AUTOMATION-INDUCED RESHORING:

An Agent-based Model of the German Manufacturing Industry

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The concept of 'Industry 4.0' signalises the rise of innovative manufacturing technologies, including industrial robots. Wider applicability of robotic automation and higher efficiency of production processes shift the profitability analysis of strategic relocation decisions. Despite the technological feasibility, diffusion of technology lowers the profitability threshold for robots. Consequently, competitive labour cost advantages, formerly motivating manufacturing firms to offshore production become less relevant. In fact, robots additionally gain importance in the case of shifted global economic realities, such as stricter environmental regulation on global trade and the convergence of the global wage gap. However, the heterogeneous levels of automation among manufacturing firms have not been taken into account when studying the macroeconomic phenomenon of reshoring. This study adds novelty by offering an agent-based perspective which has allowed insights on how the behaviour of firms, guided by simple economic rules on the micro-level, is dynamically influenced by their complex environment in regard to relocation, decision-making hypotheses. Testing various variables sensitive to initial conditions, increased environmental regulations targeting global trade and upward shifting wage levels in formerly offshore production locations have shown to be driving and inhibiting mechanisms of this socio-technical system. Therefore, the dynamic demonstrates a shift from predominantly cited economic reasoning for relocation strategies towards sustainability aspects, pressingly changing these realities on an environmental and social dimension. The popular debate is driven by increased environmental awareness and the proclaimed fear of robots killing jobs. In view of reshoring shaping the political agenda, interest in the phenomenon has recently been fuelled by the rise of populism and protectionism claiming to "bring jobs back home".

Keywords: Sustainability, System dynamics, Agent-based computational economics, Socio-technical innovation, Automation, Reshoring

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1. Introduction

Industrial robots are one of the most pressing innovative manufacturing technologies conceptualised as 'Industry 4.0'. Commonly referred to as the fourth industrial revolution, technological advances allow for wider applicability of robotic automation and higher efficiency of production processes. Diffusion of the technology additionally adds to a more comprehensive economic accessibility. (Kroll *et al.* 2018) As a consequence, competitive labour cost advantages increasingly lose their importance when it comes to strategic relocation decisions. Changed economic realities induced by rising levels of industrial automation are thus considered key drivers in regard to the reshoring phenomenon observed in manufacturing industries. (Spaeth 2017)

Informed by previously developed economic models, this research attempts to replicate the observed regularities in order to add to the understanding of how related sustainability aspects have an impact on reshoring production.

Previous studies have mainly focused on conceptualising reshoring, identifying technological innovation as a key driver (Wiesmann *et al.* 2017). This study adds novelty to the extant literature by offering a different methodological approach towards the topic under study. Agent-based modelling allows for heterogeneity of agents on the micro-level, a depiction of how their behaviour is influenced by their complex environment, as well as insights on how these dynamics aggregate into phenomena on the macro-scale (Wilensky & Rand 2015). Informed by previously developed economic models, the agent-based approach towards this study accounts for heterogenous levels of technological advancement among manufacturing firms in an attempt to replicate observed economic realities thus adding to the understanding of how automation induces reshoring. The computed model is then utilised to explore the role of environmental and social sustainability aspects within the dynamics of this complex system.

In order to anchor the topic within a real-world setting, the case of the German manufacturing industry was selected. The choice was guided by the fact that there are a number of examples categorised within this industry which are pioneering the field. This includes the German automotive industry, being a forerunner when it comes to automating production processes (Wolter *et al.* 2015). A company-specific example is the so-called 'Speedfactory' located in Germany. Operated by the German sportswear brand *Adidas*, the robot-powered production of sneakers has been celebrated as a reinvention of manufacturing (Wiener 2017).

Hence, a number of initial parameter values are taken from national statistics, but the model could in principal be used to study the reshoring phenomenon through the lens of any country.

The widely discussed topic of reshoring production processes has recently gained additional attention due to the emergence of populism and nationalistic protectionism claiming to "bring jobs back home" (Rose & Reeves 2017). In general, the societal discourse is charged with a negative connotation, namely that robots eliminate jobs (Frey & Osborne 2017). It is not a coincidence that the Oxford Dictionaries (2019) exemplary demonstrate a common usage of the word 'automation' as "unemployment due to the spread of automation". Leaving out domestic dynamics in society, the model focuses on wider sustainability aspects of reshoring production facilities. The results demonstrate how shifts of economic realities are driven by measures such as stricter environmental regulations and a more thorough awareness in regard to the social responsibility of globally fragmented supply chains.

Offering an agent-based perspective anticipates understanding of how heterogeneous degrees of technological innovation of players on the micro-level influence complex macroeconomic phenomena.

The aim is to demonstrate how dynamically changing realities require rethinking key drivers of strategic relocation decision-making.

2. Background

2.1. Research problem

Industrial labour comprises classic production work meaning "the manufacturing, processing, or assembly of a physical product for sale on the economic market" (Holzinger 2010). Up until the first decade of the 21st century, the shift in global production regularities from the perspective of the Global North was significantly characterised by the phenomena of offshoring production typically to countries of the Global South (Blinder 2006; Martínez-Mora & Merino 2014). The development of highly complex supply chains across multiple countries has also been a result of the economic paradigm holding the promise of continuing growth (Raworth 2017). Traditionally, the manufacturing location has been evaluated by four main factors namely cost, time, quality, and flexibility (Feenstra 1998). Reasons for offshoring manufacturing processes were predominantly driven by a significant reduction of costs enabled through the exploitation of labour-arbitrage opportunities, other competitive cost advantages of the respective region, convenient access to natural resources, weaker legal restrictions, increasingly efficient freight systems, and the emergence of preferential trade agreements (Tate *et al.* 2014; Hammes 2016; Rose & Reeves 2017). On this account, the Global North proliferates itself as the control centre of the global economy, whereas China in particular, as well as other countries of the Global South, have been illustrated as one gigantic factory (Burmeister & Glockner 2009). Common business strategies are increasingly challenged as environments and their conditions change (Tate *et al.* 2014). The unbalanced constellation between North and South has been proven as short-lived as countries on the periphery are developing into new economic centres of their own (Holzinger 2010). This development has started to narrow the gap of global wage differences (Fratocchi *et al.* 2016).

Additionally, spatial proximity to the respective customer base increasingly gains importance mainly due to competitive conditions in view of more flexible and faster adaptation to trends (Martínez-Mora & Merino 2014). Another observed trend is the consideration of consumers' individual demands in the finalising steps of production. The so-called concept of 'prosumption' is gauged to become a new key performance indicator which is yet again a reason for locating production close by. (Tate *et al.* 2014)

'Offshoring' has been the predominant business theme, in terms of strategic decision-making of manufacturing locations, mainly due to significant labour cost advantages (McIvor 2013). It is defined as "the performance of a task in a country different to from where a firm's headquarters are located" (Wiesmann *et al.* 2017, p. 6). In the case of Germany, 8 % of firms within the manufacturing industry have relocated production activities abroad, representing one of the lowest reshoring rates in Europe (Jäger *et al.* 2016). Increasingly identified environmental, social, and economic challenges connected with offshoring versus anticipated benefits of local production has led to reconsiderations on the matter and the emerging phenomenon of 'reshoring' (Fratocchi *et al.* 2014). The term is most often utilised to describe "the movement of offshore production back to its previous location" (Wiesmann *et al.* 2017, p. 6). However, reshoring seems to be a unidirectional phenomenon from low- to high-cost environments (ibid.). In recent years, public debate around protectionism has additionally triggered academic interest in the field of economic localisation in the Global North. The extant literature mostly focuses on conceptualising the phenomenon whilst trying to understand the motivating drivers and barriers (e.g. Fratocchi *et al.*, 2014; Kinkel, 2014; Behn, 2015; Zanoni *et al.*, 2015; Bals *et al.*, 2016; Foerstl *et al.*, 2016; Di Mauro *et al.*, 2018). Changed global market realities along with technological innovations are primarily proposed as key determinants of the socio-technical phenomenon of reshoring (Fratocchi *et al.* 2014). Historical examples show how ground-breaking technologies have the power to entirely change labour market regularities. Examples include tractors substituting physical muscle power, cash machines displacing human bank tellers, or computers versus book-keeping (Autor 2017). Scholars and practitioners alike proclaim the so-called 'Industry 4.0' which describes a set of complex automation innovations believed to be the new game changers (e.g. Brzeski & Burk, 2015; Wolter *et al.*, 2015; Varoufakis, 2016; Brzeski & Fechner, 2018). Contemporary symbols of progress include industrial robots increasingly enabling the automation of production processes. Proclaimed benefits include the achievement of superior quality, more reliability, higher efficiency and therefore increased productivity, or the application in hazardous environments (Sirkin *et al.* 2015). An analysis of robot utilisation shows that 29 % of industrial companies in Germany have already introduced some level of automation (Jäger *et al.* 2016). This development increasingly fuels concerns among the general public regarding the potentially negative impacts which are mainly related to the substitutability of jobs (ibid.). Several authors have tried to predict the effects of increased automation on the labour market. Disagreeing opinions cover a broad spectrum reaching from the assessment that there will not be a significant effect on employment, the call for changed skill requirements, to the doomed scenario of vast unemployment. (e.g. Jäger *et al.*, 2016; Frey & Osborne, 2017; Alabdulkareem *et al.*, 2018)

Next to predominantly cited economic variables, automation-enabled reshoring is also driven by reasons related to sustainability seemingly playing an increasingly important role in regard to strategic relocation decisions (Ashby 2016).

Globally fragmented supply chains entail a range of environmental issues including environmental destruction caused by manufacturing processes under weak monitoring and legal frameworks (Gray *et al.* 2013). The proximity of production locations increases the likelihood of enforced environmental regularities through improved monitoring possibilities (Fratocchi *et al.* 2014). Disparate locations of the consumer base and production facilities require the transportation of the produced goods to the market. Global trade, which mainly drives the industrial container shipping industry and is an activity impacting the environment on multiple levels through air and water pollution, contributes to climate change, and direct negative effects on biodiversity (Andersson *et al.* 2016). Thanks to a higher visibility in the public media, the effects of globalised production are increasingly scrutinised in society which shapes the political agenda (Gebler *et al.* 2014). With rising environmental awareness, political action could lead to the achievement of changed taxing landscapes, making the introduction of a CO_2 tax a likely scenario. If such a tax were to have a notable effect on prices for fossil fuels, increased transportation costs could then arguably be a strong incentive triggering a need to reconsider the manufacturing location decision (Tate *et al.* 2014).

Often hidden behind the promise of economic development, the complex interdependencies of globalisation can play a detrimental role in facilitating social injustice in producing countries typically located in the Global South (Brummitt *et al.* 2017). Despite the common assumption that enslavement is extinct and made illegal all around the globe, modern-day slavery continues to be a burning issue in the context of exploiting low-cost labour (Bales 2004). Modern slaves forced by economic dynamics keep the costs low and the return on investments high. Social responsibility along the supply chain has gained some attention but major disruptions of the global supply chain regularities have mainly been a result of international politics (Rose & Reeves 2017). Entailed risks for production operations concern the volatility of political environments, as well as shifts in international relations potentially affecting trade agreements (Tate *et al.* 2014). A revival of protectionism is mainly fuelled by domestic political interests such as the popular promise of creating jobs “at home”, improved resilience, ensuring resource security, and regaining economic independence (Baroncelli *et al.* 2017).

Just as offshoring production is mainly driven by competitive cost advantages, so are economic forces in turn key drivers of reshoring (Fratocchi *et al.* 2014). Reshoring production consequently means that surcharges specific to the production abroad are nullified. Such additional costs include taxes abroad, intermediaries, transportation costs, import tariffs, storage costs, and shares for inventory (Gray *et al.* 2013). Fluctuating oil prices have for instance jeopardised globalised trade before (Holzinger 2010). Further, a more predictable and balanced financial flow could be acquired due the elimination of being dependent on the volatility of currency exchange rates (Tate *et al.* 2014). Proactively minimising the environmental and social impact of business operations is even considered a value-adding activity in view of economic performance (Preuss 2005).

2.2. Research aim

As previous models lack the role of heterogeneity in regard to technological advancement, the research question seeks to add to the understanding on how heterogenous levels of automation among manufacturing firms have an impact on reshoring production. By adopting an agent-based perspective, the research further aims at gaining insights on how the socio-technical phenomenon of automation-induced reshoring is influenced by different variables connected to sustainability.

Increased awareness among consumers denounces the impact of global trade on the environment as a consequence of fragmented supply chains. With public opinion ideally shaping the political agenda, the introduction of a CO_2 tax does not seem too far-fetched.

> Hypothesis 1: *Rising transportation costs outweigh the competitive cost advantages of offshore production, allowing the diffusion of automation technology to drive reshoring faster.*

Emerging markets developing into economic centres of their own increasingly challenge the phenomenon of offshoring, which is mainly owed to competitive labour cost advantages typically in countries of the Global South. In addition to changed economic realities which has already led to diminishing differences between global wage levels, increased technological efficiency results in a lower quantity of human labour being required. Thus, it can be hypothesised that labour costs might lose their importance as a key performance indicator.

> Hypothesis 2: *It is suggested that increasing wage levels in former offshore destinations challenge the reasoning for continuing to produce abroad. This would be particularly true when labour costs and costs for robots converge. Consequently, firms would decide to reshore production to the home country.*

3. Methods

3.1. Agent-based modelling

Agent-based modelling (ABM) allows the study of aggregate regularities emerging on the macro-level, whilst originating from the micro-behaviour of individual units (Wilensky & Rand 2015). The named methodological approach is utilised for this study in order to test how heterogeneity of technological innovation can impact the reshoring decision of production processes.

