Towards the inclusion of power dynamics within integrated modelling: an illustration using the World Trade Model

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Towards the inclusion of power dynamics within integrated modelling: an illustration using the World Trade Model

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Abstract

Power dynamics play a crucial role in inhibiting and advancing various policies, from climate action to wage negotiations. However, current integrated models addressing socio-economic and environmental issues often fail to account for the underlying drivers of these power dynamics, thereby illuminating a significant literature gap. This omission limits the ability of the models to capture real-world complexities and may hinder effective policy design.

This paper addresses this gap by exploring how power dynamics can be incorporated within integrated models which deal with socio-economic and environmental problems. It begins with a proof of concept, demonstrating how a specific type of power dynamic, namely labour union bargaining power, can be included into the World Trade Model (WTM), a dynamic form of Input-Output Analysis. This integration is coupled with supplementary research that explains the drivers of said power dynamic in order to address the literature gap. Notably, this paper has made additional contributions by being the first instance of power dynamics included in the WTM, developing new code to convert the WTM into a Multi-Regional Input-Output format to advance the field of dynamic Input-Output Analysis, and clearly documenting this code which was previously missing.

Additionally, the paper outlines a future research strategy focused on two main areas: including power dynamics as inputs to integrated models with parallel research on the drivers of the power dynamics evaluated, and also contains ideas on how to take steps to model the power relationships between actors themselves. This approach holds promise for providing a deeper understanding of how power dynamics influence socio-economic and environmental outcomes. The author advocates for further research to ensure power dynamics are not overlooked in models in order to have a more comprehensive representation of systemic issues.

Contents

Abstract **i**

Nomenclature **iv**

1 Introduction **1**

1.1 Problem definition 1
1.2 Literature review on power dynamics in integrated models 2
1.2.1 GEMs 3
1.2.2 IAMs 3
1.2.3 MEIOs 3
1.2.4 SFCs 4
1.2.5 SDs 4
1.3 Literature gap 4
1.4 Research question and sub-research questions 4
1.5 Overview of this report 5

2 Method **7**

2.1 Literature review of bargaining power 7
2.2 Proposed power variable illustration for dynamic IO 7
2.2.1 Explanation of the World Trade Model 7
2.2.2 Existing uses of the World Trade Model 8
2.2.3 Differences between the WTM and traditional IO 9
2.2.4 Comparison between the original WTM and the adapted WTM 9
2.2.5 Steps to replicate adapted WTM variation inclusive of bargaining power 12
2.3 Code 15

3 Results **16**

3.1 Review on labour union bargaining power mechanism 16
3.2 Proposed power variable illustration for dynamic IO 18
3.2.1 Base case scenario relative to original data 18
3.2.2 Labour union scenarios relative to original data 19
3.2.3 Labour union scenarios relative to base case scenario 21

4 Discussion **23**

4.1 Illustrative model 23
4.1.1 Interpretation 23
4.1.2 Limitations 24
4.2 Strategy and future research 25
4.2.1 Power dynamics as inputs 25
4.2.2 Distinguishing power dynamics between actors 27

5 Conclusion **29**
5.1 Research questions addressed . . . 29
5.2 Implications . . . 30

References **31**

A Appendix A: Documentation **36**

B Appendix B: Model inputs **38**

C Appendix C: Scenario inputs **41**

D Appendix D: Model results **43**
D.0.1 Original data . . . 43
D.0.2 Base case run data . . . 44
D.0.3 Japan labour union model run data . . . 44
D.0.4 Guinea labour union model run data . . . 45
D.0.5 China labour union model run data . . . 46
D.0.6 Relative change of base case data compared to original data . . . 46
D.0.7 Relative change of Japan labour union compared to original data . . . 47
D.0.8 Relative change of Guinea labour union compared to original data . . . 48
D.0.9 Relative change of China labour union compared to original data . . . 49
D.0.10 Relative change of Japan labour union compared to base case run data . . . 49
D.0.11 Relative change of Guinea labour union compared to base case run data . . . 50
D.0.12 Relative change of China labour union compared to base case run data . . . 51

Nomenclature

Abbreviation	Definition
CGE	Computable General Equilibrium
EEIOA	Environmentally Extended Input–Output Analysis
EU	European Union
GEMs	General Equilibrium Models
IAMs	Integrated Assessment Models
IO	Input-Output
IOTs	Input-Output Tables
LP	Linear Programming
MEIOs	Macro-Econometric Input-Output Models
MRIO	Multi-Regional Input-Output
NPISHs	Non-Profit Institutions Serving Households
RCOT	Rectangular Choice of Technology Model
RCOT/WTM	Combined Rectangular Choice of Technology and World Trade Model
SDs	System Dynamics Models
SFCs	Stock-Flow Consistent Models
SNA	System of National Accounts
SUTs	Supply-Use Tables
WISE	Wellbeing, Inclusion, Sustainability, and the Economy
WTM	World Trade Model

1
Introduction

1.1. Problem definition

Power dynamics both interfere with and drive forward various policies, which include but are not limited to those related to climate action, employee protection, and income distribution, and in turn underlay many systemic challenges that we face today [1], [2], [3]. As defined by Korpi (1978), power resources are the properties of an actor that provide the ability to reward or punish another actor with a focus on the fact that there are structural advantages in places for some actors [4]. These disparities in power resources among different actors allow those with greater influence to either obstruct or advance policies for their benefit. A concrete example is with some of the largest meat and dairy companies using lobbying and other power resources to delay, distract, and derail from transitioning the food system, despite the status quo system responsible for approximately one third of global greenhouse gas emissions [5]. Conversely, companies such as Beyond Meat and Oatly also use financial power resources to invest heavily in advertising and innovation to improve product similarity to match non-plant based options [6]. However, despite the efforts of plant-based alternative companies and other actors, deliberate actions by major meat and dairy corporations have hindered policies from being pushed through which would transition the food system more rapidly [5].

While using power resources such as lobbying and investing is a calculated method to promote certain narratives, power dynamics are also evident in areas where policies are absent but essential to ensure fair and inclusive climate change policies across all societal groups. For instance, concrete measures to reduce emissions with bans on private jets, mega yachts, and excessive consumption by wealthy individuals are issues that are relatively easy to address in theory, but remain untouched likely due to the influence of powerful actors. This leads to pronounced inequalities in emissions driven by power imbalances, even with research on evident disparities, such as that some private jets emit two tonnes of CO2 per hour, while the average carbon footprint of citizens in the EU was around 6.8 tonnes per person in 2019 [7].

The influence of power dynamics on policies is not limited to climate change, but also evident in other areas. For example, companies may limit wage increases for their employees, whereas labor unions might leverage their bargaining power to push for higher wages through company or industry-specific policies. On the opposing side, companies may counter these efforts using various resistance mechanisms. This dynamic was evident recently for Amazon as the balance between collective bargaining power to negotiate higher wages and better working conditions clashed with the company taking efforts to dissuade workers from unionising [8].

