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Signifying Williamson's Contribution to the Transaction Cost Approach: An Agent-Based Simulation of Coasean Transaction Costs and Specialization

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ABSTRACT This article simulates Ronald Coase's transaction cost approach to firm organizing using agent-based modelling, and contextualizes and contrasts it with a division-of-labour/specialization view of the firm that Coase challenged and sought to replace. The simulation tests the firm formation process based on the different implications of transaction costs and specialization as drivers of integration, focusing especially on Coase's rejection of specialization as an explanation for integration in the firm. The results show little support for, and suggest an important shortcoming to, Coase's transaction cost theory. My findings thereby indicate a potential relationship between the specialization theory and Williamson's Transaction Cost Economics, especially the latter's emphasis on co-specialization through relationship-specific investments, which helps shed light on TCE's significant influence in the theory of the firm literature.

Keywords: agent-based model, firm formation, simulation, specialization, Transaction Cost Economics, transaction costs

INTRODUCTION

Transaction costs have become a central concept for the study of the firm and market structure. Coase (1937) developed this novel theory of the firm, challenging the then prevailing theory (e.g., Frank, 1925; Robinson, 1931). Rather than treating organization as a productivity-driven division-of-labour or *specialization* phenomenon, as had been the case in economics since Adam Smith's *Wealth of Nations*, Coase sought a way of 'linking up organization with cost' (Coase, 1988c, p. 4). The firm, he maintained, is a means for coordinating production that does not rely on prices in the open market. As the market is efficient, the firm's objective is 'to reproduce market conditions' internally (p. 4). There

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should therefore be 'no [further] specialization within the business unit' (p. 4), which distinguishes Coase's approach from modern theories emphasizing the use and combination of rare resource configurations as potential firm-specific advantages (e.g., Barney, 1991; Conner and Prahalad, 1996; Foss et al., 2008; Penrose, 1960). Coase suggested that there must be a different reason 'why a firm emerges at all in a specialised exchange economy' (Coase, 1937, p. 390), and found that firms enjoy a cost advantage by superseding the price mechanism due to inherent costs in market transactions.

Coase's account gained traction with Williamson (e.g., 1975, 1985, 1996b) whose adaptation, formalization, and extension as Transaction Cost Economics (TCE) has become the dominant perspective in contracting theory (Schepker et al., 2014). TCE 'has shifted away from Coase's initial and more general treatment' (Madhok, 2002, pp. 535–36), with a greater focus on the governance implications of 'asset specificity' (Balakrishnan and Fox, 1993; Joskow, 1993; Riordan and Williamson, 1985). Asset specificity, as a form of asset-based co-specialization within firms, was discounted by Coase as not 'an important reason for vertical integration' (Coase, 2006, p. 259). The disagreement regarding asset specificity's importance and the 'hold-up problem' that TCE predicts in line with its behavioural assumptions (Klein, 2010; Williamson, 1993), has resulted in much debate, the most notable on General Motors' acquisition of Fisher Body in the 1920s (e.g., Casadesus-Masanell and Spulber, 2000; Coase, 2000, 2006; Freeland, 2000; Klein, 1988, 2007). This particular debate pinpoints a difference between the Coasean theory and TCE that goes beyond Coase's reluctance to accept exchange hazards due to opportunistic behaviour as an explanation for integration. Coase's theory views the firm as an attempted *reproduction* of the market's allocation of resources and was originally developed as an alternative to the dominant specialization-based theory of the firm (Bylund, 2014). In contrast, asset specificity – TCE's 'most critical dimension' and the reason it is considered an 'empirical success story' (Williamson, 1985, p. 30; 1996a, p. 55; cf. David and Han, 2004; Shelanski and Klein, 1995) – appears to *reintroduce* differences in specialization intensity within the firm, as compared to the surrounding market, to explain organization similar to pre-Coasean theories of the firm.

This raises interesting questions about the relationship of Williamson's TCE not only to Coase's transaction cost theory (Coase, 1937, 1960), but also to the pre-Coasean specialization theory of the firm (Frank, 1925; Robinson, 1931, 1934). Specifically, was co-specialization/asset specificity necessary for the breakthrough of the transaction cost approach? The literature stresses empirical testing and refinements of transaction costs, with almost exclusive attention given to the more formalized TCE. Perhaps dissuaded by Williamson's claims (e.g., 1981, 1998, 2002, 2005) that TCE builds on Coase's framework, the theoretical differences between their works have not been exhaustively detailed or scrutinized. Instead, the theories are treated as practically the same – with only 'differences in emphasis' (Madhok, 2002, p. 536).

This article contributes to disentangling the transaction cost theories by simulating and so dynamically testing Coase's theory, based on the assumptions and specifications as they were originally laid out. Rather than producing a conceptual model for firm formation, as is done in, for example Bylund (forthcoming), I test the Coasean framework in an agent-based simulation and thereby contextualize the evolution of transaction cost theory by bringing to the forefront the distinct challenge in Coase's contribution. This allows us to trace reasons for why Coase's theory for decades remained 'much cited and little used' (Coase, 1972, p. 63), only to be replaced by Williamson's TCE. By teasing out the nature of Coase's original contribution, I isolate an important aspect of Williamson's later contribution (his addition and changes to Coase's theory) that suggests why TCE was a 'necessary' development.

Specifically, I simulate Coasean transaction costs using agent-based simulation, a method well suited to validate theory and especially test explanations of dynamic processes. It sheds light on the theory's strength by testing how it would explain the formation of firms from a pure market state, and contrasts it with the pre-Coasean view. The article's purpose is not to critique the Coasean analysis (this has been done elsewhere, e.g., Ghoshal and Moran, 1996; Madhok, 1996, 2002; Poppo and Zenger, 1998) but to test the theory's implied process on its own terms. It thereby contributes to our understanding of transaction cost theory, particularly Coase's distinct approach, thus indicating a reason for why TCE appears to provide better explanations.

The structure of the article is as follows. I first summarize Coase's transaction cost explanation to the firm and formulate propositions for testing. I then introduce the method and the basic simulation model. The results are discussed along with adaptations to the model, as is the common approach in the incremental discovery, design, and development of ABM simulation testing (North and Macal, 2007, pp. 6–8). I finally summarize conclusions, elaborate on how they can inform us about the transaction cost approach, and discuss future research.

THEORY AND PROPOSITIONS

Coase's point of departure is a theoretical construct he refers to as 'atomistic competition, where every transaction involving the use of another's labour, materials or money was the subject of a market transaction' and therefore 'there would be no need for an organization' (Coase, 1988c, p. 4). In this assumed 'pure market', even complex production processes are established through market contracting between independent ('self-employed') actors, coordinated through prices. It follows that '[s]ince under market conditions, the greatest use is made of the factors of production, [the] object of the organization [is] to reproduce market conditions' internally (Coase, 1988c, p. 4). This means that, compared to the market, there should be 'no specialization within the business unit' (p. 4). Consequently, resource allocation or (co-)specialization cannot be a reason 'why a firm emerges at all in a specialised exchange economy' (Coase, 1937, p. 390). Returns from specialization are therefore rejected as a reason or driver for integration in firms.