Crucial features of an ABM include agents, an environment, and rules. Agents could represent any autonomous entity. They are equipped with heterogeneous characteristics which allow for individual and dynamic behaviour. (Wilensky & Rand 2015) In this particular model, agents represent firms running production operations. Initially, each firm is configurated with an individual set of economic parameters, as well as varying technological state-of-the-art. Organizational performance and technological advances are evaluated at the end of each business cycle which typifies one time step. Firms are additionally capable of adapting to changes in their environment (Heckbert *et al.* 2010). A modelled environment is the space in which agents act. Such an environment could replicate a specific geographic location or alternatively be of a more abstract structure (Wilensky & Rand, 2015). The environment represented in this study maps out the German manufacturing industry divided into a domestic production location and an unnamed location abroad. Rule-based and analytical functions define the dynamic decision-making of the autonomous agents in interaction with their environment (Epstein & Axtell 1996). Thus, firms make strategic relocation decisions, either back to Germany or abroad, by comparing the economic profitability of their current production location with the alternative conditions.

3.2. Conceptual models

One of the earliest examples of utilising ABM in the field of economics is a microsimulation of the Swedish economy (Eliasson *et al.* 1976). More recent examples include the ‘EURACE project’ which is an attempt at constructing a closed macroeconomic model of the whole European economy (Deissenberg *et al.* 2008) or the modelling of the Icelandic credit network economy which aimed at studying the housing boom and bust (Erlingsson *et al.* 2014).

The model for this thesis was inspired by the aforementioned approaches and follows the suggestion by Janssen (2005), LeBaron & Tesfatsion (2008), and Neugart & Richiardi (2012) on future research in the field of modelling the dynamics of economic markets diffused by technological innovation. Modelling the interplay of agents in a socio-technical system has been indicated by van Dam *et al.* (2013). Rose & Reeves (2017) particularly proposed the exploration of how advanced manufacturing technologies such as robotic automation could be a game changer for global economic realities. Even more specific, Tate *et al.* (2014) suggested the development of different scenarios by varying values of parameters in order to explore affected cost implications driving or inhibiting reshoring. Specifically, the parameters of labour and shipping costs have been mentioned in the context of such a sensitivity analysis (ibid.).

Previous models have ignored the role of technological heterogeneity which is an identified gap this study seeks to close. For fulfilling this purpose, an agent-based model was developed using the common open source platform *NetLogo* (Wilensky 2019). This choice was mainly guided by the interdisciplinarity of the research approach requiring a programming tool with a low threshold.

3.3. Computed model

3.3.1. Model description

An ABM was developed with the purpose of answering how automation induces reshoring dynamics. Agents are defined as firms representing the heterogeneous micro-level under study adopting the perspective of the German manufacturing industry. Initial values therefore match real-world data of the German economy where it seemed appropriate. A comprehensive list of modelled variables, including a detailed description of their meaning, reasoning for the chosen values, the initial values, as well as their respective units, can be found in Table 1.

Initially, a certain number of firms are created. The geographic distribution of production locations is either Germany or an abstract offshore destination assigned at random. This model design intends to represent the typical North-South divide of globalised supply chain regularities. Firms are further equipped with company-specific parameters which depend on each other as well as aggregate in calculations over time. In order to allow for heterogeneity, the randomness of the initial values of the seed capital, the maximum level of automation, as well as the current level of automation is implemented. The seed capital defines the size of each firm. For simplicity, it is assumed that each firm produces only one type of product. Each product type has inherently different extents of maximum achievable automation which adds yet another layer of heterogeneity. Consequently, the maximum level of automation received at the start stays fixed throughout the simulation runs. This condition defines the agency of firms in regard to their maximum attainability of automation.

Poorer economies tend to have systemically thwarted production processes due to reasons such as institutional and infrastructural weakness (Brummitt *et al.* 2017). In order to mimic economically strategic decision-making, firms with a low potential to shift production towards a high degree of automation in the near future are naturally more likely to move production abroad motivated by cost-efficient labour wages. Thus, the model is designed to place the share of firms with the lowest degree of expected maximum automation abroad. Another facet of the design of this parameter is that the maximum degree of automation can never reach 100 % as it is assumed that tasks requiring high-skilled labour will always be required. Examples include setting up or maintaining robots. As soon as the maximum level of automation for that specific product pursuant to the specific firm is reached, the investment for research and development (R&D) drops to zero.

The technological performance of robotic systems however rises in proportion to investment in R&D up until this maximum value, which is an assumption equally made by other earlier studies (e.g. Jäger *et al.*, 2016). Only a defined share of firms introduced some sort of automation to start with which is again supposed to reflect heterogeneity in regard to technological progress thus far. In order to test the widely proclaimed fear of automation eliminating jobs, the parameter robots-kill-jobs-threshold defines the level at which automation eradicates low-skilled-labour. Levels below this threshold are additionally used to define the ratio between robots, low- and high-skilled labour employed. The level of automation equals the ratio of robots utilised, whereas the ratio of low-skilled and high-skilled labour is an initially defined variable. Combined, these variables add up to a value of one which is useful for calculating the division of labour.

Share of low-skilled labour, high-skilled labour, and robots must fit the allocated budget for labour costs. As commonly calculated in microeconomics, the planned budget for paying labour is a variable share of the capital defined at the beginning of each time step, or business cycle (Perloff 2016). The rest of the capital is needed to purchase raw materials and represent fixed costs here. For transforming raw material into products, labour units are needed which comprises the actual number of robots, low-skilled and high-skilled labour. Hence, the disposability of labour costs, the proportional shares of labour, and the respective wages define the floored number of labour as labour units are typically discrete. This is the reason why the planned and actual costs for labour differ slightly. Besides labour costs, robots generate costs for automated production which could represent energy bills or maintenance costs. Next to costs, the productivity differing between human workers and robots has an effect on the produced output of goods. It is assumed that the wages in offshore production locations would be lower than in Germany. This is why the budget for labour costs would allow a higher number of employees which then translates into greater output as it is assumed that the productivity of labour is an international standard.

Table 1: Modelled variables

Variable	Description [and reasoning for selected value]	Initial value	Unit
number-of-firms	describes the total number of firms representing the modelled economy [random]	100	firms
firm-size	defines the size of the firms depending on their working capital [random]	small, medium, or large	size of working capital
share-of-offshored-firms	percentage of firms which initially offshored production (Jäger *et al.*, 2016)	8%	%
offshored?	label reporting whether production is offshored or not [path-dependent]	true or false	label
working-capital	difference between a firm's current assets and liabilities [random]	random between >0 and <1000	euros
share-of-raw-material-costs	percentage of working capital allocated to cover raw materials costs (Perloff, 2016)	50%	%
share-of-labour-costs	percentage of working capital allocated for covering labour wages [dependency on counterpart: share-of-raw-material-costs]	50%	%
low-skilled-labour-ratio	ratio of low-skilled labour required for production [random]	0.8	ratio
high-skilled-labour-ratio	ratio of high-skilled labour required for production [dependency on counterpart: low-skilled-labour-ratio]	0.2	ratio

wages-low-skilled-labour	yearly salary per low-skilled worker in Germany [random]	11	euros
wages-high-skilled-labour	yearly salary per high-skilled worker in Germany [random]	12	euros
wages-low-skilled-labour-abroad	yearly salary per low-skilled worker abroad [random]	10	euros
wages-high-skilled-labour-abroad	yearly salary per high-skilled worker abroad [random]	11	euros
labour-productivity	amount of output a human worker produces per time step [random]	1	ratio
max-level-of-automation	maximum level of attainable efficiency of automated production [random]	random between 0 and <1	ratio
level-of-automation	current level of efficiency of automated production [random]	random between 0 and <max-level-of-automation	ratio
share-of-automated-firms	percentage of firms which initially utilised robots for production (Jäger *et al.,* 2016)	29%	%
robot-costs	costs for maintaining and running robotic automation (e.g. energy bill) [random]	20	euros
robot-productivity	amount of output a robot produces per time step [random]	10	ratio
robots-kill-jobs-threshold	technological threshold at which robots eliminate all low-skilled jobs [random]	0.8	ratio
sales-price-per-product	global sales price for finished products [random]	20	euros
share-for-r&d-investment	percentage of revenue allocated for R&D investment [random]	1%	%
share-for-foreign-surcharges	percentage of revenue which is additionally required if production is offshored (e.g. shipping costs or import tariffs) [random]	1%	%

share-for-relocation-costs	percentage of profit required in case of relocation [random]	1%	%
reshored?	label reporting whether production has been reshored or not [path-dependent]	true or false	label

It is assumed here that in each time step all produced goods are sold to a defined global sales price per product. Just like on the financial balance sheet of any business, the sold output is measured as a key performance indicator called revenue. A proportional share of the revenue is invested into R&D in order to technologically improve in the long run. Ultimately, the profit of German firms' is the outcome of deducting this investment from the revenue. Offshored firms by contrast need to consider foreign surcharges into their profit calculation. Such additional costs could include taxes, shipping costs, or import tariffs. It is a distinctive feature of the model that the firms are equipped with a double-entry balance sheet including details of assets and liabilities for producing at home in Germany or in an offshore destination as illustrated in Figure 1.

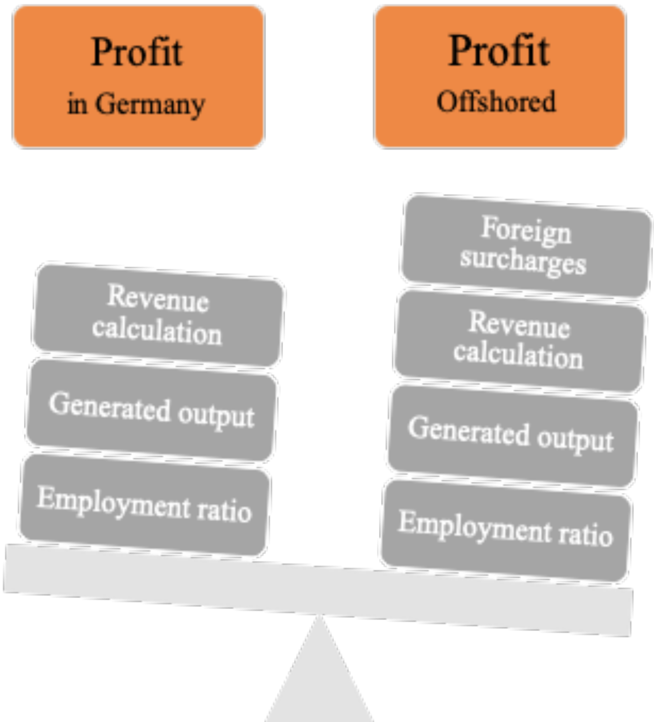

Figure 1: Profitability analysis

The actual location decision is myopic and characterised by limited information solely based on profits. In reality, total ownership costs of manufacturing operations most possibly involve funds tied up in working capital in the form of inventory which limits a firm's flexibility due to long lead times (Tate *et al.* 2014). In order to have a more realistic set of conditions when it comes to such strategic decision-making, relocation costs being a specific share of the profit is an additional variable taken into the equation here. Lastly, every firm provides information on the status of its current production location. Mimicking real-world economic dynamics, a firm can however also become bankrupt when it reaches a defined threshold. An insolvent firm no longer appears in the modelled economy in the coming time step. A visualised decision-making process depicting one business cycle can be found in Figure 2.

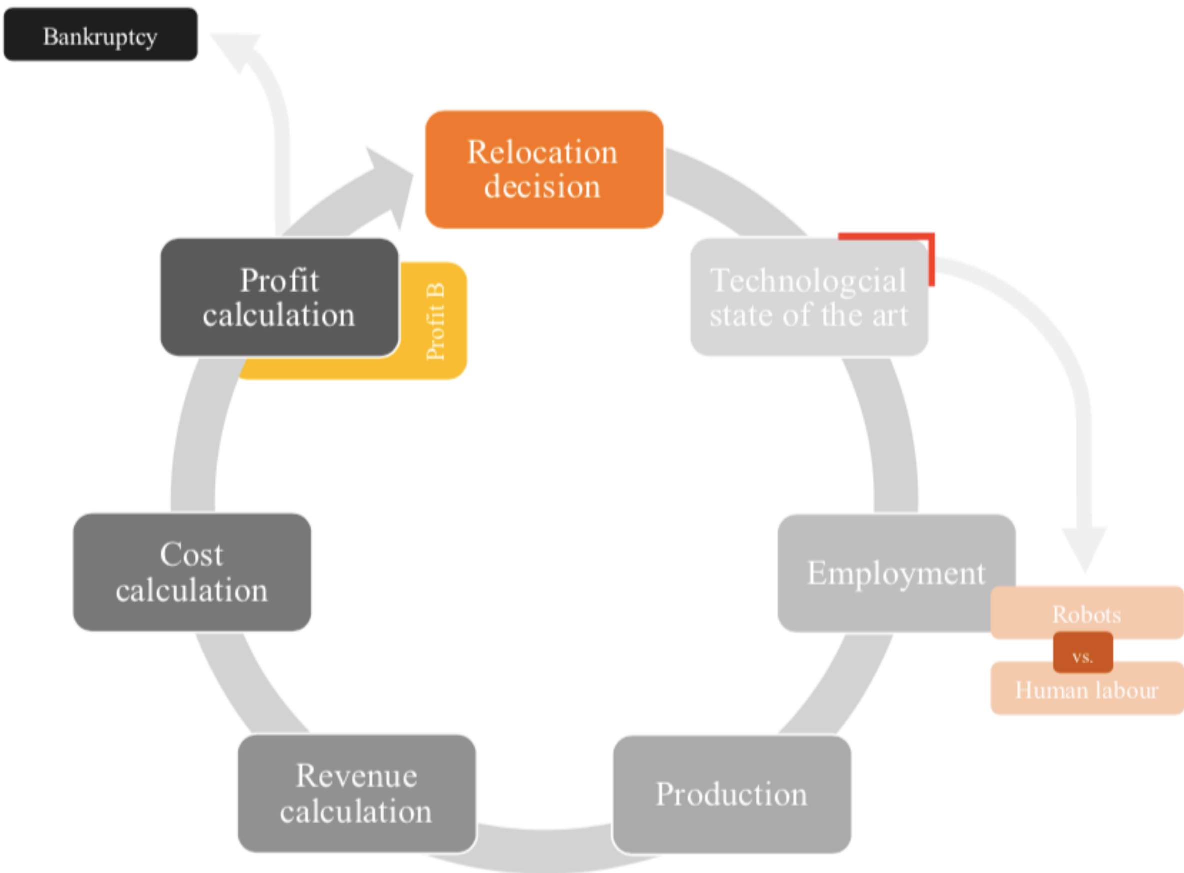

Figure 2: Relocation decision tree

A systematic description of the model in the format of an ODD+D (Overview, Design Concepts, Details and Decision) protocol as proposed by Müller *et al.* (2013) can be found in the appendix (9.1.). The protocol is an extended version of the established ODD framework developed by Grimm *et al.* (2010). The pivotal adaptation of the refined standard for describing ABMs is to better capture human decision-making processes. Hence, it includes rearranged and added guiding questions and a detailed model description containing pseudo-codes.