In the examples discussed, there is often a strong inclination among powerful actors to maintain their control over resources, status, and associated influence, which makes systemic change even more challenging and perpetuates existing power imbalances. This reluctance to relinquish power aligns with Foucault's concept of power relations, where power is seen as a pervasive force that individuals and institutions strive to retain, and when there is power there is resistance [9], [10]. For instance, the relationship between income inequality and climate change illustrates this dynamic. As the wealthy accumulate more power and resources, they contribute disproportionately to emissions. This exacerbates negative environmental impacts and primarily affects the most vulnerable, which thereby deepens their disadvantage and reinforcing the existing power imbalances [11].

However, sometimes this resistance to relinquish power can come with consequences if not aligned with the direction of societal change. For instance, from a politician's standpoint, short-term responsiveness to lobbying efforts may seem to be the most pragmatic decision, such as from those in the automotive industry advocating for the continued use of combustion engines in Germany [12]. However, as demonstrated by the massive shift in China towards electric vehicle production which has now begun to challenge traditional combustion focused automotive companies in other regions, this short-sightedness can lead to significant consequences for domestic industries [13]. Politicians, initially swayed by powerful industry lobbying, are now facing challenges from the inevitable industry shifts and global technological advancements. This example underscores how a lack of long-term foresight and adaptation to emerging trends can leave policymakers and industries unprepared for inevitable changes, regardless of how desperately these industries may cling to existing power structures, such as that of the combustion engine automotive industry.

In each of the aforementioned examples, an overview of the systemic issues at hand is described, but is not inclusive of all the actors involved. This is because the power resources and relationships between these and other actors are inherently complex systemic challenges. Nonetheless, understanding these intricate power dynamics is essential to more gain clarity on the underlying power structures that inhibit or promote certain policies.

1.2. Literature review on power dynamics in integrated models

Hence, power dynamics are an essential hurdle to address if we want to target these systemic issues such as climate change, income inequality, and other challenges through more effective policy design that accounts for these power imbalances. However, integrated models which deal with socio-economic and environmental problems are potentially capable to include power dynamics, but often lack explicit reporting upon these interactions. A review was conducted to assess what the capabilities of such models are as currently used in assessing power dynamics.

The scope of what is classified as integrated modelling which addresses socio-economic and environmental problems for the purposes of this paper are the five groups of top-down policymaker perspective macroeconomic models outlined in the WISE Horizons model review [14]. Models such as Agent-Based Models (ABMs) were excluded from the scope of the literature review as the aforementioned models come more from a top-down policymaker perspective, while models such as ABMs are more bottom-up and require large individual data information and high computational power [14]. Future research should focus on expanding the scope of this literature review.

These economic models can be broadly categorised into neoclassical, post-Keynesian, and heterodox models, each of which have distinct approaches to understanding economic dynamics [14]. Neoclassical models such as General Equilibrium Models (GEMs) and Integrated Assessment Models (IAMs) emphasise market efficiency, rational behaviour, and equilibrium states [14]. Post-Keynesian models such as Macro-Econometric Input-Output Models (MEIOs) focus on demand-driven dynamics and the role of historical data in forecasting [14]. Heterodox models, such as Stock-Flow Consistent Models (SFCs) and System Dynamics Models (SDs), include diverse methodologies to account for complexities and feedback loops in the economy with an aim to challenge traditional economic assumptions [14]. The following section aims to give some background about each of the models and how these could or have included power dynamics. Again, it is important to note that although there could be some types of these dynamics included due to the nature of the model itself, such as with wage increases as inputs, there is a gap within the discussion of what causes these dynamics across all assessed models.

1.2.1. GEMs

GEMs focus on how supply and demand interact across multiple markets to reach equilibrium, typically assume perfect competition and rational behaviour among economic agents, and can then be used to assess policy impacts under the assumption of market efficiency [15]. Some GEMs incorporate market power by allowing for monopolistic competition or oligopolies, which can set prices above marginal cost, influencing overall market efficiency and welfare distribution [16]. However, since GEMs assume market efficiency, these often omit non-market power dynamics such as institutional control and labour union influence. Moreover, the focus on equilibrium states assumes that markets reach a stable balance, and often overlook how power dynamics would shift over time, leading to an incomplete understanding of how fluid power relations impact economic and environmental outcomes. [16].

1.2.2. IAMs

IAMs combine knowledge from various scientific disciplines to assess the interactions between the economy, environment, and energy systems, representing a common method to project potential climate change adaptations. The interactions of the various economic sectors, including detailed environmental and technological data, are mostly based on observations and statistical data. In terms of modelling power dynamics, IAMs have attempted to model socio-economic interactions, while neglecting the importance of lobbying [17]. The influence of of different stakeholders such as fossil fuel industries on policy decision is therefore severely underestimated [18]. IAMs can model the control of natural resources by powerful entities through variables representing resource ownership and exploitation rates. However, IAMs do not fully capture the complexity of power dynamics as their influence evolves over time, which means these may fail to account for cumulative effects of power shifts on policy outcomes and environmental impacts [18]. Although IAMs integrate various domains at a high level, they seldom depict social complexity beyond purely economic behavior [17].

1.2.3. MEIOs

MEIOs focus on the interdependencies between different sectors of the economy and use historical data to estimate the relationships between sectors and forecasted future economic activities, thus emphasising demand-driven dynamics [14]. MEIOs have at times incorporated labour union bargaining power by adjusting labor input coefficients to reflect changes in wage levels and production costs. The role of institutions is modeled by including governance and institutional quality indices, impacting economic performance and sectoral outputs [14]. While MEIOs capture sectoral interdependencies, they may struggle with the dynamic and non-linear nature of power relations. Reliance on historical data may not adequately represent emerging power dynamics and rapid changes in economic and political landscapes [14]. This limitation means MEIOs may miss the impact of sudden shifts in labour market power or institutional changes on economic and environmental outcomes.

1.2.4. SFCs

SFCs consistently account for all stocks and flows in the economy over time, and are often used for analysing financial stability and the impacts of fiscal and monetary policies [14]. For instance, Kaleckian models, which can be considered to be a subset of SFCs, address power dynamics by typically distinguishing groups that antagonise each other, such as through consumption patterns of different household types [19]. As an example, households which earn wages and rent which also allows for room for savings and private investments could be considered capitalists, while the antagonising group of workers uses all wages on consumption with no savings. These kind of models could allow for analysis that focuses on the relationship between income redistribution, investment, and economic growth, which in turn shows the role of power relations and income shares in how these shape macroeconomic dynamics [14]. However, even with these capabilities these current models have very limited discussions on why these power dynamics exist. Additionally, while SFCs model financial flows and economic stability, they might overlook non-financial forms of power, such as political influence and social capital [19]. This oversight limits their ability to represent how political power shifts or social movements impact financial stability and economic outcomes.