Coase contrasts his theory with the then-dominant division-of-labour approach (Coase, 1937, pp. 388–89), which had been the standard explanation for firm organizing since Adam Smith. This approach holds that the firm is a vehicle for the owner or entrepreneur to bring about a different degree and kind of division of labour, which therefore enjoys productivity gains owing to increased specialization (as in, e.g., Frank, 1925; Robinson, 1931, 1934; for a recent conceptualization and model, see Bylund, 2011, forthcoming). As Coase assumes efficient markets with no additional specialization in the firm, he clearly rejects this view: market efficiency means there can be no gains from specializing further, and he thus sees a contradiction in how 'economists treat the price mechanism as a co-ordinating instrument, [but] also admit the co-ordinating function of the "entrepreneur" ' (Coase, 1937, p. 389). Holding specialization intensity constant, Coase instead points to cost savings due to relying on direction instead of prices. His view thus signifies a break with as well as a challenge to the 'pre-Coasean' division-of-labour theory.[1]

The Coasean Theory of the Firm

Despite market efficiency, Coase finds that it can be advantageous to reproduce market conditions without relying on prices due to 'a cost of using the price mechanism', especially 'of discovering what the relevant prices are' (Coase, 1937, p. 390). These transaction costs are initially explained as 'costs of marketing in the open market' (p. 395), commonly understood as costs of searching for trading partners (North and Thomas, 1973, p. 93; Stigler, 1961). Coase later expands the concept to include all costs to 'carry out a market transaction', or more specifically 'to discover who it is that one wishes to deal with, to inform people that one wishes to deal and on what terms, to conduct negotiations leading up to a bargain, to draw up the contract, to undertake the inspection needed to make sure that the terms of the contract are being observed, and so on' (Coase, 1960, p. 15), which adds contracting and negotiation costs.

Coase's transaction costs are ultimately a penalty on market trade (Bylund, 2014; see also Demsetz, 2011) that provides a comparative cost advantage for integration in firms. The 'distinguishing mark' of the firm is 'the supersession of the price mechanism' (Coase, 1937, p. 389) through adoption of centralized management with authority to 'direct the other factors of production' (Coase, 1937, p. 391). Yet while Coase's firm is often interpreted as a cluster of employment contracts, this is likely an inaccurate depiction of the Coasean firm; Coase later points out that 'one of the main weaknesses of my article' was that it 'misdirects our attention' by not dismissing the view of the firm as based solely on 'the employer–employee relationship' (Coase, 1988a, p. 37). In fact, Coase finds that the employment relation gives 'an incomplete picture of the nature of the firm' (p. 37), since the only task of management is to make sure the market's allocation of resources is reproduced. 'Management proper', Coase (1937, p. 405) states, 'merely reacts to price changes, rearranging the factors of production under its control'. Should the firm, due to internal organizing costs, turn out to be too costly, 'it is always possible to revert to the open market' (p. 392). This conclusion appears to follow directly from the assumption that there is no additional specialization within the firm.

Coase does not address the process from atomistic competition to integration of market transactions (production) in firms, and vice versa, but focuses on *why* there are firms. He thus explains the comparative statics of *ex post* organizing, and finds in transaction costs an explanation that 'succeeded in linking up organization with cost' (Coase, 1988c, p. 4). The theory's setup nevertheless suggests that the rationale should be sufficient for delineating the process, as atomistic actors choose 'integration' when the transaction costs they otherwise face are too high. This process is implied in Coase's assertion that the 'cost of using the price mechanism' (Coase, 1937, p. 390) makes it cheaper to integrate transactions in a firm where labour workers are directed rather than individually responsive to changing market prices. The assumed identical capital and labour structure, whether coordinated within a firm or in the market based on the price mechanism, means adding explicit transaction costs to the atomistically competitive market should cause firms to form. At a minimum, firms would emerge as 'clusters' of market actors choosing repeated trade over costly market search (Stigler, 1961). Proposition 1 tests this explanation for coordinating production structures in firms in a world with positive transaction costs of significant magnitudes:

> *Proposition 1*: In a high transaction cost world, market actors form relationships with trading partners that persist over time. The market will generate and find a stable equilibrium with a multitude of clusters of multi-actor (firm-like) production structures.

Specialization and Transaction Costs

Coase does not find in increasing specialization intensity an explanation for integration in the firm, but recognizes the economic significance of specialization. As argued in Bylund (2014), Coase (1937, p. 390) not only assumes 'a specialised exchange economy' but relies on resource heterogeneity (Barney, 1991, 1995; Lachmann, 1947, 1978) since trading in heterogeneous resources gives rise to the 'marketing' frictions we denote transaction costs. The level of specialization intensity, increases of which causes resource heterogenization in the market that decreases a market's perceived density, therefore plays an indirect role in Coase's transaction cost reasoning. Specialization should for this reason be implicitly or indirectly correlated with transaction costs. This suggests that the *effect* transaction costs have on the market is, to some degree, a function of the prevailing market density, which in turn is a determinant of the extent of the market and its structure (Durkheim, 1933; Smith, 1976). This is because more intensive specialization, and therefore strengthened resource heterogeneity, means any actor is relatively more unique and, therefore, that there are fewer compatible trading partners in the market. This also increases the costs for discovering relevant prices, since compatible partners are relatively farther apart. In contrast, if we, with Williamson (1993) and Klein (2010), assume opportunistic behaviour, (co-)specialization through asset specificity becomes a *direct* cause of transaction costs in TCE.

The reasoning implied by Coase (1937) is a common assumption in economics. As explained by Böhm-Bawerk (1959) and others, 'longer', more roundabout production processes with a greater number of production stages are more productive, but also put greater strain on production in the market because of the difficulty in establishing these complex processes. Thus, in a highly specialized economy, agents will be less likely to find compatible trading partners, which would lead to increased search transaction costs for opportunities to trade. Yet such a market should also produce more output due to the increased productivity of the division of labour (that is, of being more intensively specialized) (Young, 1928).

Similarly, a 'shorter' production process implies relatively higher density (access to more compatible trading partners), which makes trade less costly. But the process is also less productive since each task is less intensively specialized, which suggests poor resource utilization. In contrast, over-specialization increases the costs of exchange by decreasing the extent of the market. There should then be an implicit positive correlation between Coase's transaction cost concept and specialization through the density of the market. As noted, Coase rejects intensive specialization as a rationale for or driver of integration, yet his theory hinges on the downside of specializing: the implicit cost of specialization through its effect on market density. Coase's reasoning is, therefore, in a very limited sense, related to the pre-Coasean specialization explanation, while TCE makes this implicit reliance a cornerstone of transaction cost reasoning through emphasizing the direct effects of asset specificity on organizing production. To test the implied relationship, we propose:

Proposition 2: The shorter the production process, the more frequent the exchanges and smaller the impact of transaction costs on transacting (and vice versa).

An Alternative Explanation for Firm Formation

Coase rejected the explanation that the firm is extra-market specialization along the lines of Adam Smith's discussion on the division of labour. While market specialization is a necessary component in Coase's framework, it is made irrelevant for determining the firm–market boundary by assumption. He consequently rejects specialization as a driver of integration, which reveals a cost-based explanation of integration in firms. But this does not necessarily reject the division-of-labour argument that the firm is in effect a vehicle for specialization. The latter theory holds that firms and their boundaries are *defined* by their more intensive division of labour and are created for the purpose of implementing innovative production processes potentially more efficient than existing market-coordinated production. The firm here utilizes a different and more intensive form of specialization by bringing about an advanced 'splitting' of tasks between labourers (Frank, 1925; Robinson, 1931, 1934).[2] The argument is about entrepreneurship through *mutual specialization* (Bylund, forthcoming), which can partially resemble (but is not the same as) TCE's co-specialization through investing in relationship-specific assets.

Where the pre-Coasean theory of the firm focuses on productivity gains through innovative mutual specialization to explain firm formation, Coase, in apparent contrast, assumes a specialized and thus productive market without additional specialization intensity within firms. The explanations have different foci, but neither suggests that the concepts are mutually exclusive: the pre-Coaseans were unaware of transaction costs, and Coase does not directly address potential productivity gains of intra-firm specialization. It is therefore possible that specialization and transaction costs support each other, so that a model that acknowledges both transaction costs and differing specialization intensities could explain firm formation (thereby rendering Coase's assumption superfluous). We thus propose:

Proposition 3a: In a high transaction cost world, market actors enter relationships with innovative entrepreneurs to become part of production structures that persist over time. The market finds stable equilibrium including a multitude of firm-like production structures.