Additionally, a screenshot of the model's interface depicting the initial parameter values (9.2.), as well as the source code of the model (9.3.) are added as appendices.

3.3.2. Validation and verification

In order to validate the created model, the values of the initial setting were controlled whilst testing a minimum and maximum range of values for a selected number of variables. Table 2 lists the tested range. The behaviour of the obtained results partly mimics economic dynamics as it can be observed in the real-world which is useful for verifying the functionality of the model.

Table 2: Variables utilised for validation

Validated variable	Initial value	Minimum range	Maximum range
wages-low-skilled-labour-abroad	10	1	100
wages-high-skilled-labour-abroad	11	1	100
foreign-surcharges	1%	0.1%	10%
relocation-costs	1%	0.1%	10%

The identified trend of a diminishing gap between global wages has the potential to challenge the validity of choosing offshore production due to competitive labour cost advantages. Results depicted in Figure 3 and Figure 4 are in accordance with this finding as decreased offshoring activities can be observed in case of increasing wage levels for low-skilled or high-skilled workers in the Global South.

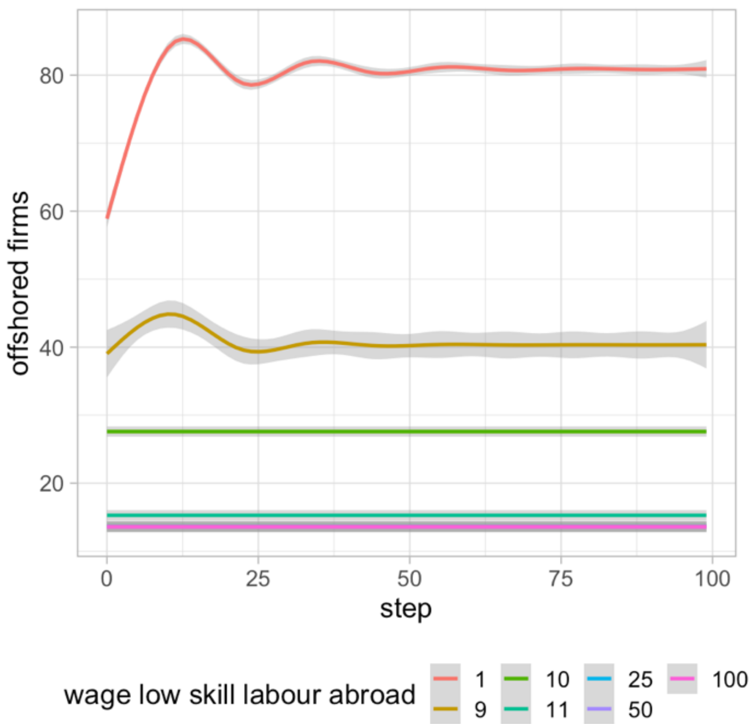

Figure 3: Timeline of varying levels of low-skilled labour wages abroad effecting the percentage of offshored firms

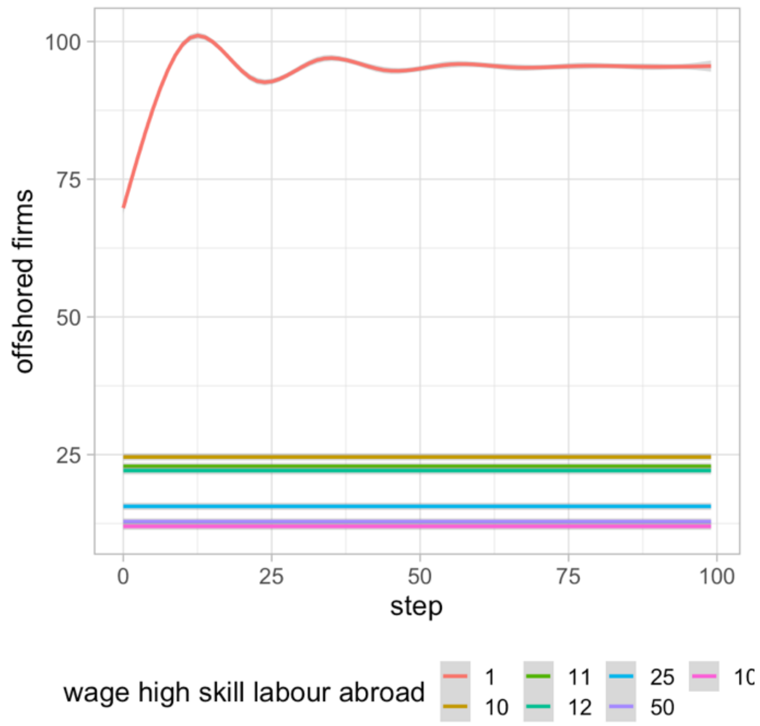

Figure 4: Timeline of varying levels of high-skilled labour wages abroad effecting the percentage of offshored firms

Several factors which could lead to fluctuating additional costs accruing in case of offshore production have been identified. Lowered obstructing surcharges, exemplary driven by lower oil prices or the emergence of beneficial trade agreements, motivate a larger share of firms to offshore which is visualised in Figure 7 by a share of 0.1%. Increased surcharges due to the introduction of a CO_2 tax, higher oil prices, the termination of trade agreements, or an unfavourable shift in international relations would however discourage firms from offshore production in the first place. As time-independently illustrated in Figure 8, too high foreign surcharges would in fact represent too high an obstacle to consider offshoring at all.

Costs required in case of relocation could potentially vary due to changed political environments. In case of a low share of profit required to relocate production, the movement of firms is more flexible and the significance of other factors defining the relocation decision become more prominent. Equally, high costs for moving production would pose an additional obstacle hindering firms to move as clearly visible in Figure 5. The statistical difference as depicted in Figure 6 supports this claim independent of time.

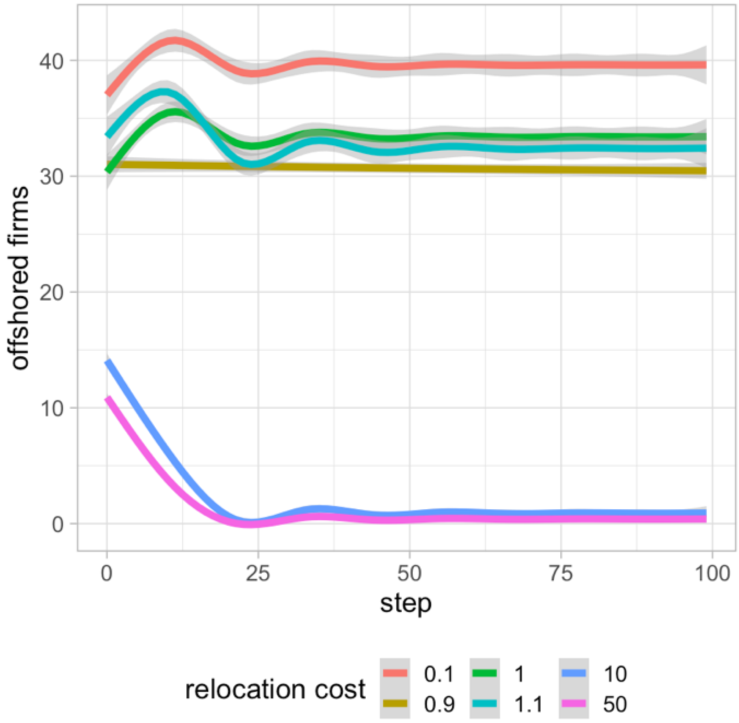

Figure 5: Timeline of varying levels of relocation costs effecting the percentage of offshored firms

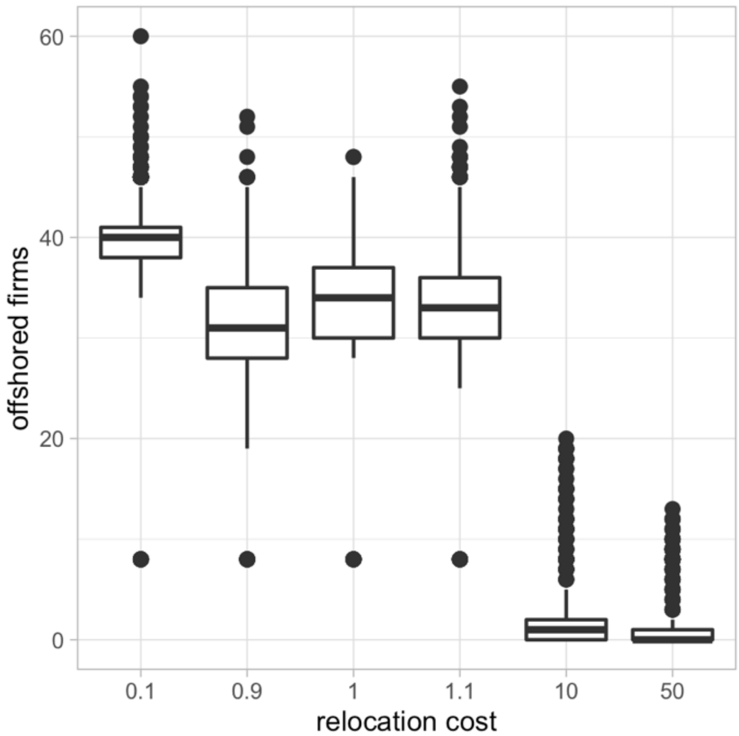

Figure 6: Box plot diagram of varying levels of relocation costs

3.3.3. Simulations

The integrated *NetLogo* simulation tool called 'BehaviorSpace' is a methodically ordered approach towards exploring a model's parameter space (García Vázquez & Sancho Caparrini 2016). For this research, a number of sustainability related parameters have been tested in order to support the claimed hypotheses. For evaluating the selected parameters on the sensitivity to their initial condition, so-called 'parameter sweeping' was performed which analyses the effect of a parameter on the output of a system by varying through a defined range of values (CSP-AIMS 2015). The purpose of this approach includes the systematic performance of a vast number of experiments in an automated manner. The data was further analysed using the statistical computing environment *R* (R Core Team 2019).

A comprehensive list of performed experiments can be found in Table 3.

Table 3: Conducted experiments

Experiment	Tested variable	Initial value	Tested range
A.) Shifting foreign surcharges	foreign-surcharges	1%	[0.1, 0.9, 1, 1.1, 10, 25, 50]
B.) Fluctuating yearly salary per low-skilled worker in Germany	wages-low-skilled-labour	11	[1, 10, 11, 12, 25, 50, 100]
C.) Fluctuating yearly salary per high-skilled worker in Germany	wages-high-skilled-labour	12	[1, 11, 12, 13, 25, 50, 100]
D.) Fluctuating yearly salary per low-skilled worker abroad	wages-low-skilled-labour-abroad	10	[1, 9, 10, 11, 25, 50, 100]
E.) Fluctuating yearly salary per high-skilled worker in abroad	wages-high-skilled-labour-abroad	11	[1, 10, 11, 12, 25, 50, 100]

4. Results

The following is a summary of the conducted experiments generated by sweeping selected parameters. The selection of parameters is guided by the research question aiming at the exploration of the importance of variables connected to sustainability. For this reason, the parameter of interest are foreign surcharges representing environmental aspects, as well as low-skilled and high-skilled labour wages in Germany and abroad respectively in order to delve into social dynamics of the issue.

The range of tested values derives from the initial value of single parameters, as well as the sensitivity to their initial condition.

A.) Foreign surcharges

Despite serving as a variable validating the functionality of the model, shifting values of the parameter representing foreign surcharges can be observed in the results of the experiments. As already elaborated, lower surcharges result in motivating a larger share of firms to offshore which is visualised in Figure 7 by the lowest tested value, a share of 0.1%. Increased surcharges due to the introduction of a CO_2 tax, higher oil prices, the termination of trade agreements, or an unfavourable shift in international relations leads to the discouragement of firms from offshore production. Time-independent analysis as illustrated in Figure 8 demonstrates how too high foreign surcharges would in fact represent an insurmountable obstacle to consider offshoring at all.