1.2.5. SDs

SDs aim to model complex systems with feedback loops and time delays, making these useful for studying dynamic behaviours over time [14]. SDs model the dynamic feedback loops between different power actors, such as corporations, governments, and civil society, by incorporating variables that represent influence and control [14]. Scenario analysis is used to explore how changes in power structures affect economic and environmental outcomes over time. While SDs are suitable for modelling dynamic interactions and feedback loops, they often require extensive data and assumptions, which can limit their accuracy [14]. The complexity of these models can make them difficult to interpret and validate, potentially limiting their use in policy making.

1.3. Literature gap

Although some of the reviewed models may have the capacity to include power dynamics, the actual implementation for power dynamics focused case studies is scarce. For example, there are models that do include wage increases as inputs. However, the gap is in how the papers themselves are lacking in the discussion of the underlying power dynamics which cause this, leading these to just be economic papers studying the impact of wages rather than explaining what kind of actors and their corresponding power resources could drive this, such as labour unions and their bargaining power. To the knowledge of the author, there were no papers which addressed this gap amongst the evaluated models. Including these dynamics could significantly enhance the comprehensiveness of such models. By overlooking such a crucial variable, it is more difficult to capture the complexities of the real world and can inhibit effective policy design.

1.4. Research question and sub-research questions

The main research question aims to address the research gap while increasing discussions in scientific research around integration of power within models, and is as follows:

How can power dynamics be incorporated within integrated models which deal with socio-economic and environmental problems?

As the topic of power dynamics in general is far too broad for one paper, the following approach is taken to address two sub-research questions (SRQs) which have a more narrow scope.

1. What proof of concept can be used as an illustration for how power dynamics could be implemented into modelling?

2. What overall strategy could be used to integrate power dynamics into modelling?

To address this first SRQ, this research applies the World Trade Model (WTM) to an illustrative case study on labour union bargaining power and its impact on domestic production and outsourcing. The WTM is a respected but empirically unproven dynamic Input-Output Analysis (IOA) model and was chosen for this reason, in addition to attempts to make it more accessible to other modellers. This approach fills a research gap by combining a discussion of power dynamics with a practical case study, addressing the lack of such combinations in existing literature. Additionally, there has been no known attempt to include power variables within the WTM developed by Duchin, making this study a novel contribution.

Moreover, the reason for shifting attention to the scope of one mechanism focused on within this paper, namely the link between union bargaining power and wages, is because it has been widely researched with a general consensus on the significant impact of unions on wage levels [20]. Overall, this indicator is well covered in fields such as sociology. Perceptions of unions vary, with some viewing them as a nuisance and others recognising their value in empowering workers politically [20]. However, declining union membership has been linked to a falling wage share and a widening gap between executives and workers [21]. In ”Power and Progress”, Acemoglu and Johnson argue that the direction of technical change depends on who has the power to decide on policies, emphasising the importance of social power in minimising inequalities, especially through trade unions [22]. There is value in exploring ways to understand how pre-distribution can be included in models to more effectively address inequality rather than only focusing on redistribution, such as through seeing how higher minimum wages can boost low-income workers' well-being without reducing employment [23]. This SRQ specifically explores the role of power in the context of trade unions, and encourages a future research path on power structures in other domains that could be included within other methods, such as those within the field of IE. Especially in the context of labour politics, theories such as rational choice, game theory, and institutionalism have been dominant, but while valuable have also lost sight of the inequality of power which is rather fundamental in labour markets [24].

To address SRQ2, a proposed strategy for future research is outlined calling for more models to use power dynamics as an input in combination with research on why those dynamics originate, along with an idea on how to integrate more analysis on power dynamics between actors. A strategy is needed since this is a new, yet relevant field.

There is not a specific hypothesis being tested as the research is exploratory and not aiming to as of yet represent a real world model. The ultimate aim of this research is to serve as a first step to create a framework for other researchers to add power relationships within integrated models rather than to use this sole model to explain causation between wielded power and the resulting effects on the global economy and environment.

1.5. Overview of this report

To develop more holistic models that accurately represent the real world, we cannot overlook the fundamental factor of power dynamics. Greater efforts must be made to include this element. Otherwise, policy recommendations risk being overly simplistic. This paper is an attempt to do so in a preliminary manner and to address this research gap. Therefore, the rest of the report is structure as follows to address the main RQ through the two SRQs. The first sub-research question is answered in Chapter 3 through the results. The second sub-research question is answered through the discussion in Chapter 4.

2
Method

The research design consists of two main components. The first component is focused on conducting a literature review on the influences on labour union bargaining power in increasing or decreasing wages. The second component uses the adapted WTM as an illustration rather than empirical evidence of how labour union bargaining power dynamics could be included in a dynamic IO model. The World Trade Model created by Duchin is used as a base for the research with some characteristics from the combined WTM/RCOT Model by Duchin and Levine [25], [26]. As such, the model used in this paper is referred to as 'adapted WTM'. The model does not aim to represent real world power dynamics, but rather to show the resulting dynamics within the WTM once labour union bargaining power is included.

2.1. Literature review of bargaining power

The methodology for the first section is rather concise, as these results are meant to provide qualitative background to the considerations of what actually influences the level of labour union bargaining power in increasing or decreasing wages. It is meant to serve as a critique and explanation of the relationship between this form of power and wages. This part consists of a literature review focused on fields such as sociology and political economy which have more extensive theories on the power dynamics within labour union bargaining power and other mechanisms. This background helps to later inform the discussion which involves more conceptual thinking of ideas around what the next steps are for power dynamics to be included within integrated models.

2.2. Proposed power variable illustration for dynamic IO

In this section, the methods outline the illustrative model used to show how labour union bargaining power could be integrated within a form of dynamic IOA. The text explains the model, conducts a literature review on relevant uses of the model, outlines the differences with the adapted model used for this research, and provides more background on how bargaining power was included for future replication.

2.2.1. Explanation of the World Trade Model

The World Trade Model is a linear program which generalises the World Model of Leontief in a manner which helps make it useful to analyse scenarios regarding sustainability [27]. The WTM is a linear program which simulates a world economy comprised of m regions, n goods, and k factors of production where endogenous variables are determined through production levels for goods which are based on comparative advantage with the constraint that no region enters into trade unless it benefits economically [25]. The original model determines regional productions and trade flows, along with global prices and scarcity rents for all regions, goods, and factors [28].

This model is intended to be an alternative to the widely used CGE models which have been attempting to model the world economy [25]. The model combines the world economy with representations of the physical environment as both physical and monetary units are included [25]. Duchin proposes that the model is to be used to assess scenarios which consider constraints on factors of production to emulate limited resources [25]. Duchin cites the need for a new generation of world models to address the question that has previously remained unanswered of what types of actions should be taken now that would significantly reduce human impact on the environment, in a manner which interfaces representations of the physical environment with the economy [25]. The scenarios that Duchin proposes require substantial and not marginal changes from current practices, which are not only driven by price and income changes. Similar case studies have been conducted to assess broader implementation of exogenous scenarios in a global MRIO model for the estimation of future environmental impacts, but all are based on Duchin's work [29].

