the system of inequalities) can result in considerable economic benefit (e.g. the results of the simulation study conducted underpin that the standardization gap is reduced significantly).

The methodical discussions in this paper may constitute the starting point for further research. Existing economic interpretations and findings have to be reconsidered carefully, explicitly taking into account the interdependencies among the standardization decisions. Due to the adapted decision behaviour, we expect differing results. In this context, economic analyses considering multiple periods and different network topologies seem to be promising. In particular, competing standards and the resulting adoption patterns for each standard should be analysed with regard to the interdependencies among the decisions and incomplete information. Our approach may provide a suitable basis for these future steps.

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