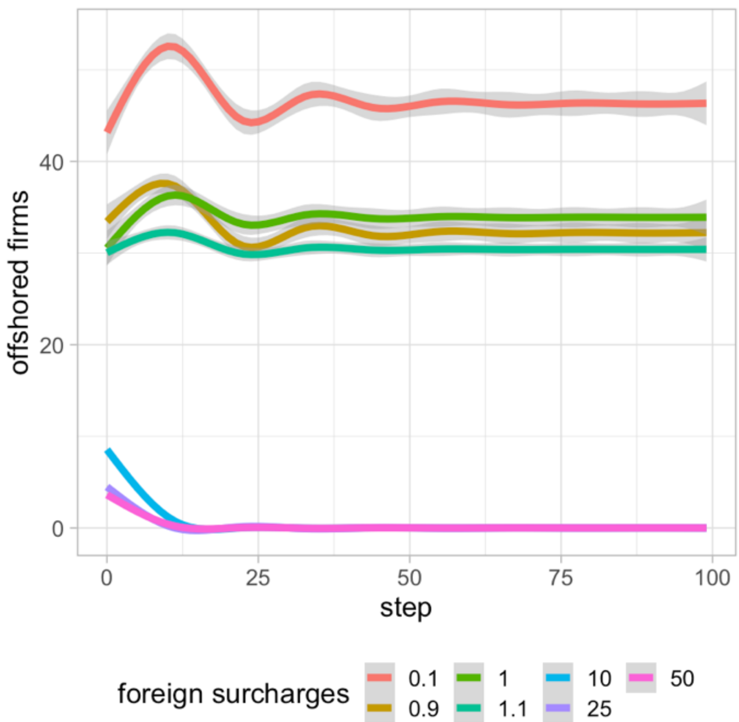

Figure 7: Timeline of varying levels of foreign surcharges effecting the percentage of offshored firms

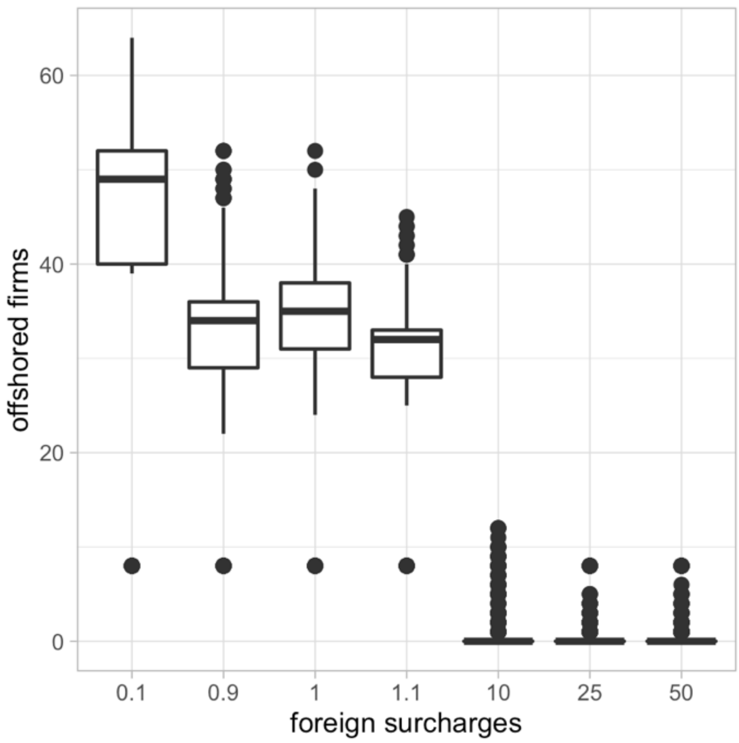

Figure 8: Box plot diagram of varying levels of foreign surcharges

B.) Fluctuating yearly salary per low-skilled worker in Germany

As depictable in Figure 9, fluctuating wages for low-skilled labour in Germany do not result in straightforward results when it comes to motivating offshoring. When wages decrease, firms are more likely to reshore production. When the wages for low-skilled labour increase, there is an observable trend towards offshoring production. After the value of 12 euros per year, the share of firms deciding to offshore does not increase any further. The tested value of 25 has roughly the same effect on the offshoring decision as a wage level of 12. If the tested value is further doubled to 50, there are even less firms which decide to offshore. Another doubling up to the level of 100 does not change this finding.

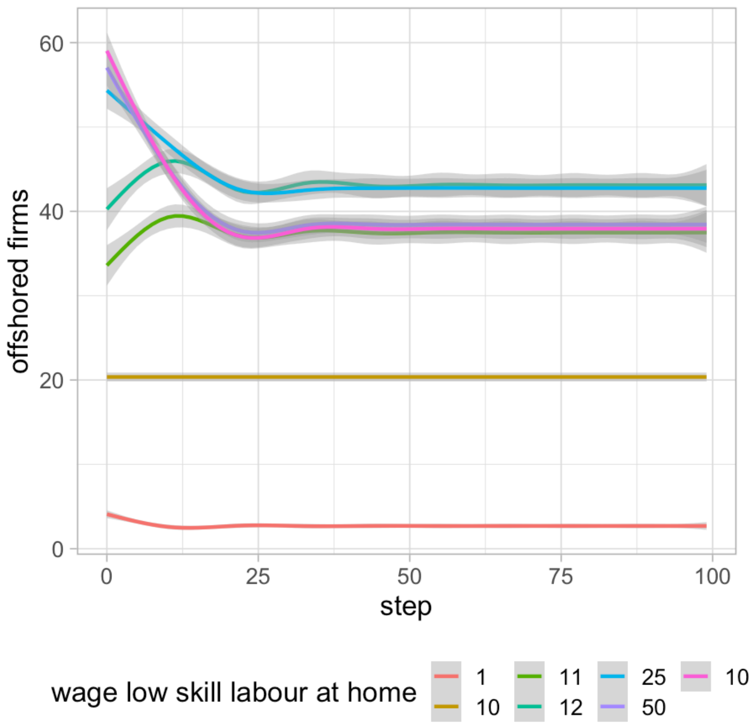

Figure 9: Timeline of varying levels of low-skilled labour wages in Germany effecting the percentage of offshored firms

C.) Fluctuating yearly salary per high-skilled worker in Germany

In regard to decreased levels of high-skilled labour wages, the observable pattern shown in Figure 10 is equal to the finding described for low-skilled labour wages, namely that firms are more likely to reshore production. However, an increase of the wage level for high-skilled labour in Germany yields to more ordered results, meaning that with increased values the incentive to offshore production equally increases. The progressivity slows down with increasing values which is explicitly observable when for example comparing the wage level of 50 euros per year as distinguished from 100 euros a year. A time-independent statistical support of these findings can be found in the box plot illustrated in Figure 11.

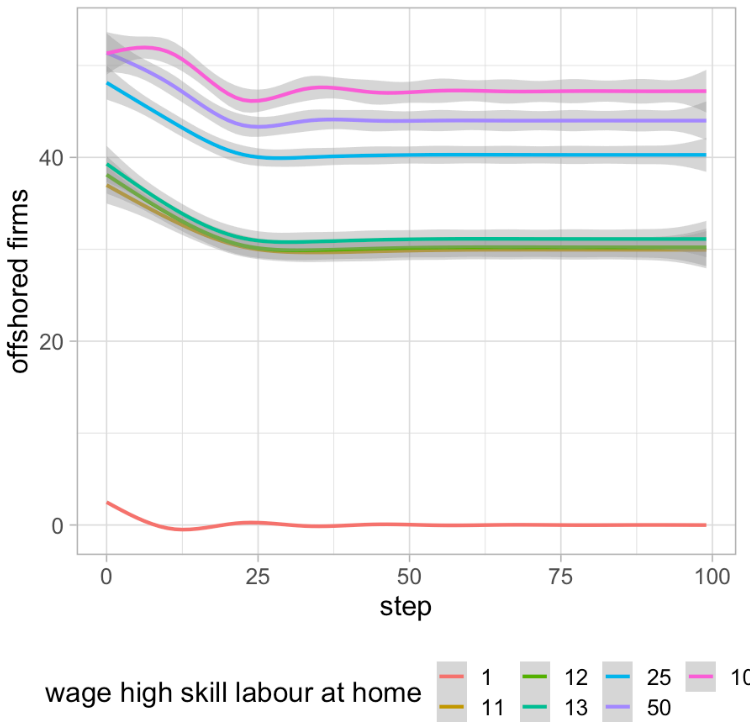

Figure 10: Timeline of varying levels of high-skilled labour wages in Germany effecting the percentage of offshored firms

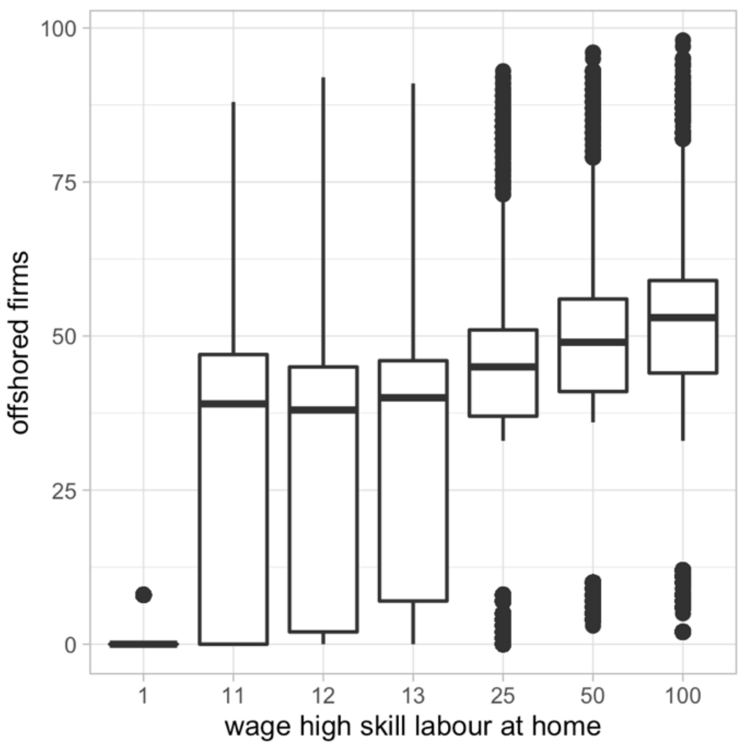

Figure 11: Box plot diagram of varying levels of high-skilled labour wages in Germany

D.) Fluctuating yearly salary per low-skilled worker abroad

The wage levels of labour abroad have been explored with the same experimental approach as the wage levels in Germany, involving discrete testing of low-skilled and high-skilled labour wages. In addition to serving as a validation parameter for the model, the results offer noteworthy insights with regard to the sensitivity of values when plotted against the same levels for wages in Germany.

As shown in Figure 12, low values required for low-skill labour wages such as one euro per year yields to about 80 % of firms deciding to offshore production. This share is half of that, namely 40 %, when the wages are increased to nine euros per year. At the initially set wage level of 10 euros per year, exactly 29 % of firms are offshored which is the initially defined share. With increasing wage values, the likelihood for reshoring further increases. The rise is however not linear. For instance, a value of 50 in comparison to a double amount of 100 does not yield a significant difference between the percentage of firms deciding to reshore at such high wage levels. When plotting firms located in Germany against offshored firms whilst varying wage levels as shown in Figure 13 and Figure 15 respectively, it can be better understood at which values the relocation dynamics would settle at an equilibrium.

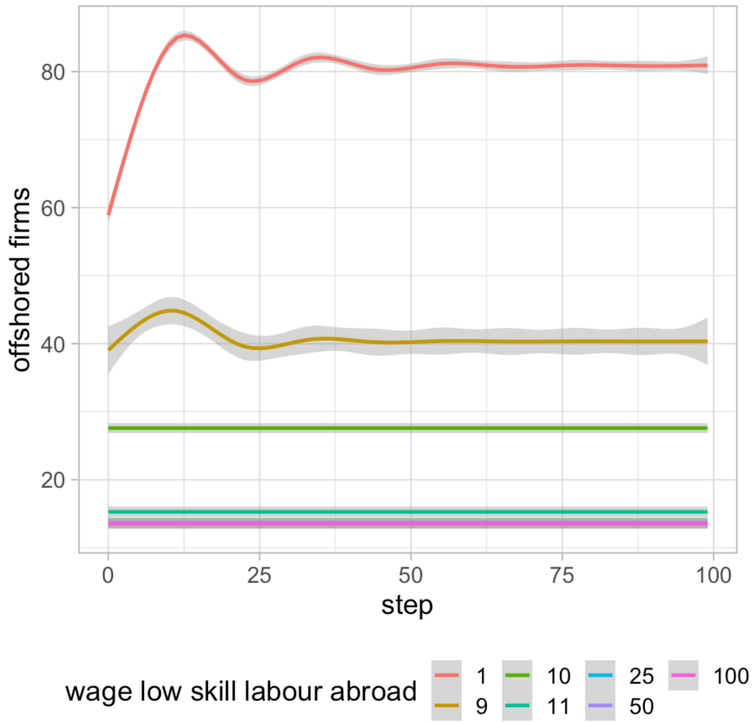

Figure 12: Timeline of varying levels of low-skilled labour wages abroad effecting the percentage of offshored firms

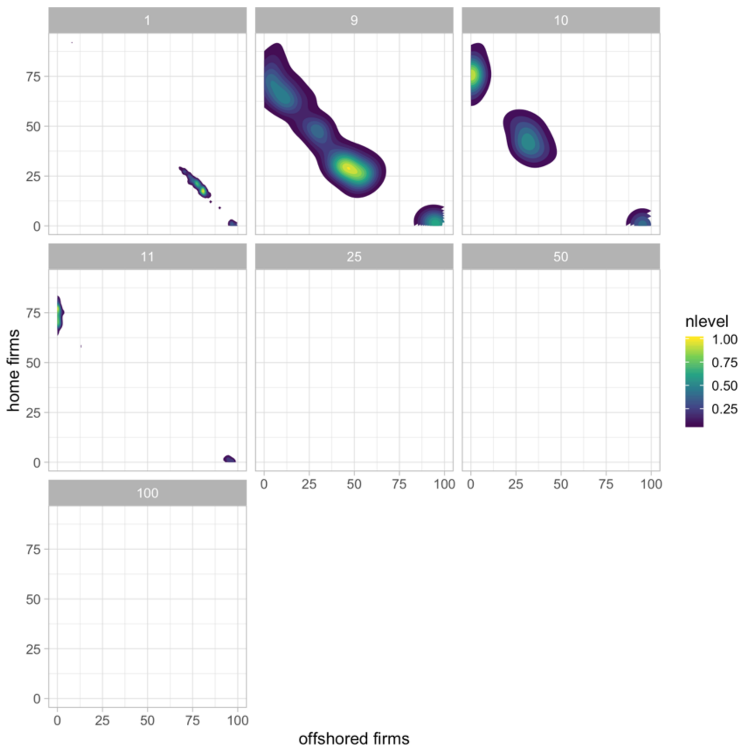

Figure 13: Phase space diagram of varying wage levels of low-skilled labour abroad

E.) Fluctuating yearly salary per high-skilled worker in abroad

The same pattern can equally be observed in the experiments with high-skilled labour wages abroad as shown in Figure 14 and Figure 15. One euro per year is again the lowest value tested which yields to an even higher percentage of offshored firms, namely over 90 %. Once again, the initially set value of 11 euros per year results in 29 % of offshored firms. Increasing wages levels above this initial setting means a non-linear decline of offshored firms.