The model has an optimisation component which aims to minimise factor inputs, represented in the original model with physical units. The results of the model would be infeasible within the selected algorithm if global factors cannot meet total global demand. Factor constraints can be used in the model to place limits on exogenously specific demand. Although an increase in demand prompts higher production, this can be constrained by the aforementioned [25]. Factors in a region which are fully utilised can accrue scarcity rents to indicate their scarcity, with an example being if an unpriced factor such as fresh water then has a non-zero scarcity rent in a water-stressed area [25]. The optimisation component of the model aims to minimise factor inputs and uses exogenous factor prices to weigh the quantities of different factors, since these are measured in physical units [25].

The solution to the original WTM creates an optimised allocation of resources which is static rather than dynamic [25]. Duchin cites the need for a dynamic trade model to include changes, such as changes in lifestyles affecting consumption patterns or international transfer of technologies affecting production capabilities, with exogenous scenario assumptions and also endogenous factor prices after the initial period of time [25].

2.2.2. Existing uses of the World Trade Model

This model has not been largely used, thus literature of extensions or applications tend to fall also on Duchin and other collaborators. For instance, Strømann and Duchin extended the model to include bi-lateral trade in the form of a World Trade Model with Bi-lateral Trade (WTMBT), where technological change is exogenous, along with exogenous changes in final demand and factor endowment [28]. Only a few additional papers applied the WTMBT towards specific case studies. For example, the aforementioned authors in collaboration with Hertwich conducted a case study to assess shifting trade patterns using the WTMBT by minimising global carbon emissions in physical units, and by integrating three sectors in the global aluminum production chain [30]. A few studies have used the WTM to analyse agriculture scenarios, such as by Juliá and Duchin who found that production shifts could provide feasible alternatives for global agriculture under climate change, but at higher prices [31]. López-Morales and Duchin applied the WTM to inter-regional exchanges in Mexico that would be needed to shift agricultural production out of water-scarce, but low-cost regions in the country [32], [33]. Springer and Duchin use more of an inter-regional approach and applies the WTM to assess the outcomes of a decisive shift of production and export of agriculture products away from the Global North and towards African and Latin American regions [34]. A conceptual study applying the model for aluminum was subsequently researched [30]. Thereafter, a supplementary RCOT model was developed which corresponds its constraints with cost of technologies used, which had a few conceptual frameworks published but minimal application [35], [36]. There have been no known attempts to include power dynamics within the WTM.

2.2.3. Differences between the WTM and traditional IO

There are a few notable differences with traditional IO. The familiar square **A** matrix and the **I** matrix become replaced with **A*** and **I*** [26]. Although **A** is still a matrix of intermediate coefficients per unit of output and **I** is the identity matrix, these are now rectangular to include additional columns for the technologies [26]. The amount of rows would not change because product producers are assumed to be indifferent to the type of technology used in its production, and instead an objective function which minimises costs for given consumption demand is used rather than maximising consumption. The rationale to have additional columns which make the matrices rectangular is to include the option for a region to have no options to produce the product of a particular sector, rather than each region needing to produce at least one product for each sector. For example, a region may not be equipped to produce a certain output, but may still require the use of this same output which it then imports. If a region does not use a product, the demand quantified in the row of intermediate inputs is also zero. Another notable difference is that different alternatives, or 'technologies' can operate simultaneously if the RCOT feature is activated in the model.

The code used in this paper primarily uses the WTM but has the possibility to be extended to include the RCOT if the 'choice of technologies' feature is added in future research, since the data for different technologies as already integrated within the inputs. As such, when referring to the model used in this research, the term 'adapted WTM' is used. The differences between the WTM and RCOT are still outlined in order to show how each of these models behave, and to help with later understanding which characteristics were used in this code from the WTM and from the RCOT. RCOT by itself converts from basic IO to a LP version of the IO model. RCOT is a linear programming input-output model used for analysis of the economy of a single region, where it allows for one or more sectors to operate more than one technology simultaneously [26]. The lowest-cost technology is used, and then supplemented by others if it encounters a binding factor constraint [26]. Then, the next cheapest technology is chosen. The resulting combination of technologies will be the one that minimises factor costs for the whole economy [26]. Some factors may involve competition for them from all sectors, such as capital and labour, while others are sector-specific or technology-specific [26]. The choice of which technology is used occurs with an objective function which minimises costs for a given consumption demand [26]. The RCOT model then solves for information depending on the scope of the model, such as sector outputs which correspond to binding factor constraints experienced by lower-cost technologies [26]. When combined with the WTM, the model uses the RCOT and adds multiple regions. Then, the choice of technology used is made across all potential technologies and all potential regions. There is simultaneous inclusion of all the regions when determining the lowest-cost international distribution of production and related world prices.

2.2.4. Comparison between the original WTM and the adapted WTM

The code within this research differs from some of the foundational elements within Duchin's original description of the WTM [26]. The main difference is that in this research, the data is converted in the optimisation itself from physical units into monetary values in order to attempt to bring the format closer to MRIO tables for future use in EEIOA.

Technologies

The original WTM does not include technologies, as these are added on within the combined WTM/RCOT model. Technologies are included in the original combined WTM/RCOT model to represent the needed technologies to enable production in the adjusted WTM/RCOT rectangular IOTs. Although this adapted WTM does not include the choice feature of technologies, the code has the data input option for these technologies that can in future research be expanded to include the 'choice' function. In contrast to the original LINGO code, this updated code considers three technologies and assigns one specific technology to each, therefore the aspect of RCOT which includes the 'choice' of technology based on cost does not occur due to the scope of the research. Rather, one technology is assigned to each sector in order to align with aim of the research to understand how domestic production changes, with less focus on which technology would be the most efficient or suitable. To minimise complexity in observing how the model interacts, technologies in the original model related to waste disposal such as recovered metals and refurbished computers are excluded. Meanwhile, technologies for virgin metals, new computers, and other machines are included. Additionally, the results do not distinguish between the different technologies, but rather focus on overall total production by country and sector. The reasoning for focusing on the aggregated production outputs instead of distinguishing across technologies is that the focus of the research question is on using an illustration related to power dynamics rather than including a feature which would focus on selecting the most efficient low cost technology, which is ultimately not the focus of the paper.