While Proposition 3a suggests an expanded application of Coase's basic reasoning, the effect of transaction costs in terms of firm formation cannot be separated from the effect of task-splitting specialization in or through firms. It is possible that Coasean transaction costs and intra-firm specialization interact towards firm formation. In order to separate the transaction cost effect from that of intensive specialization, we propose:

Proposition 3b: In a low transaction cost world, market actors do not enter relationships with innovative entrepreneurs or become part of production structures that persist over time. The market finds stable equilibrium with no lasting firm-like production structures.

THE SIMULATION MODEL

Agent-based simulation models (ABM) effectively test dynamic causes and mechanisms that bring about phenomena that we observe empirically, but cannot fully identify or comprehend only by observation. This method has recently been adopted in management and entrepreneurship research (Bonabeau, 2002; cf. Burton and Obel, 2011), for example to study decision-making and entrepreneurship in organizations (Küchle et al., 2006; Lant and Mezias, 1990; Ross and Westgren, 2009; Stahl and Zimmerer, 1984; Walter et al., 2006), embeddedness, clustering, and growth (Provance and Carayannis, 2011; Wang et al., 2010; Zhang, 2003), organizational routines (Miller et al., 2012), and demand dynamics (Miller et al., 2009), and for theory development (Crawford and McKelvey, 2010; McKelvey, 2004; cf. Davis et al., 2007).

As shown in previous work (e.g., Chang and Harrington, 2007; Coen and Maritan, 2011; Miller and Lin, 2010), ABM helps identify microfoundations of observable, complex, and dynamic phenomena by simulating the behaviour and interaction of agents in an artificial world (Simon, 1996). 'Agents' are self-contained entities acting in response to their perceptions of the operating environment (Gilbert and Troitzsch, 1999; Huhns and Singh, 1998; Woodridge and Jennings, 1995); they are autonomous and interact according to simple rules; they differ in attribute values but not in behavioural rules, and respond to changes in the environment accordingly (Gilbert and Troitzsch, 1999; Woodridge and Jennings, 1995). By simulating specific behaviour, macro-level patterns are generated (Axelrod, 1997; Axtell, 2000; Schelling, 1978) from the bottom up (Lustick, 2002). ABM is distinct from other types of simulations, which are generally top-down. Societies are 'grown' (Epstein and Axtell, 1996) and indicate 'how the results can be more than the sum of the parts' (Axelrod and Tesfatsion, 2006, p. 1649; cf. North and Macal, 2007, p. 276). Fioretti (2013, p. 229) describes the testing process as 'construct[ing] an artificial environment where decision makers [agents] meet, eventually repeating certain interactions along recurring patterns that constitute a kind of collective decision process'; this provides insight into 'the emergence of self-organization' (Macal and North, 2010, p. 151).

Accordingly, the model used here includes only specific rules of behaviour that have no direct bearing on the pattern they generate. This does not mean the outcome is unknown; instead, the aim is to generate it by letting agent behaviour play out (Epstein and Axtell, 1996); eventually, a structurally new object may emerge (Lane, 1993a, 1993b). The contribution is in *how it is generated*, thereby testing the *sufficiency* of agents' rules or attributes in generating the macro phenomenon. The process and, especially, what drives it, is core:

> The surprise consists precisely in the emergence of familiar macrostructures *from the bottom up* – from simple local rules that outwardly appear quite remote from the social or collective phenomena they generate. In short, *it is not the emergent macroscopic object per se that is surprising, but the generative sufficiency of the simple local rules*. (Epstein and Axtell, 1996, pp. 51–52; emphasis in original)

ABM is commonly treated as an 'empirical' method for falsifying hypotheses derived from theory or empirical data (Epstein, 1999). Its reasoning tends to be cumulative and the results are described verbally or as pictorial representations (North and Macal, 2007, p. 280; cf. Epstein and Axtell, 1996). As it is a dynamic process, it is particularly well suited to investigate the transaction cost explanation of firm formation (Axelrod, 1997; North and Macal, 2007, p. 100).

The Model Structure

The base model[3] simulates a market place consisting solely of independent agents who seek to trade with each other for profit (and, indirectly, to complete the production process), similar to Coase's (1937, 1988c) atomistically competitive market. The model facilitates trade, but does not generate firms (persistent clustering of agents), and consists of 200 agents spread out randomly on a 100×100 torus space.[4,5] The space represents the size of the world, the population, the extent of the market. Neither the number of agents nor that of possible positions is of analytical importance, since the analysis focuses on the effects of agents *transacting*. Larger (smaller) market space or smaller (larger) population both mean interactions are less (more) frequent, but this does not affect the nature of the interactions since they play out according to the agents' behavioural rules. Only the ratio between space and population size (the market's *density*) is relevant, since it determines the frequency with which agents can interact (trade).

Each transaction carried out adds to an agent's production experience and also provides an opportunity to stay with a partner over time (resembling a firm). Higher density increases overall interaction frequency and may generate macro phenomena sooner, but does not affect the nature of interaction between any pair of agents.[6] This view of market density is similar to that held by the pre-Coaseans, and was also acknowledged in Coase's recognition of the effects of communication technology on coordination (Coase, 1937, p. 397). The effect of transaction costs under different market densities is examined in Proposition 2.

In order to simulate 'a specialized exchange economy', by which is meant a division of labour to carry out specific tasks, all actors are randomly assigned a role in a predefined, specialized production process. It consists of five tasks and is represented by the production interval (0–5) divided into five serially interdependent production stages or tasks: (0–1), (1–2), (2–3), (3–4), and (4–5). These stages can be thought of as value-added from start (0) to finish (5), though it would be more accurate to think of the full continuum (0–5) as the progression through the production process, and thus any point thereon represents the relative completion of the end product. A product at 4.5 on the continuum would then be 90 per cent completed.

Agents are specialized producers assigned to one of the stages; they, therefore, purchase the outputs of the preceding stage and sell inputs to the following stage. To produce outputs, agents must first acquire the inputs necessary for the stage.[7] Each agent is initially endowed with a random amount of funds and inputs so that the simulation immediately functions as a live market place. Agents produce their stages, trade with each other and, ultimately, the end product (5.0) is sold to an assumed consumer (not part of the model). When not trading, agents walk (search) randomly across the market space one step at a time unless they identify a potential trading partner, in which case they approach in order to trade.

Agents and Configuration

Agents are configured to facilitate exchange transactions through the production process in accordance with the Coasean framework, and generate data to track their performance in the market. Table I shows agent configuration and variables.

Agents can 'see' other agents at a distance of two positions in each of four directions (N, S, W, E) – that is, an expanded von Neumann neighbourhood (North and Macal, 2007, p. 49). Any agent is consequently able to see a total of nine positions (two in each direction plus the agent's own position), which amounts to 'seeing' 5 per cent of the market horizontally and vertically. This is the minimum possible without causing de facto blindness and therefore random trade. Increasing agents' vision greatly increases perceived density in the market and, as agents prefer profitable trade, the risk of adverse behaviour.[8] To facilitate transactions, the object of this study, this risk is minimized by the vision limitation; it also represents a lack of omniscience in real markets and thus conforms with Coase's emphasis on the importance of realism (Hsiung and Gunning, 2002) as well as the potential impact of communication technology noted above.