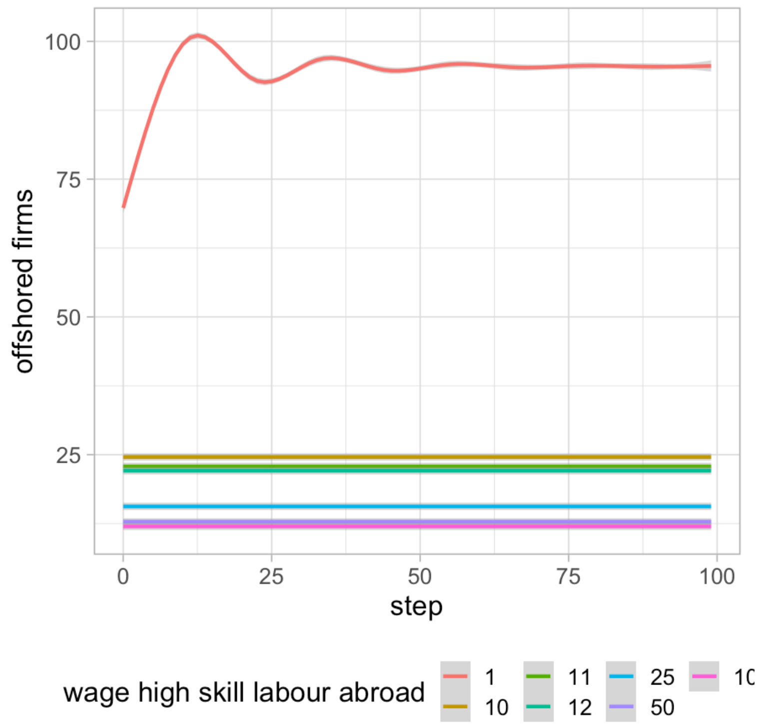

Figure 14: Timeline of varying levels of high-skilled labour wages abroad on the percentage of offshored firms

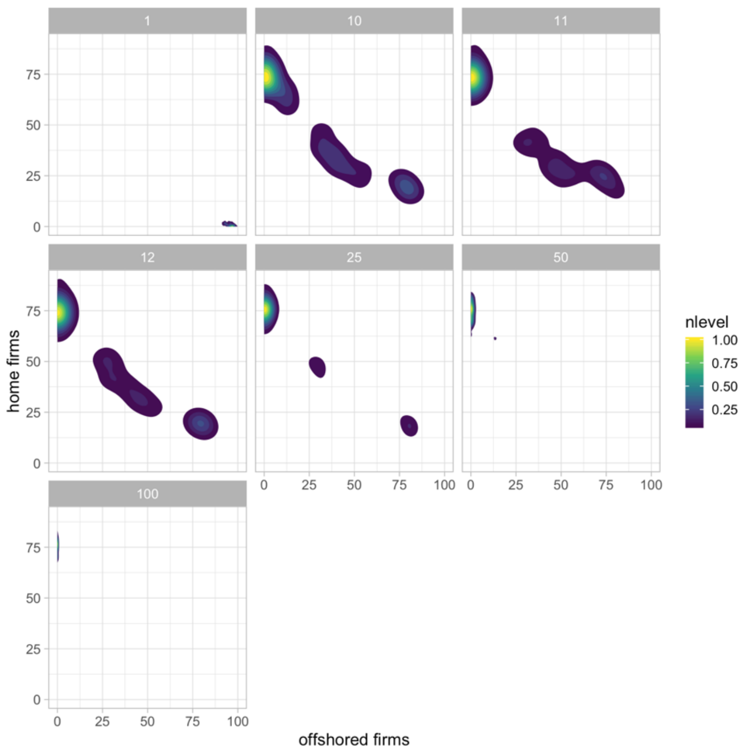

Figure 15: Phase space diagram of varying wage levels of high-skilled labour abroad

5. Discussion

The development of an agent-based model on automation-induced reshoring has allowed insights on how different variables connected to sustainability influence this socio-technical phenomenon. The research focus guided the choice of tested variables in order to explore both, environmental and social aspects of the economic analysis.

The first hypothesis of this research proposes that rising transportation costs outweigh the competitive cost advantages of offshore production which consequently allows the diffusion of automation technology to drive reshoring faster. Foreign surcharges representatively symbolising additional costs required for producing abroad could, for instance, include shipping costs and import tariffs. The conducted experiments show in how far increased surcharges motivate the reshoring of production facilities. The rise of such surcharges is not all too far-fetched given rising environmental awareness among the public, increasingly pushing the topic onto political agendas. Stricter environmental regulations could therefore involve the introduction of a CO_2 tax leading to higher prices for fossil fuels which would in turn increase transportation costs. Such developments have the potential to challenge the international container shipping regularities forcing a reconsideration of global trade realities.

The secondly stated hypothesis concerning labour wages claims that increasing wage levels in formerly offshore destinations challenge the reasoning for continuing to produce abroad. It is suggested that this would be particularly true when labour costs and costs for robots converge. The proposed consequence would be an increased trend towards reshoring production to the home country. The results of the simulations have shown that by lowering both low-skilled and high-skilled labour wages, there is a clear trend towards reshoring. As automation in Germany increases, an increasing amount of low-skilled jobs are eliminated. This is why low wage levels for low-skilled labour lose their attractiveness to offshore production almost entirely. In fact, low values of high-skilled wages in Germany nullify the phenomenon of offshoring. If high-skilled wages for engineering or IT services drop, there is no longer any incentive to offshore production. This line of argumentation is supported through the findings of increased labour wages for low-skilled labour in Germany. Up to a level of 12 euros per year, firms are incentivised to offshore production. More than 40 % of firms make this decision at the stated wage level presumably because labour wages are too costly. This seems to be a ceiling share as even higher wage levels do not result in higher percentages of offshored firms. This can be explained through the increasingly automated production landscape. Firms producing in Germany have the ability to attain higher levels of maximum automation. This initial competitive advantage of technological progress is designed to realistically replicate the reasoning that firms with a presumptively large share of manual production tasks would opt for offshoring as labour wages are lower there. Even though it is not specified that the share of automated firms is located in Germany from the start, the defined level is however a value between zero and the maximum attainability of automation. This is why the level of automation of firms abroad is lower than the firms in Germany. A high level of automation consequently results in shifted labour ratios. As the low-skilled labour ratio shrinks all the way to zero as soon as the maximum level of automation is reached, the effect of high labour wages is absorbed thanks to the utilisation of robots.

The same effect is not visible in the results acquired for high-skilled labour wages as the ratio for high-skilled labour is always at 0.2, despite increased levels of automation. This is why ever higher wage levels for high-skilled labour in Germany will drive firms towards the decision to offshore production as labour costs are simply not competitive in comparison. Further, it can be argued that increasing wage levels for high-skilled labour in Germany drive a significant number of firms out of business due to unprofitability.

The result of the experiments run with varying values of wages abroad could in fact additionally be used for validating the model. The result is straight forward in the sense that they replicate the initial motivation for globalising production due to competitive cost advantages in locations abroad. Low wage levels seem to be a strong incentive to offshore production, attracting almost every single firm of the modelled economy.

Interestingly, there is a large gap between a very low wage level for high-skilled labour translating to over 90 % of firms deciding to offshore in comparison to a 10 times higher value resulting in only about 25 % respectively. The same pattern can be observed by varying the levels of low-skilled labour wages at the exact same values which translates into slightly less percentages of offshore firms, namely 80 % and 28 % respectively. The difference could be explained by taking the initial values of the parameter into consideration. The initial value for high-skilled labour abroad is set to 11 in contrast to a value of 10 for low-skilled labour. This means that the highest and lowest percentage will vary as the difference to the initial value varies accordingly. It can therefore be expected that same differences would yield same percentages.

Further, the decrease in percentage of offshored firms drops slower with ever higher values which is true for both low-skilled and high-skilled wages. In order to interpret this result, the wage levels in Germany need to be added to the equation. Initially, this value is at 12 euros per year for high-skilled labour in contrast to 11 euros per year for high-skilled labour abroad, whereas the initially set wages for low-skilled labour are 11 euros per year in Germany and 10 euros per year abroad. Therefore, it can be argued that if the wages align or even exceed the levels in Germany, the competitive cost advantage becomes void. This is the reason why less firms would then still decide to offshore production. To sum up, the results support the claim that offshoring is significantly driven by labour wages.

The results are particularly interesting when comparing the same wage levels tested for Germany and abroad alike. For instance, when the wage level for low-skilled labour in Germany and abroad is at 10 euros per year, the shares of offshored firms are 20 % in Germany in contrast to 29 % abroad. The same finding is observable when comparing high-skilled labour wages. 11 euros per year in Germany exemplary translates into approximately 30 % of offshored firms, whereas the same wage level abroad yields to less than 25 %. The varying effect of the same wage levels can be explained when considering the shifting labour ratios required for automated production. Labour tasks are shared between low-skilled labour, high-skilled labour, and robots. The defined ratio for low-skilled labour is set to 0.8 compared to 0.2 of high-skilled labour. The share of robots utilised for production is defined by the current level of automation. Linking this information back to the fact that firms with a lower maximum level of automation are initially offshored due to their assumably larger share of manual production tasks explains the varying effect. In sum, it ultimately means that even though the wage level might be the same, the required number of human labour and particularly the number of low-skilled labour tends to be higher for offshored firms. Due to this rationale, low labour costs abroad have a more crucial relevance in the relocation decision than low labour costs in Germany.

"*Essentially, all models are wrong, but some are useful.*" (Box & Draper, 1987, p. 424)

As any other model, this model is unfinished and incomplete (Meadows *et al.,* 1972). The most important limitations of this model are the following:

- According to the most recent national statistics, 23,242 firms are registered within the German manufacturing industry in the year 2018 (DESTATIS 2019). In order to allow for a reasonable running time of the simulations, the initial number of agents is set to 100. Despite the admittedly small representation of the actual amount, increasing this parameter had no effect on the results.
- In line with the theoretical, but unrealistic, growth model of neoclassical economics, the firms accumulate capital exponentially (Raworth 2017).

- In order to avoid too much noise, it is assumed here that each firm produces one type of product only. Most firms in real life produce more than one product type which again is itemised into specific requirements of production processes.
- The system boundaries are unique to the problem statement which means that the interactions of the system with its external structure such as the financial market such as currency fluctuation, exchange rates, inflation rate. Further, dynamics of various supplier networks, the customer base, and legal circumstances have not been taken into account.
- As the labour market was not the field of interest for this study, the unlimited availability of workers on the German, as well as the foreign, labour market is an exogenous variables of this model.
- Due to the limited scope of the research, employing labour as a business expense is represented as an exiguous cost reflected in the wages. There is in fact much more to employment, such as the enquiry of suitable labour, hiring costs, a decreased productivity during the initial training period, compensations in case of short-term termination of the labour contract, etc.
- The knowledge and available skill-set of required labour is yet another assumption.
- Another exogenous factor is the assumption that investing into technology will advance the level of automation. In fact, the share of R&D investment translates into a proportionally increased level of automation. When taking a closer look at the motivation for investing in robot technology it has been noted that firms which could benefit from the utilisation of robots are also more likely to reinvest in improved technology (Jäger *et al.* 2016).
- It is assumed that no new firms enter the economy after the initial setup.
- A true ABM is characterised not only by the non-linear behaviour of agents, their interactions within the surrounding environment, as well as the influence of exogenous input, but also by interactions with each other (Epstein & Axtell 1996). In this model design, agents do not interact with each.
- Lastly, any system as an object of study generally depends on the perspective of the analysis and the person conducting the analysis (Dekkers 2017).

6. Conclusion

The research aims to add to the understanding of how heterogeneous degrees of technological innovation among manufacturing firms have an impact on the macroeconomic phenomenon of reshoring production. The chosen methodological approach of developing an agent-based model has allowed insights on how the behaviour of firms guided by simple economic rules on the micro-level is dynamically influenced by the complexity of their surrounding environment. In the course of the study, hypotheses related to environmental and social sustainability aspects have been tested in regard to their sensitivity to initial condition. The computational simulations served as a virtual lab for demonstrating how increased environmental regulations targeting global trade and upward shifting wage levels in formerly offshore production locations are key driving and inhibiting mechanisms of this socio-technical system. Next to the role of technological innovations as the main key determinant of shifted economic realities, the aforementioned drivers and barriers are in line with the extant literature on reshoring. Academic debate predominantly focused on conceptualising the phenomenon has been enriched by offering a novel perspective on the macroeconomic matter by accounting for the heterogeneity on the micro-level.

In an endeavour to replicate a complex system such as the global dynamics of the manufacturing industry must be severely limited. As with modelling in general, the system boundaries reflect the problem statement whilst excluding exogenous factors such as in this case the supply of natural resources required for raw material, labour market dynamics, fluctuating sales market regularities, the financial system, domestic politics, and international relations. However, the boldest assumption of the model is perhaps the continuously increasing degree of technological advancement solely driven by investing in R&D.

”*Everything should be made as simple as possible, but not simpler*.”

Articulated in the principle of Occam’s razor and in spite of the aforementioned limitations, the study at its present state might already be sufficiently developed to be of some use in informing politicians and strategic decision-makers in the field about the importance of environmental and social sustainability aspects regarding the future of manufacturing locations. The developed model for this study will be available on the *NetLogo* website. The setup of the open source model library allows for scrutinising, revising, and expanding the proposed assumptions which is desirable as knowledge and available databases gradually progress over time. Thanks to simplified features, the model encapsulates knowledge in an easily transferable manner allowing for unlimited possibilities of testing seemingly further relevant variables. Considering the flexibility of simulations in regard to time spans, ABM allows for a long-term perspective in exploring potential future scenarios of reshoring dynamics. Equipped with a flexible plotting system, ABM further enables accessible communication of simulation results through explicit visualisation. The explanatory power of modelling is particularly valuable for educational purposes (Hoekstra *et al.* 2017).