Primal and dual model

The WTM has a quantity primal and a price dual, which are components of a special type of optimisation problem often encountered in economic analysis [37]. These can both just be seen as different aspects of the same economic system with the primal focusing on physical quantities and resource allocation, while the dual focuses on economic values and market equilibrium. In the WTM, the primal quantity model solves for output, trade flows, and factor use, while the price dual model determines product prices and scarcity rents on factors of production which are fully utilised [25]. Appendix A shows the formulas which were originally used in the model created by Duchin for both the primal and dual functions [25]. Only the primal function was included in this paper and rents from the dual were not calculated due to the scope of the research. Future research can consider this integration. The formula below with an adapted constraint is the primal that was used within this adapted WTM code. This formula includes technologies since those were used in the adapted WTM, but the function to activate the choice between the technologies based on the lowest cost was not used, as justified in the aforementioned paragraph. [36].

Primal:

$$\mathrm{Min}\, Z = \Sigma_{\mathrm{i}} \pi_{\mathrm{i}}^{T} \mathbf{F}_{\mathrm{i}}{}^{*} \mathbf{x}_{\mathrm{i}}{}^{*} \tag{2.1}$$

subject to:

$$\mathbf{F}_{\mathrm{i}}{}^{*}\mathbf{x}_{\mathbf{i}}{}^{*} \leq \mathbf{f}_{\mathbf{i}}, \mathrm{i} = 1, \ldots, \mathrm{m}$$

$$\mathbf{x}_{\mathbf{i}}{}^{*} \geq \mathbf{0}, \mathrm{i} = 1, .., \mathrm{m}$$

In order to minimise Z, the total cost associated with producing the output using the given factor prices and factor requirements in the aforementioned formula, Figure 2.1, Figure 2.2, and Figure 2.3 provide clarity on what the variables used for these formulas mean and how they are applied within this research where relevant. In the original WTM with formulas in Appendix A, these are subject to the three constraints that the total output is sufficient to meet the final demand when accounting for intermediate consumption, that the production does not exceed the available factor endowments, and that the outputs cannot be negative. In this adapted WTM as in Equation 2.1, the main difference is with the first constraint which is absent, as instead of intermediate consumption being greater than or equal to the final demand, it rather is solved for and not included as a constraint where it must be less than or equal to the intermediate production, as in Equation 2.1. Net output is a result rather than a constraint as it was in the original WTM formula. This is further elaborated upon as a contribution of this adapted WTM in the 'Final demand' section of Section 2.2.4.

Variable	Description	Examples within this research
m	Number of regions	3 (Japan, China, Guinea)
n, i	Goods and services which are produced (**n**) across that number of sectors (**i**)	3 (metals, computers, other machineries)
t	Technologies	3 (virgin metals, new computers, other machineries)
k, k_r	**k:** Total number of unique factors of production utilised in all regions combined **k_r:** Number of factors of production which are available in a specific region **r**	3 (labour, ore, used computers)

Figure 2.1: Distinct model variables in the WTM.

Variable	Description	Dimensions
m	Number of regions	3 (Japan, China, Guinea)
A*	Similar to the traditional A in IOA in representing produced output for the region, but with rectangular with n rows for the number of alternative ways to produce output of the row sector.	Dimensions of $A_r^* = n \times s_r$ Size of domestic production = number of goods & services produced (x) number of technologies available for the region
I*	Similar to the traditional I in IOA with containing n rows with one for each sector, but may also contain 0, 1, or any amount of 1s or 0s. The number of rows is the number of intermediate inputs. The presence of a 1 in a row means a particular input can be produced domestically. More than one occurrence of a '1' in a row means that there is more than one	Dimensions of $I_r^* = n \times s_r$ Size of domestic input production identity = number of goods & services produced (x) number of technologies available for the region
y	Represents the domestic final demand.	Dimensions of $y_r = n \times 1$ Size of domestic final demand for a region = number of goods and services produced x 1
F*	Matrix of factor input requirements per unit of output, and can be rectangular depending on the number of technologies available.	Dimensions of $F_r^* = k_r \times s_r$ Size of factor input requirements per unit of output for a region = number of factors of production available in the region (x) number of technologies available for the region
f	Represents a vector of factor endowments.	Dimensions of $f_r = k_r \times 1$ Size of factor endowments for a region = number of factors of production available in the region (x) 1
π	Represents a vector of unit prices of the factors.	Dimensions of $\pi_r = k_r \times 1$ Size of unit prices of factors for a region = number of factors of production available in the region (x) 1

Figure 2.2: Input variables in the WTM.

Variable	Description	Dimensions
x*	Represents the output by technology.	Dimensions of $x_r^* = s_r$ x 1 Size of output by technology for a region = number of technologies available in a region x 1
x	Represents the output by sector.	Dimensions of x r = n x 1 Size of output by sector for a region = number of goods and services produced x 1

Figure 2.3: Variables solved for in the WTM.

Optimisation function

The IOTs themselves do not include optimisation as these are sourced from data. EEIOA also does not use optimisation in its static state, unlike the WTM. Moreover, the optimisation function used in the MATLAB updated code is different from the LINGO code. The updated code uses the fmincon interior-point algorithm which is non-linear, while LINGO uses a built-in linear programming solver [38], [39]. The interior-point algorithm was selected as the MATLAB documentation recommends to first use this one for minimisation within the different fmincon algorithms to achieve a minimisation goal, and then adjust to others if necessary [40]. The interior-point algorithm satisfies bounds within all iterations, and is more flexible than other algorithms with its ability to be used for both problems with large and small amounts of variables and constraints, as well as matrices with both many zeros and those with many non-zeros [40]. Other algorithms may suit the model better, but this one was used illustratively and selected according to the documentation recommendations.

Final demand

One of the most notable contributions within the updated model is that this code solves for domestic final demand while having constraints on other parts of the code, such as factor endowments. Using this makes the model more compatible with future potential EEIOA research. Duchin's original model does not solve for final demand, but rather sets a maximum constraint on what final demand should be [36]. The final demand is solved for throughout the optimisation process which aims to minimise costs rather than existing as an explicit constraint, in turn implicitly ensuring that production meets final demand.

Monetary and physical units

The adjusted code uses monetary units for the optimisation itself of the primal model which minimises costs, and solves for final demand. This is unlike the original code which only integrates costs in the optimisation in the dual model portion. However, it is important to also note that in the updated WTM the variable being solved for in the optimisation and shown in the results is the multi-regional A* which is in physical units and shows the domestic production. The costs are what are being minimised in order to solve for the A*, composed of the x and x* in Figure 2.3. This change was made to better replicate current MRIO format for the primal model as well [41].

2.2.5. Steps to replicate adapted WTM variation inclusive of bargaining power

The intention of this section is to document the steps required to replicate the adapted version of the WTM used here. Appendix B shows what all the input variables were in detail and Appendix C outlines how the scenarios were constructed.