The vision limitation may go beyond the analysis in Coase (1960) by imposing 'costs' of imperfect information, but is in line with Coase's original analysis; his discussion on communication technology strongly suggests that he assumes imperfect information.[9] Coase's (1937, 1988b, 1988c) theory holds that low transaction costs pose no economic problem of coordination. They drive integration only when significantly higher than a firm's organizing costs (decreasing returns to management and imperfect reproduction of the market's resource allocation). Transaction costs can thus be present even under atomistic competition without generating firms.[10] Agents move ('search') when they are not already located next to the best possible trading partner in sight (lowest-price seller of the agent's inputs or highest-price buyer of its outputs) willing and able to sell inputs or buy outputs (subject to agent's current needs). This follows from the fact that, as all exchange opportunities entail gains from trade, there is no reason to move unless the

Table I. Overview of model's agent configuration with variable types and default values

Variable	*Type*	*Start value/limit*	*Notes*
Position	coordinates	[random]	Denotes agent's current position; updated when moving
Stock	real	[random, 0–10]	Inputs on hand, necessary to produce output
MoneyOnHand	money	[random, 0–10]	Funds on hand, necessary to purchase inputs
Experience	int	0	Number of products produced and sold
ProductionIntervalLowerLimit	real	[random]	Lower limit of agent's 'skill' or production capability; randomly set 0.0–0.5 below stage (i.e., within 1.5–2.0 for stage 3's interval 2.0–3.0)
ProductionIntervalUpperLimit	real	[random]	Upper limit of agent's 'skill' or production capability; randomly set 0.0–0.5 above stage (i.e., within 3.0–3.5 for stage 3's interval 2.0–3.0)
RiskAversion	int	[random, 0–10]	Denotes agent heterogeneity; risk aversion is in some tests used as cost on certain 'risky' behaviour
TotalIncome	real	0	Total money sales from start of simulation run
TotalOutlays	real	0	Total money payments (purchases)
TotalProductionCost	real	0	Total cost of production (cost due to making output from input)
TotalProfit	real	0	Tracks profits made (TotalIncome – TotalOutlays – TotalProductionCost)

agent either has no possibility for exchange or is aware of a superior opportunity. Agents cannot occupy the same space and they can trade only with agents in adjacent positions.

The full production process requires inputs to be taken through all of the stages in order – that is, from 0 to 5. To allow for limited agent heterogeneity as well as fluctuation in prices (as stressed by Coase), agents are assigned a production stage with expanded competence. An agent that is assigned stage 3 (here the production interval 2.00–3.00) gets additional competence, for example 1.80–3.15, which means it is capable to 'take over' production before and keep producing after the formal 'limits' of the production stage. Agents will thus have overlapping competencies that facilitate choice of trading partner and negotiation of 'who does what'. Every pair of agents find the price at the overlap midpoint,[11] so the price in a transaction where agent *A*, with competence 1.80–3.15 (stage 3), sells to agent *B*, with competence 2.90–4.05 (stage 4), is 3.025. Prices consequently fluctuate between agent pairs, which necessitates price discovery prior to transacting, as well as a choice of with whom to trade if multiple trading partners are available. The exchanged quantity is limited by the products in *A*'s stock and *B*'s funds.

Production is here implemented as a cost borne by an agent for transforming inputs into outputs. It is calculated at the time of sale as a fraction[12] of the seller's competence interval (in the case of A, 3.15–1.80 = 1.35) adjusted for 'experience' (number of previously sold products). This simulates increased productivity due to learning as agents gain experience. Production is assumed instantaneous and the product changing hands is represented by the upper bound of the produced stage. Agents act as profit maximizers by trading in order of profitability if located adjacent to more than one compatible agent, which is realistic and does not adversely affect the outcome of agent interaction. These design choices are deliberately made to facilitate trade between agents, without influencing market structure (which is dependent on transaction cost magnitude or density), since the unit of analysis in the Coasean theory of the firm is *the transaction*.

In any given round, each agent 'looks around' to identify trading partners within its von Neumann neighbourhood. If compatible trading partners are in adjacent locations, the agent contacts, in order of profitability (based on offered prices), the agents and engages in exchange. The agent maximizes its outcome of the trading opportunities by selling as many products as possible and buying as many inputs as possible, less a measure for risk aversion calculated as the amount necessary to cover the transaction costs (when applicable) for an initially assigned number of steps for continued search. (This number is set randomly for each agent at simulation initiation.) Where there are no compatible trading partners in adjacent locations, the agent scans the neighbourhood for compatible partners and moves one step in the direction of the most profitable such. Where no compatible partner exists within the agent's field of view, the agent moves in a random direction. Figure 1 illustrates agent behaviour.

Model Testing

The basic model's consistency with theory is corroborated by running validation tests under low transaction costs (Fagiolo et al., 2007; North and Macal, 2007, pp. 222–26). 'Low' here denotes a configuration that only includes whatever transaction costs may be implied by the model's basic structure, while 'high' transaction costs denotes implemented specific costs of transacting in the simulation (see further in the results section). Model tests confirm that no agent relationships appear that persist over long periods of time, which suggests that the simulation accurately represents Coase's 'atomistic competition' model. The starting point (the basic model structure) is therefore validated. Figure 2 shows typical outcome of validation tests.

I adopt a deliberately generous view of the firm as long-term (repeated) trading relationships to test the literature's varying interpretations of Coase's theory. The firm is thus signified by stable relationships between at least two agents, who avoid transaction costs through repeated exchange. In contrast to TCE, Coase's firm is simply a collection of single contracts that replace a 'series of [market] contracts' (Coase, 1937, p. 391) between parties. Hence, agents in a firm can easily part ways should the firm not, as Coase's theory predicts, produce at lower cost. Clusters of agents that remain for at least 50 rounds are considered stable enough to resemble a firm.

As the results of any individual simulation run may differ somewhat from previous ones (due to random initial attribute values, production stage assignment, and agents'

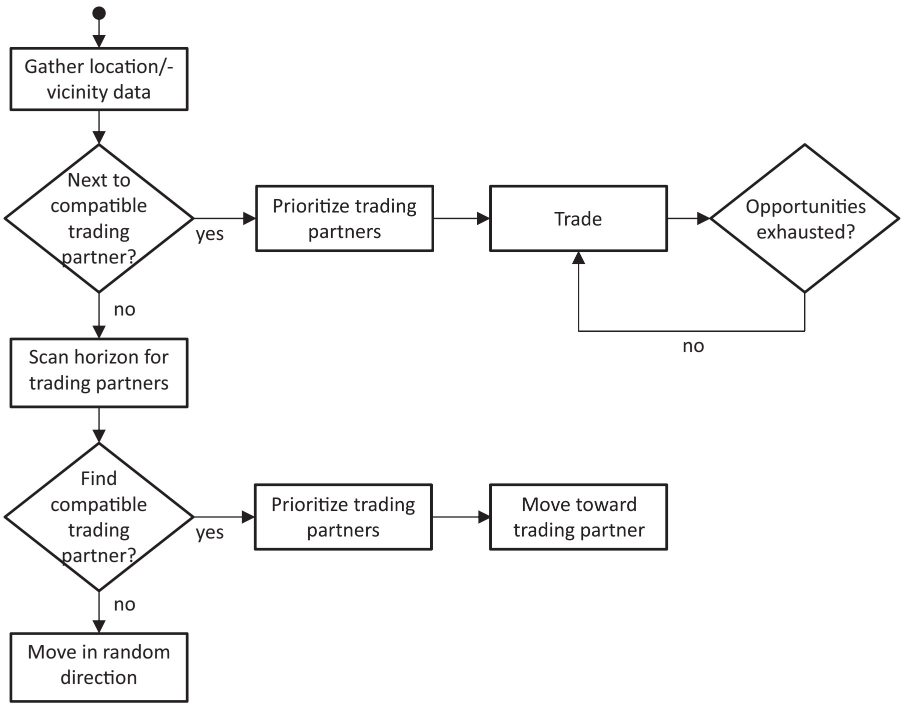

Figure 1. Decision structure with comprehensive agent behaviour

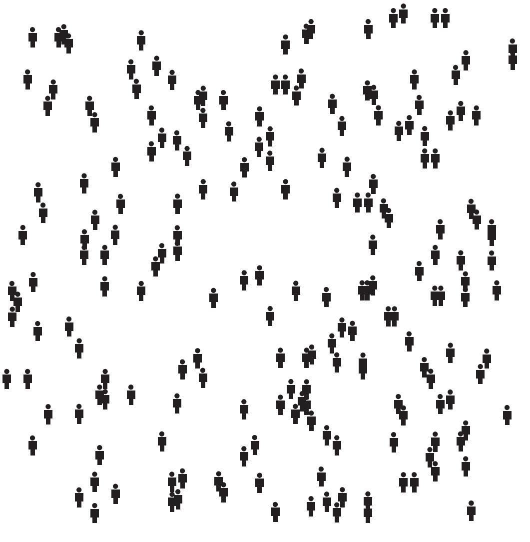

Figure 2. Typical result of the agent-based simulation model (no firms)