Looking ahead, ABM could be utilised to challenge mainstream economic assumptions beyond the much challenged, but still predominantly accounted factor of the ‘homo economicus’ paradigm; the self-interested, rational, and fully informed actor (e.g. Raworth, 2017). Due to the ability to encapsulate learning, adaptation, and dynamic decision-making, the model could be extended by changing the simple set of rules from solely valuing economic profitability towards integrating a value system truly accounting for environmental and social sustainability aspects. The human versus robot debate could be particularly interesting when shifting from a technological-economic perspective towards incorporating a social lens for exploring potential societal developments enabled through technological innovations. It has been argued that new technologies such as automation will take over mundane tasks which could free up humans to focus on higher-value activities and skills such as human interaction, technical expertise, problem solving, intuitive mastery, inspiration, creativity, and judgement (Wood, 2016; Autor, 2017).

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”*The house is on fire*.” By Greta Thunberg

Thank you for reminding the world of the urgency for Sustainable Development.

I feel privileged to be a European citizen, which has allowed me the opportunity to study in a progressive environment amongst an innovative society in the country of Sweden.

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[1] https://scholar.google.se

[2] Capra, B. (1990). *Mindwalk*. Feature film, Triton Pictures.

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9. Appendices

9.1. ODD+D protocol

The table below is a systematic description of the model as proposed by Müller *et al.* (2013).

		Guiding questions	ODD+D model description
I) Overview	I.i Purpose	I.i.a What is the purpose of the study?	This study adds novelty to the extant literature on automation-induced reshoring by offering a system understanding on how the behaviour of firms, guided by simple economic rules on the micro-level, is dynamically influenced by their complex environment in regard to identified relocation decision-making hypotheses. Informed by previously developed economic models, the research attempts to replicate the observed regularities in order to add to the particular understanding of how related sustainability aspects have an impact on reshoring production.
		I.ii.b For whom is the model designed?	○ Scientists ○ Economists ○ Political decision makers
	I.ii Entities, state variables, and scales	I.ii.a What kinds of entities are in the model?	○ <u>One type of agent:</u> German manufacturing firms either located at home or abroad ○ <u>Two types of geographic environments:</u> Germany and an unspecified production location in the Global South

		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterised?	Of firms: Capital, firm size defined by the size of capital, maximum level of automation, current level of automation, costs for maintaining and running automated production, number of utilised robots, number of total labour units required, actual low-skilled labour ratio, actual high-skilled labour ratio, number of low-skilled labour employed, number of high-skilled labour employed, number of total labour employed, planned budget for labour costs, actual labour costs, raw material costs, production output, revenue, investment in research and development (R&D), relocation costs, profit, label reporting the status of location, economically strategic decision-making Of the manufacturing industry: Number of firms, price for raw material, share of automated firms, costs per robot, robot productivity, threshold at which robots eliminate low-skilled jobs, labour productivity, low-skilled labour ratio, high-skilled labour ratio, share for R&D investment, share for relocation costs, sales price for finished product Of the German economy: Wages for low-skilled labour, wages for high skilled labour Of the foreign economy: Wages for low-skilled labour, wages for high skilled labour, share of offshored firms, foreign surcharges
		I.ii.c What are the exogenous factors / drivers of the model?	Generally: Exponential economic growth, non-competing economic market, dynamics of the financial market (such as currency fluctuation, exchange rates, inflation rate), labour market, various supplier networks, customer base, domestic politics, international relations, legal circumstances, R&D Specifically: Price for raw material, foreign surcharges, sales price for finished product, relocation costs, wages, robot productivity,

			human labour productivity, technological innovation
		I.ii.d If applicable, how is space included in the model?	The modelling world is divided in a Global North and Global South, whilst agents move from one geographic location to the other depending on their relocation decision.
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	Yearly time steps representing business cycles with a simulation length of 100 ticks. Relocation decisions are taken on the basis of the annual financial statement at the end of the year meeting. Firms are distributed randomly across their geographic production location. The exact location is inconsequential.
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	<u>Set-up of the economy:</u> 1. Modelled world is set according to the North-South divide, colouring Germany in the North in blue, the equator as a border white, and the abstracted Global South in yellow 2. Creation of a defined number of firms <u>Set-up of the industry:</u> **1. Set-up firms:** Defines the initial parameter values of firms. The initial seed capital is a random value between >0 and <1000 and the maximum level of attainable efficiency in automation is defined as a fixed random value between >0 and <1. ask *firms [* set *working-capital random 1000* set *max-level-of-automation 0 + random-float 1]* **2. Offshoring:** Initially, all firms report that they have neither offshored nor reshored. Defined by

a given share, the initial number of offshored firms is calculated. Firms with a lower attainability of automation have a higher incentive to offshore where manual labour is cheaper. The firms are then distributed on the modelled economy according to their location, but randomly on the map of the respective country.

ask *firms [*

set *offshored? false*

set *reshored? false*

let *offshored-firms (min-n-of (count firms * (share-of-offshored-firms / 100)) firms [max-level-of-automation])*

ask *offshored-firms [*

setxy *random-xcor random-between (-10) -1*

set *offshored? true]]*

ask *firms with [offshored? = false] [*

setxy *random-xcor random-between (10) 1*

3. **Tech-state-of-the-art:** States the firms' technological state of the art. Only a defined share of firms already utilises robots at the initial set-up. The current efficiency of automated production is a random value between >0 and the specified maximum attainable level of automation. A dark orange colour shading depicts a low level of automation, whereas a light orange stands for high levels of automation.

ask *n-of (count firms * (share-of-automated-firms / 100)) firms [*

set *level-of-automation random-between (0.01) max-level-of-automation]*

ask *firms [*

set *color scale-color orange level-of-automation 0 1]*

4. **Costs-calculation:** Firstly, the amount covering raw material costs is allocated by a defined share. The working capital is then divided into raw material costs and the budget allocated for covering labour wages.

ask *firms [*

set *raw-material-costs working-capital * (share-of-raw-material-costs / 100)*

set *budget-for-labour-costs working-capital - raw-material-costs]*

5. **Human-vs-robot:** Defines the ratios of low-skilled human labour, high-skilled human labour, and robots required for production. Firstly, the ratio of high-skilled labour is calculated in proportion to a defined ratio of low-skilled labour. If the technological threshold at which robots eliminate all low-skilled jobs is reached, all low-skilled labour becomes obsolete and labour is shared between high-skilled labour and robots. If this is not the case, the division of labour is calculated depending on the current level of automation, as well as the defined ratio for low-skilled and high-skilled labour.

ask *firms [*

set *high-skilled-labour-ratio 1 - low-skilled-labour-ratio*

ifelse *(level-of-automation >= robots-kill-jobs-threshold) [*

set *actual-low-skilled-labour-ratio 0*

set *actual-high-skilled-labour-ratio 1 - level-of-automation] [*

set *actual-low-skilled-labour-ratio (1 - level-of-automation) * low-skilled-labour-ratio* set *actual-high-skilled-labour-ratio (1 - level-of-automation) * high-skilled-labour-ratio]]*

6. **Employment:** Calculates the type of labour units employed or utilised. Ratios determine the varying shares of the three different types of labour units, namely low-skilled labour, high-skilled labour, and robots. Further, the budget allocated for covering the different labour unit costs and wages is calculated. The planned budget is then squared with the actual amount of labour units which can be afforded for production of this business cycle. These numbers show how many human labour units are actually employed for production. Equally, it is shown how many labour units are utilised in total. The calculations differ depending on the geographic location of the production facilities.

ask *firms [*

let *budget-for-robots budget-for-labour-costs * level-of-automation*

let *budget-for-low-skilled-labour budget-for-labour-costs * actual-low-skilled-labour-ratio*

let *budget-for-high-skilled-labour budget-for-labour-costs * actual-high-skilled-labour-ratio*

set *robots floor (budget-for-robots / robot-costs)*

set *low-skilled-labour floor (budget-for-low-skilled-labour / wages-low-skilled-labour)*

set *high-skilled-labour floor (budget-for-high-skilled-labour / wages-high-skilled-labour)*

set *human-labour low-skilled-labour + high-skilled-labour*

set *labour-units robots + low-skilled-labour + high-skilled-labour* set *low-skilled-labour-abroad floor (budget-for-low-skilled-labour / wages-low-skilled-labour-abroad)*

set *high-skilled-labour-abroad floor (budget-for-high-skilled-labour / wages-high-skilled-labour-abroad)*

set *human-labour-abroad low-skilled-labour-abroad + high-skilled-labour-abroad*

set *labour-units-abroad robots + low-skilled-labour-abroad + high-skilled-labour-abroad*

Consequently, the actual numbers of afforded labour units define the actual budget covering labour wages and robot utilisation. Calculations again differ depending on the geographic location of the production facilities.

ask *firms [*

ifelse *(offshored? = false) [*

set *actual-labour-costs (low-skilled-labour * wages-low-skilled-labour) + (high-skilled-labour * wages-high-skilled-labour)*

set *automation-costs robots * robot-costs] [*

set *actual-labour-costs (low-skilled-labour-abroad * wages-low-skilled-labour-abroad) + (high-skilled-labour-abroad * wages-high-skilled-labour-abroad)*

set *automation-costs robots * robot-costs]]*

7. **Output-calculation:** Calculates the amount of produced goods. The amount of output differs between human labour and robots due to varying levels of productivity. As different numbers of labour units are employed and utilised in Germany in comparison to offshore production, also this calculation varies.

ask *firms [*

set *output (human-labour * labour-productivity) + (robots * robot-productivity)*

set *output-abroad (human-labour-abroad * labour-productivity) + (robots * robot-productivity)]*

8. **Revenue-calculation:** Calculates the total income received by selling produced goods to a global sales price. The revenue is computed twice due to the fact that the output varies between the two alternative production locations as described above.

ask *firms [*

set *revenue output * sales-price-per-product*

set *revenue-abroad output-abroad * sales-price-per-product]*

9. **R&D-calculation:** Allocates the particular share of revenue invested in R&D. As revenues differ between the two geographic locations, the share invested in R&D logically differs as well. If the current level of automation however reaches its maximum attainable level, investment in R&D is no longer needed and, hence, is set to zero.

ask *firms [*

set *r&d-investment revenue * (share-for-r&d-investment / 100)*

set *r&d-investment-abroad revenue-abroad * (share-for-r&d-investment / 100)*

if *level-of-automation = max-level-of-automation [*

set *r&d-investment 0*

set *r&d-investment-abroad 0]]*

10. **Profit-calculation:** When production is offshore, a defined percentage of revenue is additionally required for foreign

surcharges (e.g. shipping costs or import tariffs). Only then, the net financial gain at the end of a business cycle is calculated. Two differing calculations are yet again required here due to geographically differing circumstances.

ask *firms [*

set *foreign-surcharges revenue-abroad * (share-for-foreign-surcharges / 100)*

set *profit revenue - r&d-investment*

set *profit-abroad revenue-abroad - r&d-investment-abroad - foreign-surcharges]*

11. **Firms-size-ratio:** Defines the size of firms in relation to firms' seed capital. The 10 % firms with the highest value of seed capital are large in size. Firms which are not particularly low or high in seed capital are of medium size. And the 30 % firms with the lowest value of seed capital are small in size. The firms are shaped as factory facilities for visualisation purposes.

ask *firms [*

set *firm-size "medium"*

set *size 1*

set *shape "house"]*

ask *(max-n-of (number-of-firms * 0.1) firms [working-capital]) [*

set *firm-size "large"*

set *size 1.5*

set *shape "house"]*

ask *(min-n-of (number-of-firms * 0.3) firms [working-capital]) [*

set *firm-size "small"*

set *size 0.5*

set *shape "house"]*

Go:

12. **Stocktaking of working capital:** Working capital of the coming business cycle is calculated by deducting last time periods' liabilities from the assets. Calculations differ depending on the production location.

ask *firms [*

ifelse *(offshored? = false) [*

set *working-capital working-capital - raw-material-costs - actual-labour-costs - automation-costs + profit] [*

set *working-capital working-capital - raw-material-costs - actual-labour-costs - automation-costs + profit-abroad]]*

13. **Technological-progress:** Firstly, the condition whether the current level of automation has reached the maximum attainable level is inquired. If this is the case, the R&D investment logically cannot increase the level of automation beyond that value. Otherwise, the efficiency of automated production increases proportional to the R&D investment. The calculation differs between firms which produce in Germany and the ones which are offshore.

ask *firms with [offshored? = false] [*

ifelse *((level-of-automation + r&d-investment) < max-level-of-automation) [*

set *level-of-automation level-of-automation + r&d-investment] [*

set *level-of-automation max-level-of-automation]]*

ask *firms with [offshored? = true] [*

ifelse *((level-of-automation + r&d-investment-abroad) < max-level-of-automation) [*

set *level-of-automation level-of-automation + r&d-investment-abroad] [*

set *level-of-automation max-level-of-automation]]*

ask *firms [*

set *color scale-color orange level-of-automation 0 1]*

14. **Costs-calculation:** See elaboration above.

15. **Human-vs-robot:** See elaboration above.

16. **Employment:** See elaboration above.

17. **Output-calculation:** See elaboration above.

18. **Revenue-calculation:** See elaboration above.

19. **R&D-calculation:** See elaboration above.

20. **Profit-calculation:** See elaboration above.

21. **Location-decision:** States the conditions of decision-making concerning relocation. Depending on the geographic location on the modelled world, the specific percentage of profit required for relocation is calculated. If the profit when producing in the current production location is smaller than the profit the firm could have generated if located at the alternative location despite taking relocation costs into account, than the firm decides to move production, namely re- or offshore. For visualisation purposes, the agent is asked to move to a spot on the modelled map where there is no other agent

already located. At the end of the decision-making process, the conclusion is reported.

ask *firms with [offshored? = false] [*

set *relocation-costs (share-for-relocation-costs / 100) * profit*

if *(profit < (profit-abroad - relocation-costs)) [*

move-to *one-of patches with [pcolor = 48 and not any? turtles-here]*

set *offshored? true*

set *reshored? false]]*

ask *firms with [offshored? = true] [*

set *relocation-costs (share-for-relocation-costs / 100) * profit-abroad*

if *(profit-abroad < (profit - relocation-costs)) [*

move-to *one-of patches with [pcolor = 98 and not any? turtles-here]*

set *offshored? false*

set *reshored? true]]*

22. **Firms-size-ratio:** Defines the size of firms in relation to firms' working capital. The sizing corresponds with the one at initial set-up of the industry.