Source data used

The underlying data of the model is sourced from a paper from Duchin and Levine which applies the RCOT/WTM to the recovery of products and materials for reuse which was obtained by contacting the authors [36]. However, there is limited transparency on where exactly this data and the underlying production recipe are sourced from by the authors. The three regions selected are characterised below in the aforementioned paper and are roughly modelled on these countries. The purpose of taking a national perspective is to elevate concerns with countries having varying levels of access to resources, and with decisions taken by some actors having repercussions that are prevalent throughout the global economy [36]. These representations are broad and the specific source data used to represent each grouping is not sourced in the paper. The original paper intended to propose a framework to gain new insights into the global resource economy in order to design cooperative strategies amongst governance institutions [36].

Region 1 is Japan and represents countries which have rich and industrialised economies, limited material resources leading to high dependency on imports, and high quantities of built capital for material recovery [36]. Region 2 is Guinea and represents countries which have poorer economies, high material resource endowments leading to large dependency on exports rather than imports to support the domestic economy, and low quantities of built capital for material recovery [36]. Region 3 is either China or India and represents countries which have growing and large economies, medium levels of material resources, and medium levels of built capital for material recovery which are also rapidly growing [36].

Inclusion of the bargaining power factor

As seen in Appendix C, several scenarios were constructed after running the base case. As this research is exploratory, the ’bargaining power factor’ is simply an addition of 20% as an input for each of the countries when it was considered that a labour union exists within the ’factor price’ input for labour. The intention of this decision is to show how the model reacts in response to one input variable change. Figure 2.4 documents the supplementary MATLAB code in more detail with relevant formulas, input data, and processes of the entire procedure. The purpose of this diagram is to show how what variables were used in the code itself in order to reach the optimisation. The variables used in the updated WTM code are bolded and italicised. Relevant formulas are included as well. The code itself is also documented in more detail in the comments. The sectors used in this updated model are metals, computers, and other machinery. Although technologies are included as virgin metals, new computers, and other machines, the choice of technology feature is not applied but can be in future research. The factors used are labour, ore, and used computers. The input variable being changed for the bargaining power factor in the scenarios is within the ’factor prices’ input, with the labour factor price being increased for each corresponding scenario by an additional 20% on top of the original data.

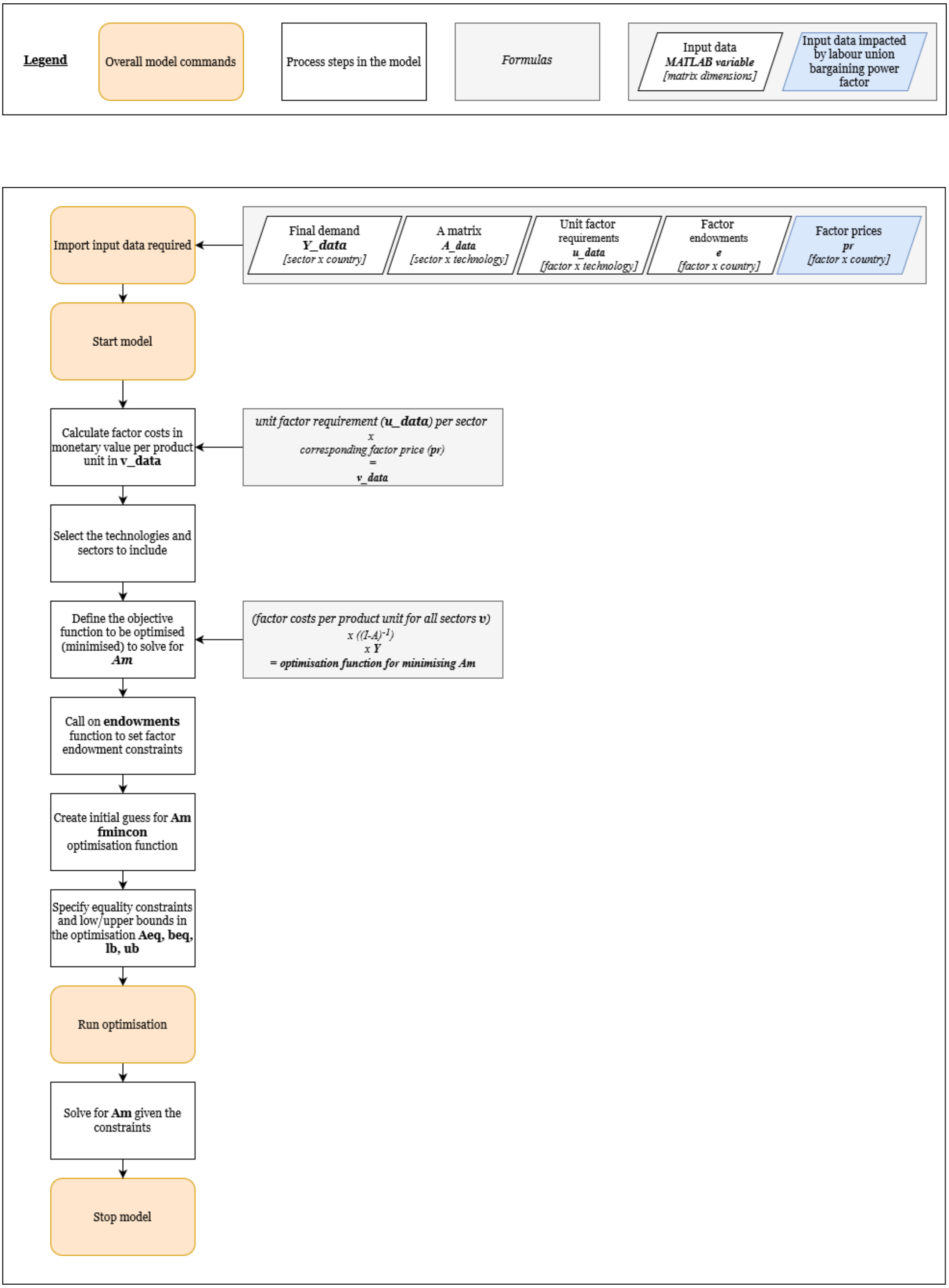

Figure 2.4: Model flowchart.

Modelling framework
The adapted MATLAB model sources data from the supplementary WTM_data.xlsx file. For each labour union bargaining power scenario, the labour within the 'Factor price' tab is adapted for each of the countries. In addition to the base case, three other scenarios were run all using the same conditions within the interior point algorithm. The base case does not include the labour union bargaining power factor, and runs the model based on the inputs found in Appendix B. In scenario 1, Japan has a labour union and the labour factor price for Japan is increased by 20%. In scenario 2, Guinea has a labour union and the labour factor price for Guinea is increased by 20%. Finally, in scenario 3, China has a labour union and the labour factor price for China is increased by 20%. The precise scenario inputs for replication can be found in Appendix C.