Table II. Results from testing, and their respective implementation and tested magnitudes

Propositions	*Implementation*	*Values*	*Conclusion*
P1: High transaction costs (TC) cause integration	Fixed, universal search cost	TC: [0.05–1.00] (0.05 increments)	Not supported
	Fixed, varied search cost	TC: [random, 0–1]	Not supported
	Cost of transacting	TC: [random, 0–2.5]	Not supported
P2: Impact of TC is higher with greater specialization, vice versa	Different production process lengths, 2–10 stages	TC: [0.05–1.00] (0.05 increments) Stages: [2–10]	Supported
P3a: High TC and entrepreneurship cause firms to form	Transaction costs according to P1, plus 'innovation' module	TC: [0.05–1.00] (0.05 increments)	Supported
P3b: Low TC and entrepreneurship do *not* cause firms to form	No transaction costs, but 'innovation' module	TC: 0	Not supported

starting positions), repeated runs produce results that converge around the mean. By running all simulation configurations numerous (100+) times, any arbitrary effects due to random spatial distribution of agents and their random initial values are accounted for. The results reported throughout this article are the definitive results rather than the specific outcome of any individual run.

TESTING AND RESULTS

Testing the propositions is partly a cumulative process. For this reason, as is common in studies using ABM (see, e.g., Aggarwal et al., 2011), this section discusses configuration and modifications made to the model during the testing phase along with reporting the results of testing the propositions. The results with configurations are summarized in Table II.

Proposition 1: The Effect of Transaction Costs

Proposition 1 suggested that, in a high transaction cost world, market actors will form relationships with trading partners that persist over time by forming clusters of multi-actor production structures or firms. The effect of transaction costs on the market structure is tested using two interpretations: transaction costs due to 'search' (Coase, 1937; Stigler, 1961) and to 'carrying out' the transaction (Coase, 1960).

Search costs are borne by an agent when moving across the market space. My models have two baseline criteria. First, when an agent engages in repeated exchange, movement is unnecessary and agents therefore do not, with in the stable relationships formed (firms), incur the cost of the market. Second, agents are able to search only if they have sufficient funds to cover another step's worth of transaction costs. Agents with insufficient funds cannot move and can therefore only transact when another agent approaches them.

In my first simulation of search (case 1), I assume a general cost of movement that affects all agents equally. I tested the range of costs for one stage of production at intervals of 0.05 from 0.05 to 1.00. The upper limit is approximately the same as an agent's income from sale less cost of input – which initially is 2.5 times average profit – per sold product.

In the second search cost scenario (case 2), I allowed the magnitude of search costs to vary across agents with an agent's individual transaction cost assigned randomly and unchanging for the model. Thus, search cost effects vary for agents as they move across the market space. Because the purpose of case 2 is to test the general effect on the market of agents with different transaction costs rather than the effect of transaction costs *per se* (as in case 1), I tested different distributions of agent search costs. A minimal distribution of randomly assigned 'personal' transaction costs between 0.05 and 0.10 resembles the fixed general transaction cost covered in the previous implementation. Therefore, I tested three separate cases with agents randomly assigned transaction costs in the ranges 0.05–0.25, 0.05–0.50, and 0.05–1.00, respectively.

The test results for all transaction cost magnitudes (case 1) and ranges (case 2) trend over time towards search costs surpassing agent profits earned through trade and therefore ultimately cause a complete standstill in the market with only passive agents. Interestingly, even at the low end of implemented transaction cost magnitudes (0.05 and up), the market eventually subsides from rapid activity to a landscape of non-moving agents. Considering how repeated trade is not subject to transaction costs, we anticipated some level of continuing activity throughout the simulation tests. But the number of agents assuming a non-moving position in the market increases over time and progressively fewer agents are re-energized (gain money) as still moving agents transact with them – until market activity eventually stops. The dampening effect of transaction costs on market trade corroborates Coase's view.

However, and in contrast to Coase's predictions, agents do not at any time or at any magnitude of transaction costs form stable relationships for repeated trade in the performed simulation tests. Agents choose to remain with a trading partner for brief periods, but the relationship does not persist for more than a few repeated exchanges. This result is unexpected, since it is obviously cheaper for an agent to conduct repeat trades with compatible agents than to wander across the market space searching. Yet this does not happen – agents in both configurations tend to stop at locations not adjacent to other actors regardless of trade compatibility. They remain in locations that are evenly distributed across the market space – with what seems to be a global maximization of space between any pair of actors. We therefore reject Proposition 1 for transaction costs implemented as search costs.

To test transaction costs as costs for 'carry[ing] out a market transaction', we implement a cost penalty on each initial but not repeated transaction. This cost applies to both parties in our implementation of the transaction with the buyer paying a higher price and the seller receiving a lower payment. Both agents bear the cost of transacting but, in these scenarios, there is no cost for moving across the market space. This implementation models Coase's (1960) view by imposing costs on *forming* a firm, but not on *maintaining* it, that is equal to conducting a transaction in the market. This implication of Coase's theory constrains an agent's ability to identify an opportunity for forming a 'firm' until already trading (see limitations).[13]

The model results show that even though transaction costs are avoided when agents engage in repeated trading, the trading relationships do not last over time. Even though agents will find repeat transactions with a compatible partner less costly, we find that they choose to 'try their luck' in the market. We therefore reject Proposition 1 when transaction costs are implemented as costs of contracting similar to our findings with transaction search costs.

Proposition 2: The Effect of Market Density

Proposition 2 argues that shorter production processes lead to more frequent exchanges and therefore smaller impact of transaction costs. I tested this proposition by running the simulation with the production process divided into several different numbers of stages while preserving the production continuum (0–5). Tests included processes from 2 (the minimum necessary to make trade possible) to 10 (twice the basic model structure) production stages, with stages of equal lengths rounded to the second decimal, and the same number of agents as previously (200). I assume in these models that agents are specialized to one stage and competency is randomly assigned. Each process configuration is run with a range of transaction search costs from 0.05 to 1.00 at intervals of 0.05.

In the simulation runs, the transaction search cost impact on an agent's movement across the landscape increases with longer production processes. Agents in a more highly specialized market suffer more severely from transaction costs and the market reaches stasis sooner. This dampening effect varies slightly with transaction cost magnitude, but is consistent for all tested magnitudes. This finding indicates that more specialized markets are subject to greater costs due to incompatibilities. In other words, the more highly specialized the agent, the higher the real transaction costs due to longer search time between transactions for compatible trading partners, leading to overall lower profitability.

In contrast, shorter production processes result in shorter search times and greater frequency in and so higher volumes of transactions with more opportunities to engage in trade and higher profitability. Thus, there seems to be a strong positive relationship between specialization intensiveness and the effect of transaction costs, where increased specialization (a greater number of stages) increases the effect of transaction costs on market trade. Proposition 2 is therefore supported.