23. **Bankruptcy:** States the conditions leading to bankruptcy. When firms reach a specified threshold, they are no longer part of the economy.

ask *firms [*

if *working-capital <= 10 [die]]*

24. **Tick:** Advances the tick counter by one time period.

tick

25. States the length of each simulation run:

			if *ticks = 100 [stop]*
II) Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?	The model design follows mainstream neoclassical economic concepts and theories.
		II.i.b On what assumptions is/are the agents' decision model(s) based?	**Inspired by studies of:** (Eliasson *et al.* 1976; Deissenberg *et al.* 2008; Erlingsson *et al.* 2014) **Suggested in studies of:** Janssen (2005); LeBaron & Tesfatsion (2008); Neugart & Richiardi (2012); van Dam *et al.* (2013); Tate *et al.* (2014); Rose & Reeves (2017) **Based on established microeconomic theories:** *Homo oeconomicus* (capital calculation, output calculation, calculation of investment and surcharges, revenue calculation, profit calculation) **Following real-world observations:** Identified and outlined problem statement of studied phenomenon in extant literature including previous economic models (e.g. Wiesmann *et al.* 2017; Krenz *et al.* 2018)
		II.i.c Why is a/are certain decision model(s) chosen?	In reference to previous economic models, theoretical considerations follow established concepts in order to ensure scientific reliability of the model. Further, the availability of national statistics guaranteed independent data collection.
		II.i.d If the model / a submodel (e.g. the decision	Some of the parameter values are chosen at random during the calibration

	model) is based on empirical data, where does the data come from?	process of the model whilst directly observing the behaviour of the modelled dynamics.
	II.i.e At which level of aggregation were the data available?	National level
II.ii Individual Decision Making	II.ii.a What are the subjects and objects of decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?	Subjects: Individual firms on the microeconomic level Objects of decisions: Technological progress, cost calculation, labour unit ratio (human labour versus robots), employment, output calculation, revenue calculation, R&D calculation, profit calculation, bankruptcy The relocation decision is made at the end of each simulated business cycle. Over the simulation, all steps of production, as well as cost calculations, aggregate, adding to the final decision-making process.
	II.ii.b What is the basic rationality behind agents' decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	Decision-making in the model follows rational choice theory aiming at the maximisation of utility.
	II.ii.c How do agents make their decisions?	The decision tree is based on the function of utility maximisation. This means that decisions are solely based on economic profitability.
	II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?	Adaption is dependent on: Endogenous variables: ○ **Level of automation** (with an increased level of automation, the firm utilises more robots and hires less human labour which has an effect on the costs for automation as well as the costs for labour wages) ○ **R&D investment** (as soon as the maximum level of automation is

			reached, the firms stop to invest in R&D which also means that a larger share of the revenue can be entered as profit) o **Relocation costs** (as the costs needed for relocation are a share of the profit, they are recalculated prior to each relocation decision) o **Profits** (after deducting the costs from the income, the profit of that business cycle is determined) o **Capital** (depending on the profit of the previous business cycle, firms have more or less capital to spend on production operations of the coming period) Exogenous variables: o **Low-skilled and high-skilled labour ratio** (depending on this ratio, it is determined which mix of skillset is needed to produce goods. This will then have an effect on labour wages as low-skilled and high-skilled workers are paid different wage levels) o **Level of wages** (changed levels of wages in the respective countries determine how many workers can be employed given the planned budget for labour unit costs) o **Automation costs** (changing the costs for running and maintaining automated production determines how many industrial robots can be utilised given the planned budget for labour unit costs) o **Share required for foreign surcharges** (varying shares indicate more or less revenue respectively) o **Share required for relocation costs** (varying shares indicate more or less profit respectively)
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	-

	II.ii.f Do spatial aspects play a role in the decision process?	Yes. Dependent on whether firms produce in Germany or abroad, different national wage levels are determining a firm's ability to hire more or less workers respectively. Within the country, the wages between low-skilled and high-skilled labour yet again differs. Also, there are foreign surcharges (e.g. shipping costs or import tariffs) which only apply when production is located abroad.
	II.ii.g Do temporal aspects play a role in the decision process?	Yes. Accounting is cumulative which means that the financial balance sheet of each business cycle aggregates onto the economic performance of the previous time steps. Next to aggregating economic indicators, the level of automation is assumed to rise in proportion to a firm's R&D investment. As soon as the maximum level of automation is reached, this value stays fix and the investment costs for R&D drop to zero from this point onwards. Depending on the level of automation, as well as the threshold at which robots eliminate low-skilled jobs, the ratio of utilised robots versus human workers adjusts accordingly at every time step.
	II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	-
II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	-
	II.iii.b Is collective learning implemented in the model?	-
II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	<u>Endogenous state variables:</u> o Internal business operations including administration, scouting, hiring process, etc. o Business competition <u>Exogenous state variables:</u>

			- Natural resource supply - Labour market (unlimited pool of low-skilled and high-skilled labour is assumed) - Sales market - Financial market - Dynamics of a competitive market economy
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	-
		II.iv.c What is the spatial scale of sensing?	The spatial scale includes the individual firm-level, as well as the national and global level.
		II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?	Profit calculations occur on the local, namely the microeconomic level following a specific timely order mimicking a yearly business cycle. Global information is directly accessible by any agent at any time.
		II.iv.e Are costs for cognition and costs for gathering information inclu-ded in the model?	-
	II.v Individual Prediction	II.v.a Which data uses the agent to predict future conditions?	Firms use data from financial sheets of past business cycles to predict future conditions.
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	The unique process of this model is the direct comparison of a double-entry balance sheet. More specifically, this means the profit calculation of operations in the current production location to the profit which could have been generated in the alternative destination. As national parameters and exogeneous factors do not change within simulation runs, balancing of accounts can be predicted accurately.

		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	-
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	There are no direct nor indirect interactions among agents. Agents however interact directly with the modelled economy.
		II.vi.b On what do the interactions depend?	Geographic location
		II.vi.c If the interactions involve communication, how are such communications represented?	-
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	-
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	The geographic location determines the two type of agents. There are firms which produce in Germany and others which offshored production. The share of these two types is initially assigned by the modeller, but as firms have the ability to relocate, firms might move back and forth, hence changing their classification.
		II.vii.b How are collectives represented?	The two different types of agents are equipped with separate kinds of entities depending on their production location, as well as own state variables and traits.
	II.viii Heterogeneity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	Yes, the agents are initially provided with heterogeneous state variables. These are the seed capital, the current technological state of the art, the initial selection of firms which are set abroad, as well as the maximum level of automation.
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or	The decision-making is heterogeneous in the sense that firms which produce abroad have to take additional costs (here: foreign surcharges) into account. For firms

	decision objects differ between the agents?	producing in Germany, there are no extra costs, as the sales market is assumed to be in Germany.
II.ix Stochasticity	II.ix.a What processes (including initialization) are modelled by assuming they are random or partly random?	All of the heterogeneous state variables differentiate at initial set-up which means that they significantly influence the outcome of all following processes as the lead conditions vary among each and every firm. More specifically, this means that all business internal calculations of each company start off with their given seed capital. A firm's current level of automation determines how many human labour units are employed, as well as how many robots are utilised. Further, it is assumed that firms with a lower attainability of automation have a higher incentive to offshore where manual labour is cheaper. This is why the initial share of offshored firms are the ones with the lowest value of maximum levels of automation. The maximum level of automation delimits the attainable technological progress.
II.x Observation	II.x.a What data are collected from the ABM for testing, understanding, and analysing it, and how and when are they collected?	<u>Testing via parameter sweeping:</u> After validating the behaviour of the model to mimic the real-world phenomenon under study, the model was then tested via parameter sweeping (CSP-AIMS 2015). First, analysis was manual at random which aimed at identifying parameters which are observably relevant for significantly modifying the behaviour of the ABM. In order to answer the research question of the conducted study, the main focus lied upon parameters related to sustainability. In order to allow for an environmental angle to the studied topic, foreign surcharges were analysed, as well as fluctuating labour wages in Germany and abroad in order to study the social dimension of reshoring. Further, these specific parameters were tested through a methodologically more ordered approach, utilising *NetLogo*'s simulation tool 'BehaviorSpace' (García Vázquez & Sancho Caparrini 2016). The purpose of this approach includes the systematic performance of a vast number of

			experiments in an automated manner. The logic behind testing the values selected was to allow for a minimum and maximum range, as well as a more sensitive range around the initially calibrated value. The data was further analysed using the statistical computing environment *R* (R Core Team 2019).
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)	Allowing for an agent-based perspective allowed insights on how the behaviour of firms, guided by simple economic rules on the micro-level, is dynamically influenced by the complexity of their surrounding environment. Hypotheses related to environmental and social sustainability aspects have been tested in regard to their sensitivity to initial condition. The computational simulations served as a virtual lab for demonstrating how increased environmental regulations targeting global trade and upward shifting wage levels in formerly offshore production locations are key driving and inhibiting mechanisms of this socio-technical system. This has shown the importance of the aforementioned drivers and barriers, next to the role of technological innovations as the main key determinants of shifted economic realities leading to the phenomenon of reshoring.
III) Details	II.i Implementation Details	III.i.a How has the model been implemented?	<u>Computer system:</u> *NetLogo* <u>Programming language:</u> Logo <u>Simulation platform:</u> BehaviorSpace <u>Simulation runtime:</u> 100 ticks <u>Development time:</u>

			January 15th, 2019 until May, 16th 2019
		III.i.b Is the model accessible and if so where?	Will be accessible on the *OpenABM* library: https://www.comses.net/
	III.ii Initialisation	III.ii.a What is the initial state of the model world, i.e. at time t=0 of a simulation run?	Variable: **number-of-firms** Description: describes the total number of firms representing the modelled economy Initial value: 100 Unit: firm Variable: **firm-size** Description: defines the size of the firms depending on their working capital Initial value: small, medium, or large Unit: size of working capital Variable: **share-of-offshored-firms** Description: percentage of firms which initially offshored production Initial value: 8 % Unit: percentage Variable: **offshored?** Description: label reporting whether production is offshored or not [path-dependent] Initial value: true or false Unit: label Variable: **working capital** Description: difference between a firm's current assets and liabilities Initial value: random between >0 and <1000 Unit: euros Variable: **share-of-raw-material-costs**

Description: percentage of working capital allocated to cover raw materials costs

Initial value: 50 %

Unit: percentage

Variable: **share-of-labour-costs**

Description: percentage of working capital allocated for covering labour wages (Perloff, 2016)

Initial value: 50 %

Unit: percentage

Variable: **low-skilled-labour-ratio**

Description: ratio of low-skilled labour required for production [random]

Initial value: 0.8

Unit: ratio

Variable: **high-skilled-labour-ratio**

Description: ratio of high-skilled labour required for production [random]

Initial value: 0.2

Unit: ratio

Variable: **wages-low-skilled-labour**

Description: yearly salary per low-skilled worker in Germany [random]

Initial value: 11

Unit: euros

Variable: **wages-high-skilled-labour**

Description: yearly salary per high-skilled worker in Germany [random]

Initial value: 12

Unit: euros

Variable: **wages-low-skilled-labour-abroad**

Description: yearly salary per low-skilled worker abroad [random]

Initial value: 10

Unit: euros

Variable: **wages-high-skilled-labour-abroad**

Description: yearly salary per high-skilled worker abroad [random]

Initial value: 11

Unit: euros

Variable: **labour-productivity**

Description: amount of output a human worker produces per time step [random]

Initial value: 1

Unit: ratio

Variable: **max-level-of-automation**

Description: maximum level of attainable efficiency of automated production [random]

Initial value: random between 0 and <1

Unit: ratio

Variable: **level-of-automation**

Description: current level of efficiency of automated production [random]

Initial value: random between 0 and <max-level-of-automation

Unit: ratio

Variable: **share-of-automated-firms**

Description: percentage of firms which initially utilised robots for production (Jäger *et al.*, 2016)

Initial value: 29 %

Unit: percentage

Variable: **robot-costs**

			Description: costs for maintaining and running robotic automation (e.g. energy bill) [random] Initial value: 20 Unit: euros Variable: **robot-productivity** Description: amount of output a robot produces per time step [random] Initial value: 10 Unit: ratio Variable: **robots-kill-jobs-threshold** Description: technological threshold at which robots eliminate all low-skilled jobs [random] Initial value: 0.8 Unit: ratio Variable: **sales-price-per-product** Description: global sales price for finished products [random] Initial value: 20 Unit: euros Variable: **share-for-r&d-investment** Description: percentage of revenue allocated for R&D investment [random] Initial value: 1 % Unit: percentage Variable: **share-for-foreign-surcharges** Description: percentage of revenue which is additionally required if production is offshored (e.g. shipping costs or import tariffs) [random] Initial value: 1 % Unit: percentage Variable: **share-for-relocation-costs**

Description: percentage of profit required in case of relocation [random]

Initial value: 1 %

Unit: percentage

Values of the following variables are path-dependent, meaning that they aggregate only after originating from other variables. This means they are heterogeneous for every single firm:

Variable: **actual-low-skilled-labour-ratio**

Description: calculated ratio accounting for the level of automation which has already replaced low-skilled jobs

Unit: ratio

Variable: **actual-high-skilled-labour-ratio**

Description: calculated ratio accounting for the level of automation which has already replaced high-skilled jobs

Unit: ratio

Variable: **robots**

Description: afforded amount of robots utilised for production

Unit: robot

Variable: **low-skilled-labour**

Description: afforded number of low-skilled labour employed for production in Germany