The purpose of this modelling decision is to illustrate how the model operates, rather than to represent any reality. This is evident as the direct relationship between a labour union existing solely in one country, and thus the increased wage percentage by exactly 20% immediately for one industry amongst a three industry economy is indeed non-representative of the real world. To reiterate, the purpose of the model is to then illustrate how one type of power dynamic mechanism can be included, and to observe the resulting effects on the model. The manner with which the results are analysed is by comparing the original data with the base case results, in which the model is run with the original data for labour factor prices to first understand how other inputs can affect the results. Then, each of the three scenarios with each country containing a labour union were compared against the base case scenario, in order to assess differences in how various unions could produce alternate results due to other inputs, such as factor endowments and the original intermediate good production levels. The comparison is between the proportion of intermediate goods subject to total domestic production compared to those allocated to total imports, both relative to the respective base case domestic production and imports. The results for intermediate production are then analysed across the different scenarios and regions.

2.3. Code

The code with documented comments can be found in the supplementary material. This contains the commented MATLAB code which was created for this paper, the required source files, and the LINGO code created by Duchin and Levine which had additional documentation added in the comments. Please note that the LINGO code was not used for this model, was not created by the author, and was rather used more to understand the theory underlying the model.

3

Results

3.1. Review on labour union bargaining power mechanism

The intention of this section is to outline a type of mechanism in which power dynamics can be shown based on existing literature to use as a base for the discussion section, which considers ideas for how this can included within integrated models.

The relationship between labour union bargaining power and wages has been extensively studied, providing valuable insights into how collective bargaining impacts wage outcomes across different contexts. This section consolidates the findings from various studies and highlights key factors that influence union bargaining strength, while also noting the challenges in identifying a true causal impact of unions on wages. The strength of the actual power mechanism in this case is analysed, namely the influences on increasing or reducing the ability of unions to negotiate higher wages.

The bargaining power of labour unions is closely tied to the proportion of the workforce they represent. Studies have consistently demonstrated that a higher percentage of unionised workers correlates with stronger bargaining power, leading to an increased union wage premium [42], [43], [44], [45], [46]. This enhanced bargaining power enables unions to negotiate better wages and benefits for their members. However, it is important to not only consider union membership as a proxy for power in compressing wage differentials, but also to understand that this ability to negotiate higher wages is contingent on the type of industry and country. For instance, a theory exists regarding industries where product demand is price inelastic, and claims that unions are then more successful in securing wage increases because employers can either draw from higher profit margins or pass the increased costs onto consumers without significant competition [20]. If unionised workers are predominantly in higher paying jobs, the effect on wage compression may also be less pronounced than those in lower income positions [20]. The level at which collective bargaining occurs, such as at a national versus company level, and the amount of coordination between different levels can also impact this differential, with more centralised and coordinated bargaining systems tending to produce more uniform wage outcomes across different sectors [20]. Moreover, regional differences may impact if union membership is even a suitable proxy for increased union power. For instance, in regions such as Continental Europe, concentrating exclusively on union membership is less insightful because collective bargaining agreements frequently encompass the majority of workers, irrespective of whether they are union members [20]. Here it could be more useful to analyse the types of collective bargaining which can also influence non-union sectors. A few studies have examined the regional differences between different levels of bargaining on wages [47], [48]. For instance, their research shows that in Belgium and Denmark, company-level agreements increase average wages and widen wage dispersion compared to multi-employer agreements [47], [48]. In contrast, in Spain, company-level agreements also raise average wages but result in lower wage dispersion. The authors explain that in Belgium and Denmark, employers use company-level agreements to tailor pay structures to the firm's needs, while in Spain, unions use these agreements to reduce wage inequality [47], [48].

There are also findings regarding other more indirect mechanisms which can influence relative wage increases or decreases for union members beyond their negotiating power. Traditionally, it is assumed that unions create a wage premium through direct wage negotiations for associated workers [20]. However, various other factors can contribute to union-non-union wage differentials. First, during periods of economic downturn, non-unionised workers often face wage cuts or freezes as employers attempt to reduce costs, while unions can negotiate to protect their members from such wage reductions and in turn maintain higher wage levels compared to their non-union counterparts [20]. Second, the threat effect can occur when non-union employers proactively raise wages to avoid unionisation amongst their workforce [20].

Despite the association between union presence and higher wages, isolating the exact causal impact of unions is challenging. One difficulty is in identifying a scenario which explains what wages would look like in the absence of unions, thus making it hard to isolate the true causal impact of unions on wages [20]. Without a clear baseline, attributing wage differences solely to union activities is complex. Additionally, most research on union wage effects is concentrated in the United States and the United Kingdom along with some limited focus on Continental Europe, thereby limiting the generalisability of findings to other regions [20]. Moreover, certain types of theories more rooted in other disciplines, such as sociology and political economy, bring additional insights around power which are directly relevant and are useful to supplement IE research. Power resource theory as described in 'The Working Class in Welfare Capitalism' considers that the power of labour unions and working class movements is critical in shaping welfare state policy [4]. This is an empirical approach to analyse the characteristics and effects of social policies within industrialised nations, which ultimately concludes that social welfare is larger and income inequality is lower in nations with higher political organisation amongst the working class [49], [50].

Beyond the context of labour unions, power resource theory examines how different groups in a society mobilise and wield power to influence economic, political, and social outcomes, and posits that groups with greater access to resources can exert more influence on policies and decision-making, often leading to inequality and power disparities [4]. The theory ultimately advocates for organised and strategic action in altering power structures and achieving desired goals [4]. The field has critiqued that empirical analyses of power resources typically use very rudimentary indicators, such as union density or collective bargaining centralisation, in order to estimate the power resources of unions [24]. In the context of labour unions, extensions of the power resource theory advocate for the inclusion of at least five disaggregated types of power resources which add more nuance to the types of power held by labour union workers, namely structural, associational, institutional, ideational, and coalitional power resources [24].

Structural power resources are derived from workers' positions in the production system, by for instance enabling them to disrupt operations through strikes, slowdowns, or road blockages [51]. This power includes workplace power, based on employer dependence on workers, and marketplace power, influenced by overall labour market conditions, job supply, and economic cycles [51]. Associational power resources stem from collective worker organisational structures, but also highly depends upon whether the members are active and willing to engage in the movement [51]. Institutional power resources use established legal and regulatory frameworks that govern labour relations, providing structured methods for conflict resolution and negotiation [24]. Ideational power resources use ideas and norms to create internal cohesion within unions to foster alignment on a common message and to activate collective action [24]. Coalitional power resources include the ability to form coalitions with other groups or collective actors [24]. The purpose of writing out these more disaggregated definitions of power resources on a high level aims to motivate researchers to consider alternative and more nuanced examples of what should be considered in determining the amount of power an actor has, such as a labour union with its bargaining power.

Ultimately, the complexities of the systems humanity exists in suggest that establishing clear-cut causational links is challenging. Thus, a deeper more qualitative review of the potential linkage between labour union bargaining power influence on wages requires more background. The subsequent section illustrates a more basic connection between more labour union bargaining power strength driving wage increases and domestic production within dynamic IO frameworks given the introductory nature of this research. However, this background more in depth research on the complexities of this relationship is necessary in order to first understand how these complex interactions are difficult to all effectively model and come with limitations. The second reason is to convey that although these interactions are complex this field is worth evaluating to better understand changes in distribution and composition of power resources in order to drive societal change. Ideas on what the next steps are for research in this area and for additional case studies can be found in the discussion section.