Proposition 3: The Effect of Differing Specialization Intensities

Testing the pre-Coasean conception of the firm (Propositions 3a and 3b) requires the addition of a module that supports innovation through agents splitting tasks (see Bylund, forthcoming, for a conceptualization). Innovative agents here 'realize' a new production process is possible by splitting their production stage into separate tasks (2 to 5 tasks per stage tested). As the actors establish more specialized production processes, they act, in a sense, as entrepreneurs or innovators. To illustrate, an agent producing the third stage (2–3) 'innovates' by splitting the stage into the sub-stages (2–2.5) and (2.5–3), each of which is carried out by an individual agent specialized to the task. Thus, the model

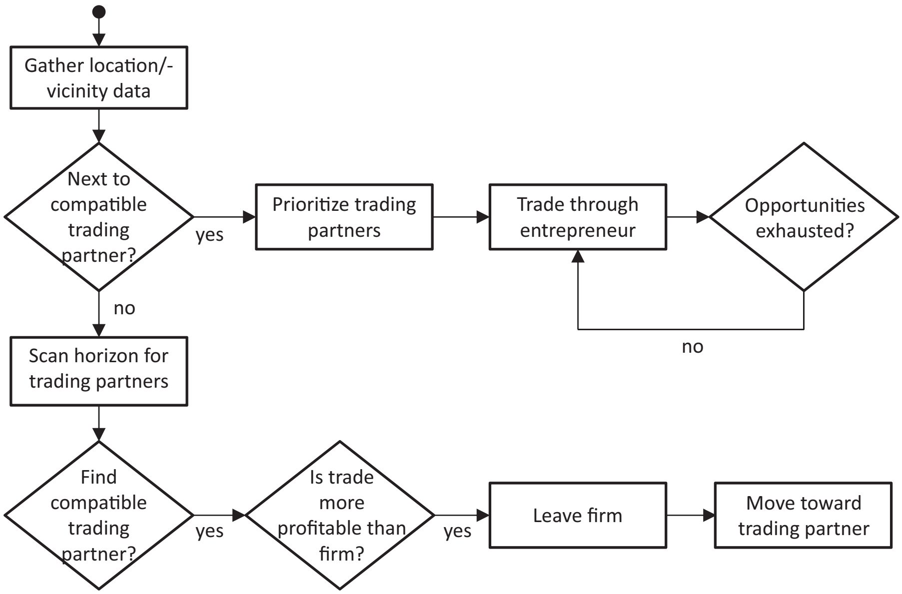

Figure 3. Simulation of decision structure with comprehensive agent behaviour for 'employees'

requires 'employment' of an agent who is competent to produce the third stage (2–3) and who can then 'specialize' in producing one of the sub-stages (either (2–2.5) or (2.5–3)).

After agents recognize the opportunity to innovate (a random, low-probability event), they look for compatible agents to produce part of the production stage and invite them to join the 'firm'. The invitation consists of an offer of expected payment calculated as an equal profit share based on the innovator's trade experience. The offer is accepted if it is more profitable than the agent's experienced market profitability up to that point, adjusted for the lesser risk inside the firm using the agent's risk aversion measure. A similar comparison is repeated every time an 'employee' encounters potential trading partners, which allows them to frequently reconsider their 'employment' and, if the firm is not sufficiently profitable, exit the firm and re-enter the market with their previous production stage competency. When an agent joins a firm, the agent is directed to a position relative to other employees and instructed not to move unless leaving the firm. The firm they join is also stationary, similar to most firms in the real world. These modifications of agent behaviour are shown in the model in Figure 3.[14]

The firm's total production ability is expanded to the joint maximum competencies of employees (the lowest lower limit and highest upper limit), and this increased collective 'competency', in addition to transaction cost avoidance, amounts to its potential competitive advantage. From a pre-Coasean point of view, this simulates the increased efficiency of comparatively more intensive divisions of labour within the firm. Where sufficient, this advantage allows the 'firm' to compete with production established through exchange and contracting in the market.

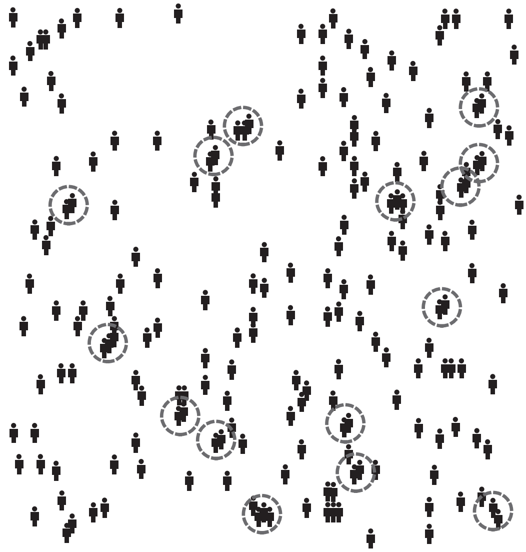

Figure 4. Agent-based simulation of 'firms' (circled) established around entrepreneurs

All the firm's exchanges are handled by the innovator (owner-manager or entrepreneur) but channelled through an 'employee', which means a firm in effect acts as one (is centralized) in terms of pricing, cost, storage of inputs, and trading experience (Coase, 1937). The innovator accumulates profits from trade, which are paid as wages after operating costs are covered. Operating costs include – in addition to production costs – the innovator's risk aversion, which is a cost of uncertainty-bearing that we may interpret as the cost of capital, organizing, etc. 'Employees' bear this cost in the market as a limitation on their trade volume (see above), but it does not apply to them individually within a firm.

Testing of Proposition 3a is carried out with the same transaction cost levels as used above, in the range between 0.05 and 1.00 at intervals of 0.05. We find that agents at all levels join innovators to form firm-like structures that persist over time; Proposition 3a is supported. The results are independent of the length of the firm's production process and, consequently, the number of agents sharing firm profits. A firm with only one innovator and one 'employee' is as likely to persist over time as is a firm consisting of one innovator and four 'employees' (the maximum in this implementation). The results are also consistent across different transaction cost magnitudes, which suggests these costs may have only a minor impact on organizing. Agents profit from joining firms and remain more profitable within the firm, as illustrated in Figures 4 and 5.

Running the simulation with no implemented transaction costs produces the same scenario and outcome: agents willingly join and tend not to leave the innovator's firm. The only noticeable difference to the above is that the low transaction cost simulation shows considerably smaller profitability differences between agents in firms and in the market. Testing of the agent-based models shows support for Proposition 3a but does not support Proposition 3b.

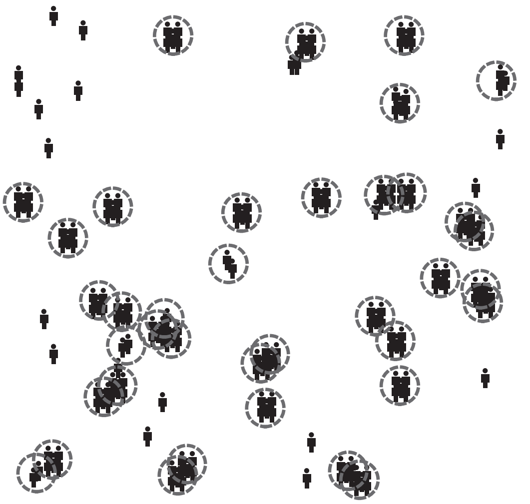

Figure 5. 'Firms' (circled) at a late stage in the agent-based simulation

DISCUSSION AND CONCLUSIONS

This study compares theory and simulates firm formation in an agent-based model (ABM) of Coase's (1937) original transaction cost theory and the earlier division-of-labour/specialization theory of firm formation that Coase sought to replace. The Coasean process has not previously been tested using agent-based simulation and the theoretical contextualization used here provides additional import and relevance to the article's contribution. The results suggest a shortcoming in Coase's theoretical system that may explain why his theory has been sidelined – if not fully replaced – by Williamson's TCE. Williamson's approach appears, to some extent, to reintroduce the concept Coase sought to remove from the theory of the firm: specialization. Specialization from the division of labour was a focus of theorists prior to Coase and it appears more closely related to transaction costs than Coase acknowledged. My findings in this study provide additional evidence of the explanatory power to specialization in firm formation.