Unit: human worker

Variable: **high-skilled-labour**

Description: afforded number of high-skilled labour employed for production in Germany

Unit: human worker

Variable: **low-skilled-labour-abroad**

			Description: afforded number of low-skilled labour employed for offshored production Unit: human worker Variable: **high-skilled-labour-abroad** Description: afforded number of high-skilled labour employed for offshored production Unit: human worker Variable: **human-labour** Description: number of human labour units employed for production in Germany Unit: human worker Variable: **human-labour-abroad** Description: number of human labour units employed for offshored production Unit: human worker Variable: **labour-units** Description: total number of all labour units employed or utilised for production in Germany Unit: robots and/ human worker Variable: **labour-units-abroad** Description: total number of all labour units employed or utilised for offshored production Unit: robots and/or human worker Variable: **budget-for-labour-costs** Description: initially allocated budget for covering labour wages Unit: euros Variable: **actual-labour-costs** Description: actual budget covering labour wages

			Unit: euros Variable: **automation-costs** Description: actual budget covering robot utilisation (e.g. energy bill) Unit: euros Variable: **output** Description: amount of produced goods if production is located in Germany Unit: abstracted product Variable: **output-abroad** Description: amount of produced goods if production is offshored Unit: abstracted product Variable: **revenue** Description: total income received by selling produced goods if production is located in Germany Unit: euros Variable: **revenue-abroad** Description: total income received by selling produced goods if production is offshored Unit: euros Variable: **r&d-investment** Description: allocated investment in R&D if production is located in Germany Unit: euros Variable: **r&d-investment-abroad** Description: allocated investment in R&D if production is offshored Unit: euros Variable: **foreign-surcharges**

		Description: allocated surcharges if production is offshored (e.g. shipping costs or import tariffs) Unit: euros Variable: **relocation-costs** Description: allocated costs required in case of relocation Unit: euros Variable: **profit** Description: net financial gain at the end of a business cycle if production is in Germany Unit: euros Variable: **profit-abroad** Description: net financial gain at the end of a business cycle if production is offshored Unit: euros Variable: **offshored?** Description: label reporting whether production is offshored or not Initial value: true or false Unit: label Variable: **reshored?** Description: label reporting whether production has been reshored or not Initial value: true or false Unit: label
	III.ii.b Is initialisation always the same, or is it allowed to vary among simulations?	The initialisation of parameters varied during analysis.
	III.ii.c Are the initial values chosen arbitrarily or based on data?	The initial values have been taken from real-world data whenever it seemed sensible to do so. This includes: **share-of-offshored-firms** mimicking the most

			recent data of the actual percentage stating how many firms within the manufacturing industry have currently offshored production (Jäger *et al.*, 2016); **share-of-automated-firms** which is a value taken from an analysis of robot utilisation showing how many industrial companies in Germany have already introduced some level of automation (Jäger *et al.* 2016) The **share-of-raw-material-costs** is inspired by microeconomic textbook examples (Perloff, 2016). Most values have been assigned at random: ○ **number-of-firms** ○ **firm-size** ○ **working-capital** ○ **low-skilled-labour-ratio** ○ **wages-low-skilled-labour** ○ **wages-high-skilled-labour** ○ **wages-low-skilled-labour-abroad** ○ **wages-high-skilled-labour-abroad** ○ **labour-productivity** ○ **max-level-of-automation** ○ **level-of-automation** ○ **robot-costs** ○ **robot-productivity** ○ **robots-kill-jobs-threshold** ○ **sales-price-per-product** ○ **share-for-r&d-investment** ○ **share-for-foreign-surcharges** ○ **share-for-relocation-costs** Exceptions are variables which are dependent on their counterpart: ○ **high-skilled-labour-ratio** (counterpart: low-skilled-labour-ratio) ○ **share-of-labour-costs** (counterpart: share-of-raw-material-costs)
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent	No.

	processes that change over time?	
III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	○ **setup**: sets up the modelled world ○ **setup-economy**: sets up the modelled economy ○ **setup-industry**: sets up the modelled industry ○ **setup-firms**: sets up the initial values for a firm's seed capital and maximum level of automation ○ **offshoring**: determines which firms are initially offshored, namely the ones with the lowest level of attainability when it comes to the maximum level of automation ○ **tech-state-of-the-art**: determines how many firms already utilise automation among their production processes, as well as the firms' current level of automation ○ **go**: describes the process of one simulation run ○ **technological-progress**: determines that firms' level of automation rise in proportion to their R&D investment ○ **costs-calculation**: determines how much of working capital is allocated for raw material costs and how much is then left for the budget meant for labour costs ○ **human-vs-robot**: according to the defined low-skilled labour ratio, its counterpart, the high-skilled labour ratio is defined. Depending on the level of automation and whether it

has already reached the threshold which eliminates all low-skilled jobs, the actual ratios for human labour are calculated.

- **employment**: the planned budget for robot costs and human labour wages are now matched with the current level of automation and the actual human labour ratios respectively. Further, it is determined how many labour units (robots, low-skilled, or high-skilled workers) can be utilised or employed given the planned budget. In reverse, the identified numbers of labour units only then inform about the actual automation and human labour costs.

- **output-calculation**: calculates how much output is produced depending on the actual number of human labour employed, matched with a defined labour productivity. The automation-induced production is likewise depending on the number of robots utilised, matched up with a defined level of efficiency. The produced output is calculated twice, adding to the double-balance sheet in order to allow for comparison during the location decision process.

- **revenue-calculation**: by selling the produced goods to a defined global sales price per product, yielded revenue is similarly calculated twice for the same logic as stated above.

- **r&d-calculation**: a defined share of revenue is allocated for investment in R&D and, yet again, defined differently depening on the production location. If the current level of automation however reaches the maximum attainable level, the investment is dropped to zero.

		○ **profit-calculation**: if production is located in Germany, the profits are the made out of the revenue by subtracting the allocated R&D investment. For offshore production, foreign surcharges which are a particular share of the revenue, need to be taken into the equation as well. ○ **location-decision**: utilising the aggregated double-balance sheet, the profit of the current production location is directly compared with the profit which could have been generated in the alternative location, given the same business configuration. As an additional hurdle for deciding to relocate production, an extra cost for relocation production facilities factors in here, too. ○ **firms-size-ratio**: determines the size of the various firms according to their working capital ○ **bankruptcy**: described the conditions at which a firm declares bankruptcy
	III.iv.b What are the model parameters, their dimensions and reference values?	Variable: **number-of-firms** Description: describes the total number of firms representing the modelled economy Initial value: 100 Unit: firm Variable: **firm-size** Description: defines the size of the firms depending on their working capital Initial value: small, medium, or large Unit: size of working capital

			Variable: **share-of-offshored-firms** Description: percentage of firms which initially offshored production Initial value: 8 % Unit: percentage Variable: **offshored?** Description: label reporting whether production is offshored or not [path-dependent] Initial value: true or false Unit: label Variable: **working capital** Description: difference between a firm's current assets and liabilities Initial value: random between >0 and <1000 Unit: euros Variable: **share-of-raw-material-costs** Description: percentage of working capital allocated to cover raw materials costs Initial value: 50 % Unit: percentage Variable: **share-of-labour-costs** Description: percentage of working capital allocated for covering labour wages (Perloff, 2016) Initial value: 50 % Unit: percentage Variable: **low-skilled-labour-ratio** Description: ratio of low-skilled labour required for production [random] Initial value: 0.8 Unit: ratio Variable: **high-skilled-labour-ratio**

			Description: ratio of high-skilled labour required for production [random] Initial value: 0.2 Unit: ratio Variable: **wages-low-skilled-labour** Description: yearly salary per low-skilled worker in Germany [random] Initial value: 11 Unit: euros Variable: **wages-high-skilled-labour** Description: yearly salary per high-skilled worker in Germany [random] Initial value: 12 Unit: euros Variable: **wages-low-skilled-labour-abroad** Description: yearly salary per low-skilled worker abroad [random] Initial value: 10 Unit: euros Variable: **wages-high-skilled-labour-abroad** Description: yearly salary per high-skilled worker abroad [random] Initial value: 11 Unit: euros Variable: **labour-productivity** Description: amount of output a human worker produces per time step [random] Initial value: 1 Unit: ratio Variable: **max-level-of-automation**

Description: maximum level of attainable efficiency of automated production [random]

Initial value: random between 0 and <1

Unit: ratio

Variable: **level-of-automation**

Description: current level of efficiency of automated production [random]

Initial value: random between 0 and <max-level-of-automation

Unit: ratio

Variable: **share-of-automated-firms**

Description: percentage of firms which initially utilised robots for production (Jäger *et al.,* 2016)

Initial value: 29 %

Unit: percentage

Variable: **robot-costs**

Description: costs for maintaining and running robotic automation (e.g. energy bill) [random]

Initial value: 20

Unit: euros

Variable: **robot-productivity**

Description: amount of output a robot produces per time step [random]

Initial value: 10

Unit: ratio

Variable: **robots-kill-jobs-threshold**

Description: technological threshold at which robots eliminate all low-skilled jobs [random]

Initial value: 0.8

Unit: ratio

			Variable: **sales-price-per-product** Description: global sales price for finished products [random] Initial value: 20 Unit: euros Variable: **share-for-r&d-investment** Description: percentage of revenue allocated for R&D investment [random] Initial value: 1 % Unit: percentage Variable: **share-for-foreign-surcharges** Description: percentage of revenue which is additionally required if production is offshored (e.g. shipping costs or import tariffs) [random] Initial value: 1 % Unit: percentage Variable: **share-for-relocation-costs** Description: percentage of profit required in case of relocation [random] Initial value: 1 % Unit: percentage Variable: **reshored?** Description: label reporting whether production has been reshored or not [path-dependent] Initial value: true or false Unit: label
		III.iv.c How were submodels designed or chosen, and how were they parameterised and then tested?	Parameterisation: The timely order of the submodels initially follows an intuitive order of setting up the economy, industry, and firms first. Further, the production location of the firms is determined. Zooming in on the firm-specific set-up, the individual firms are equipped with a seed capital and a firm's own technological state of the art. These

			two randomised initial values in combination with defined global parameters result in the aggregation of all other path-dependent submodels. This includes the technological-progress, costs-calculation, human-vs-robot, employment, output-calculation, revenue-calculation, r&d-calculation, profit-calculation, location-decision, firm-size-ratio, and bankruptcy. The parameterisation of production, sales, and financial calculation processes follow microeconomic textbook examples (Perloff 2016). During calibration, values of different parameters were adjusted at random aiming at the behaviour of the model to replicate the desired phenomenon, namely the ability of firms to relocate production freely. <u>Testing and validation:</u> In order to validate the created model, the values of the initial setting were controlled whilst testing a minimum and maximum range of values for a selected number of variables. The selection was guided by the reasoning to obtain results which mimick economic dynamics as they can be observed in the real-world which is useful for verifying the functionality of the model.

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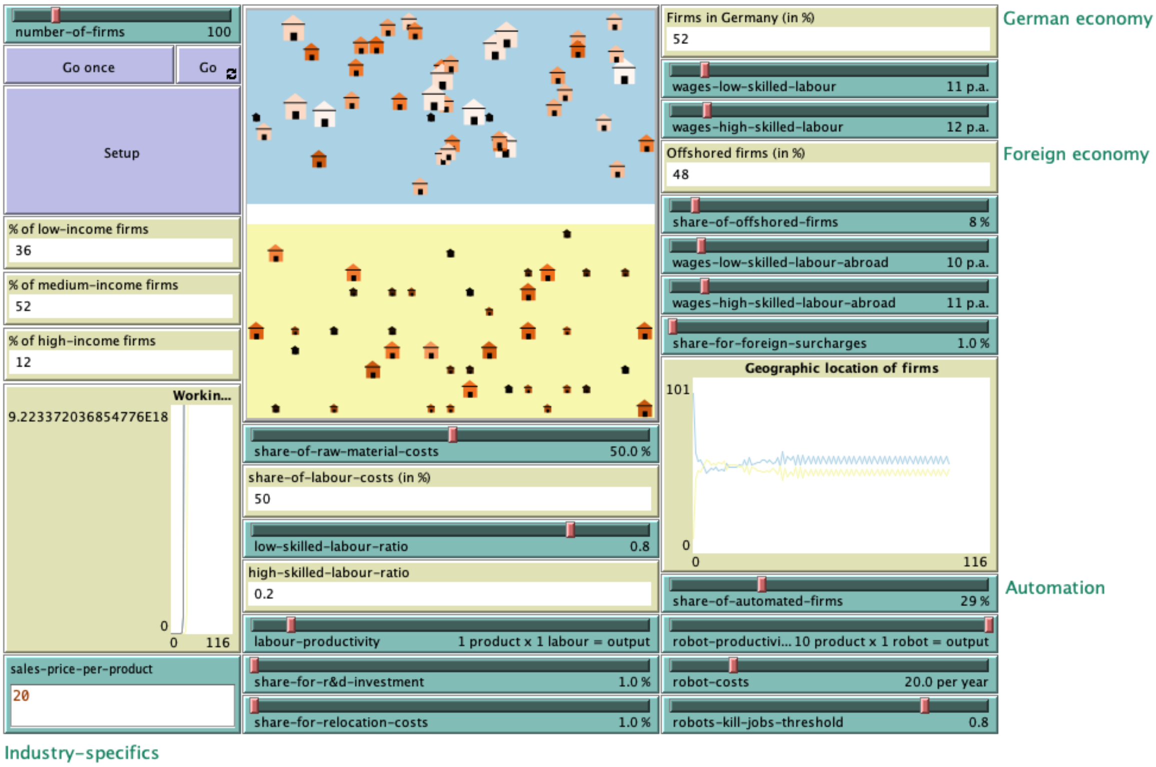
9.2. Model interface

The image below is a screenshot of the model interface depicting the initial parameter values at the point of set-up.



9.3. Model source code

The model can be accessed online at the *CoMSES network*'s open source model library via the following link: https://www.comses.net/codebase-release/1f8b36e1-652e-49d4-a9c0-983dccbc3793/