The tests fail to corroborate Coase's explanation that market frictions, by making it costly to discover relevant prices, cause integration (Proposition 1), raising questions about its veracity. Agents in the simulation choose the open market even though it is less costly to repeat exchange with trading partner(s). A possible explanation of this effect may be that agents prefer to exhaust profit opportunities in each round (as would be expected from profit maximizers), leaving as few profitable transactions undone as possible. Unless the selling agent has access to more inputs from a supplier, and the buying agent has access to customers to increase funds through sale, the agents seem reluctant to establish a continued relationship. As Coase (1937) suggested, the economic rationale for integration exists for *full* processes, but this does not necessarily mean the rationale is applicable for partial processes.

This is an interesting puzzle that has not been sufficiently examined in the literature. Transaction costs apply to all market transactions, even *between firms*, which makes partial integration of production processes subject to transaction costs. The effect of transaction costs on resource allocation is consequently limited, as Coase assumes. But this is not the case under full vertical integration, in which case inputs move smoothly with costless transactions through the whole production process within a single firm. The effect of complete transaction cost avoidance should thus arise only when there is no longer a market imposing such costs on transacting (cf. Barnett *et al.*, 2005; Block, 1977). But this suggests a possible flaw in Coase's transaction cost approach – firms cannot 'reproduce' the market's allocation if *all* transactions have been integrated and the price mechanism is fully superseded. This perhaps explains why Coase (1937) resorts to 'competition' as an important factor limiting integration (Bylund, 2014).

One way to avoid this problem is to assume a stronger distinction between firm and market than Coase is willing to accept. Another, but more limited solution, may be possible by adopting a clear distinction between market (weak) and employment (strong) contracts, but this too was never Coase's intent. A third solution would be to see the firm as an implementation of a different resource allocation or specialization – in line with the pre-Coaseans and TCE, and a view that Coase's approach does not support and that Coase explicitly rejects (Coase, 2006).

Strangely, Coase pays no attention to whether trading is *profitable* (cf. Zajac and Olsen, 1993). As noted, a cost to market search combined with profits from transacting seems to bring about an even distribution of agents rather than bring them together, which contests Coase's predicted outcome. This may be a result of implementing transaction costs specifically as search costs, which penalizes agents who search but do *not* trade. This appears quite different from how Coase's theory is often understood (as a cost specifically of *transacting*), but this may in fact be an intentional implication of the theory. Considering the discussion above, market actors who intend to trade under Coase's system, but find the discovered prices or other contract terms unfavourable, can choose not to go through with the transaction – but they nevertheless bear the costs of price discovery through search. Whether or not they choose to go through with the exchange is a separate matter.

We find support for an implicit relationship between overall market specialization (which, in the pre-Coasean discourse, amounts also to a measure of market density) and the impact of transaction costs (Proposition 2). This is interesting, since Coase's theory challenged the view that firms are defined by a different kind of division of labour. It is also interesting as it suggests a rationale for reintroducing the specialization concept to explain the firm, perhaps as a complement to transaction costs. Indeed, the tests show how the specialization intensiveness correlates with the effect of transaction costs, where the functioning of the specialized market's complex production processes is more vulnerable to costly market exchange. Hence, the more specialized the market, the more it appears to suffer from transaction costs.

More testing is needed to establish this link – especially any causal relationship – but the correlation should be surprising considering how Coase positioned his theory in contrast to the then-dominant division-of-labour theory. (This, however, falls outside the scope of this article.) Perhaps of greater interest to modern scholars in the theory of the firm, this fact also suggests an explanation for the comparative influence and contribution of TCE, which focuses on costs due to guileful exploits of specific assets – *co*-specialization through investments intended to support a particular transaction – rather than actors' price discovery. TCE's focus on relationship-specific investments is not the type of specialization used by pre-Coasean theorists (division of labour or task-splitting), but is sufficiently similar to be (perhaps limitedly) correlated in our tests as well as in empirical studies. To the degree that Williamsonian asset specificity entails a form of specialization, it should be interesting to test TCE's predictions under different market specialization regimes and densities. This is also a potential implication of this simulation model, as it can be argued that the simulation model above indirectly invokes a Williamsonian logic of opportunism, though explicit costs of opportunism are not implemented, in testing Proposition 2.

This hypothetical connection is reinforced when testing the effect of Coasean transaction costs where firms are defined by their utilization of a more intensive division of labour (Proposition 3). The results suggest that firms under these assumptions emerge *regardless* of transaction cost magnitude. The implications are interesting: firms emerge with similar frequency with or without transaction costs of magnitude, which offers no substantial support for Coase's transaction cost theory. But agents *within* firms generally earn lower profits under low transaction costs (Madhok, 1996), though this changes as the firm's production experience increases and its per item production cost therefore (marginally) drops. High transaction costs consequently correlate with firm profitability. These results, however, apply only in the short term, since long-term profitability for a firm depends on the 'size' of the remaining market. This is a possible limitation of this model as it takes no account of existing market size (supply of inputs, demand of outputs) when agents decide whether to join an innovator, which means the number of firms in the simulation model tends to increase until there are only very few agents who are unemployed and therefore left to trade with in the market. At this point, firms (since they do not move) can no longer trade and therefore make no profits. As the results suggest, Coasean transaction costs correlate closely with firm *profitability* but not with firm *formation*, which Coase intended to explain This supposition is little studied in the literature, and raises questions about the implications of 'survivor bias' (only sufficiently profitable firms appear in the data) in empirical studies.

The results show, however, that as firms have greater ability (expanded production interval) they tend to pay less for inputs and get higher prices for outputs than atomistic agents – the former at least in line with Coase (1937). The profitability of firms remains somewhat higher than for atomistic agents throughout the simulation runs, even when virtually the whole market is integrated in firms or exchanges can take place no longer. As in previous tests, markets with high transaction costs tend to reach a standstill sooner than markets with low transaction costs – despite firms' comparatively high profitability under high transaction costs.

In summary, the results suggest that Coasean transaction costs are not sufficient to explain firm formation (Proposition 1); that they are not necessary (Proposition 3); and that there is a seemingly strong relationship between the effect of transaction costs and specialization in the market (Proposition 2), despite Coase's formulation of the former as a distinct alternative to the latter. This may in turn signify Williamson's contribution to transaction cost analysis as a *retraction* from Coase's position. Perhaps Coase was too quick to dismiss specialization.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

While these implications are interesting and important, the results hinge on the accuracy of the model, its implementation, and interpretations of both theory and simulation design similar to other modelling studies (cf. Davis et al., 2007). This provides future research opportunities to contribute to and increase our understanding of the results here indicated by addressing and attempting to overcome the potential limitations of this study.

Coase's definitions are imprecise and his theorizing at times ambiguous, which necessitates interpretations susceptible to debate. For these reasons, the transaction cost interpretation in this article relies on Coase's original work (Coase, 1937, 1960), his comments on interpretations and uses of his theory (Coase 1988a, 1988b, 1988c), his explicit opposition to Williamson's approach (Coase, 2000, 2006), and third-party contextualization of the Coasean theory (e.g., Bylund, 2014, forthcoming; Jacobsen, 2008). In addition, the model adopts the common interpretation of transaction costs as costs of search in the market (Stigler, 1961). Another possible limitation of the simulation model is the use of Coase's own broad definition of the firm, which is much less integrated than other theoretical views of the firm (Propositions 1–2). While important to the testing of Coase's theory here, his notions of the firm as simply a 'reproduction' of the market's allocation of resources internally, easy reversion to market if the firm is not successful, and de-emphasis of employment contracts may understate the nature and complexity of firm formation and operation in the real world. Future studies might test a more elaborate definition of the firm to corroborate the findings in this article.

It may also be the case that the model's structure insufficiently resembles the type of market assumed by Coase when developing the theory. The basic model of 'atomistic competition' is structured based on Coase's statements and is confirmed to produce the outcome predicted by Coase's theory. Due to its lack of detail regarding, for example, the assumed characteristics and behaviour of market actors (later introduced and operationalized by Williamson), it is possible that the models fail to capture aspects of the market that Coase implicitly assumed. But we should feel comfortable from our findings, that this configuration does not generate firms. Future research could contribute to our understanding of transaction cost theory by implementing and testing Williamson's TCE, perhaps comparing it with Coase's theory, with specialization, and with other competing theories. Other types of simulation or formal modelling may also prove useful when testing the formation of firms and evolution of market structure.

The scope of the models studied was limited and intended only to test Coase's theory of firm formation in contrast with relevant competing theories. The models, therefore, lack production structures that indirectly compete with each other through demand for inputs in factor markets; they also disregard consumer demands and shifts in preferences. Trade between firms is not satisfactorily implemented to accurately reflect an advanced exchange market, partly due to the fact that firms do not move across the market space. Similar studies could be conducted using different models of the market, such as addressing competition for resources between differently configured production processes, testing the impact on production by transaction costs under changing consumer preferences, addressing how imperfect and varying abilities of management affect firms and the market, and testing the impact of transaction costs under different market structures such as monopoly, oligopoly, and perfect competition (with perfect information and thus no vision limitation).

Future studies might also use a thicker conception of specialization than TCE's asset specificity to provide important insights about market structure and the applicability, scope, and possible overlap of contemporary approaches and theories. Also, the simulation model used here grants only very limited gains[15] from specialization as a result of the increased production interval when 'employing' workers. Even so, these gains are sufficient for firms to emerge. This suggests that specialization may be an interesting avenue for further research.

It would also be interesting to investigate the implications of profitability, pricing power, and price differentials – concepts which are only cursorily addressed in this study – along with implications of profit and pricing strategies. Testing the impact of communications technology and infrastructure, different impacts of incremental or disruptive innovation, and organizational learning could also provide valuable insights, as would elaborate testing of the role of the entrepreneur in firm formation and as a 'driving force' in markets subject to different transaction cost regimes. There are also implications of policy on entrepreneurship, firm formation, and innovation, that relate to the conditions of firm organizing, economic and political incentives for integration and expansion, and different organizational forms. These are but a few examples of theoretical issues and extensions that this article may inspire future scholars to address in this fertile research area.

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NOTES

[1] Interestingly, Coase's theory rejects a core component of, but still draws from, the work of division-of-labour view theorist E. A. G. Robinson (Jacobsen, 2008), who also influenced Edith Penrose and thus indirectly the resource-based view (Jacobsen, 2011).

[2] See, for example, Bylund (2011, forthcoming), Lewin (2011), and Foss and Klein (2012) for recent theories sharing several core assumptions with pre-Coasean theories.

[3] The model was implemented and tested in the software program AnyLogic version 6.7. This software provides a graphical user interface with a set of standardized functions and support for agent-based simulations.

[4] The model's configuration was validated according to the validation process described below.

[5] A torus space is a never-ending space with a limited number of positions, in this case 10,000 (100 × 100). Its width and height of 100 means there are 100 positions available left–right and top–bottom

across the space, where the 101st horizontal position (one step to the right of the 'boundary') is also the 1st position (on the left). Likewise, one step left of the 1st position is the 100th position. The same applies 'vertically'.

[6] A possible effect of density may be on the frequency of situations occurring where an agent can choose to trade with several agents. While this may marginally affect the agent's profitability (through allowing choice of the better trading partner), the *frequency* of this situation occurring is rather irrelevant when investigating the effects of different levels and implementations of transaction costs and specialization. As the aim of this study is to test Coase's transaction cost theory, which emphasizes costs of search and price discovery, a too dense market would undermine the model's usefulness. See further below.

[7] Agents producing the first stage have their input stocks refilled the round after depletion, and last-stage producers sell their output the round after procurement of inputs. This increases the model's realism as compared to unlimited supply/automatic sales. Conducted validation tests show that this configuration avoids severe distortions, while not affecting simulation results.

[8] Assuming perfect information (unlimited vision), as in Coase (1960), would not necessarily increase agents' ability to trade with their respective 'best' trading partners, for two reasons. First, perfect vision may entail aiming for agents that also move, so that preferred trading partners become moving targets, and so affect exchange negatively. Second, the best trading partner *j* for any agent *i* does not necessarily mean *i* is the best trading partner for *j*. Best-partner reciprocity is not assumed by Coase, nor in this article.

[9] As identified by Williamson (1998), Coase analyses transaction costs on two levels: the institutions of governance or the 'play of the game' (Coase, 1937); and the institutional environment (mainly the legal framework) or 'rules of the game' (Coase, 1960). Only the former is directly relevant to our study of the formation of firms, as we are interested in the causes of firm creation regardless (at least at this point) of the institutional framework. We therefore concentrate on Coase's analysis of the effects of transaction costs on organizing in the 1937 article.

[10] The simulation model has been validated under atomistic competition. As the objective here is to study firm formation, this configuration is sufficiently consistent with Coase's theory. Alternative configurations of the model are potentially interesting, but beyond the scope of this article. For instance, endowing agents with perfect information ('seeing' the whole market) simulates the zero-transaction cost world in Coase (1960), and can therefore be used to test cross-market resource allocation and the effects of legal institutions and rulings of judges.

[11] Since our concern is not price determination, but to what extent integration is due to costs of discovering real prices, there is no reason to include a full-scale price negotiation module. The fact that prices vary, and thus must be discovered, is sufficient for our purposes.

[12] The cost of production simulates decreasing returns to experience by starting at 60 per cent of the agent's competence interval and is then adjusted downwards by 4 × log of agent's trading experience. Costs cannot go below 25 per cent. All agents have the same production cost function, which suggests that they are behaviourally consistent while (potentially) differing in terms of profitability. Our sensitivity analysis indicates different cost levels have little to no effect on transactions, which is expected since agent behaviour is structured identically and all agents exchange for profit; higher production cost means smaller overall profit, but does not otherwise affect choice of trading partner or imply that exchange is unprofitable.

[13] This raises a question regarding Coase's framework as it is here implemented: is it reasonable to assume the transaction cost is the same for simple market trade and for long-term contracting that establishes integration? (cf. Coase, 1937, pp. 391–92).

[14] The fixed firm position is, by design, to minimize model complexity and thus avoid potential programming errors. It implies that firms cannot trade with other firms (unless located adjacent to each other) and that they depend on moving agents to trade with them (supply inputs and purchase outputs, unless the firm comprises the first/last stage). Neither implication affects the study of firm *formation* or the profitability of individual transactions. Firms' reach are maximized by placing 'employees' diagonally from the innovator, which increases the likelihood for trade with moving agents.

[15] Compare the example from Adam Smith's *Wealth of Nations*, where one worker could 'make one pin in a day, and certainly could not make twenty' whereas through the division of labour in the manufacture 'ten persons . . . could make among them upwards of forty-eight thousand pins in a day' (Smith, 1976, pp. 8–9). The gains from the division of labour in Smith's example are therefore a productivity increase by between 240 and 4800 times.

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