3.2. Proposed power variable illustration for dynamic IO

The full raw results of the Am matrix, and the relative absolute value changes to the original data and the base case data can be found in Appendix D. This section shows only the summarised graphs.

3.2.1. Base case scenario relative to original data

The base case scenario results in Figure 3.1 are shown in the same way as the other labour union bargaining power scenarios to illustrate how each of the countries behaves in terms of domestic production and imports purely based on the original constraints and assumptions of the model. Relative to the original data, China sees a large decrease in domestic production of -1,241kg, while Japan and Guinea see very minimal reduction in domestic production at -1kg for both. On the contrary, total imports relative to the original data are much more prominent with increasing for Japan at 860kg and for Guinea at 381kg. China then has a very minor increase in the relative imports of 1kg. Overall, only China's domestic productive decreases significantly, while Japan has the highest increase in relative imports and Guinea has the second largest increase in relative imports.

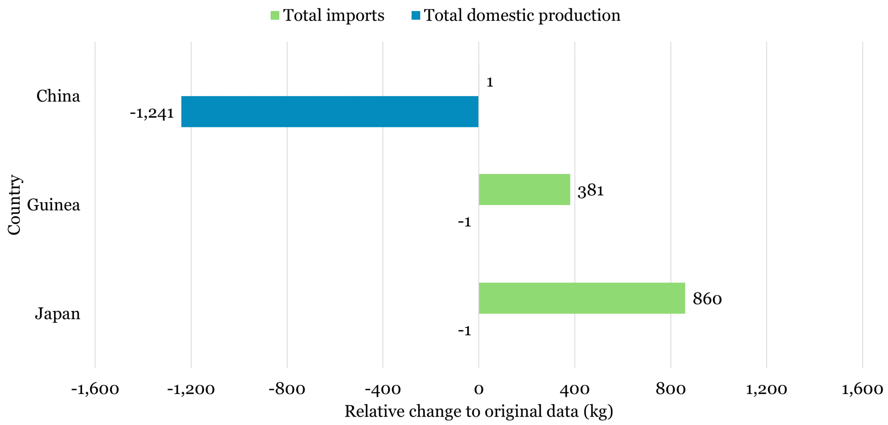

Figure 3.1: Base case run of model relative to the original data for each country with no labour unions in any country.

3.2.2. Labour union scenarios relative to original data

Three labour union scenarios were tested and compared to the original data. In the first scenario, the factor price input for labour for only Japan was increased by 20% implying Japan has increased labour union bargaining power thereby driving wages up with results in Figure 3.2. There were no changes relative to the original data for domestic production in Japan and Guinea, and for imports in China. The largest increase in relative imports came from Guinea with 1,321kg and Japan had a relative increase by 250kg. Meanwhile, China had a large relative decrease by -1,571kg.

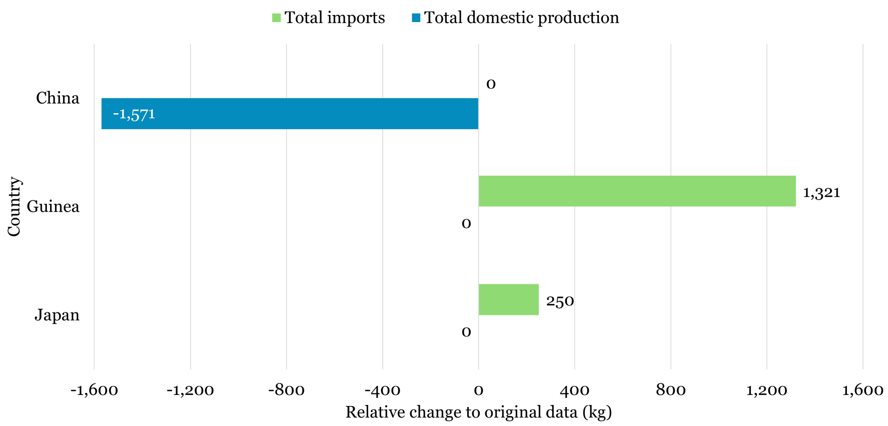

Figure 3.2: Labour union scenario run of model relative to the original data for each country with a labour union in only Japan.

In the scenario with Guinea having increased labour union bargaining power and thus higher wages, the results are in Figure 3.3. Here Japan was much less sensitive than the other two countries with a small decrease in relative domestic production by -2kg and a slightly larger increase in relative imports by 143kg. Conversely, Guinea and China both had similar trends with domestic production reducing by -894kg and -904kg respectively. The relative imports increased slightly more for Guinea by 875kg and by 782kg for China.

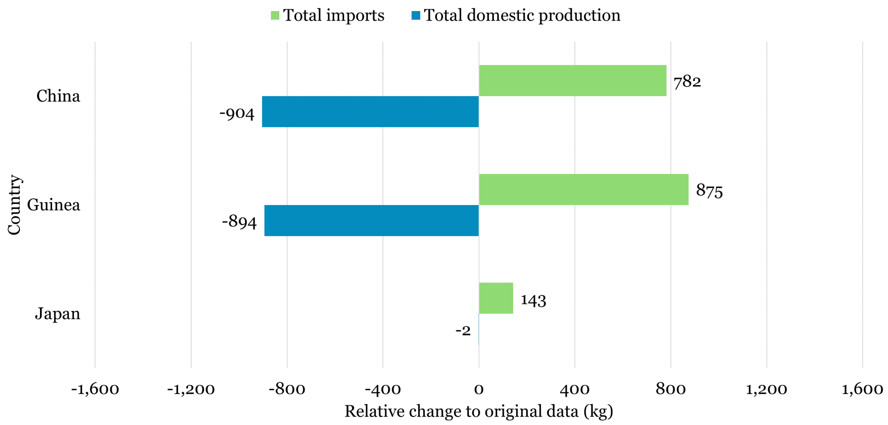

Figure 3.3: Labour union scenario run of model relative to the original data for each country with a labour union in only Guinea.

With China having increased labour union bargaining power and thereby higher wages, the results are shown in Figure 3.4. All countries were much more sensitive in this scenario with a general trend of relative domestic production reducing by large amounts and relative imports increasing by large amounts. Japan had the largest decrease in relative domestic production with -1,100kg, Guinea had slightly smaller of a decrease with -1,060kg, and China had the smallest decrease which was still close at -949kg. The relative increases of imports across all countries had an opposite trend from the relative domestic production, meaning that the country with the largest decrease in relative domestic production, Japan, had lowest increase in relative imports with 967kg. Additionally, the country with the smallest decrease in relative domestic production, China, had the highest increase in relative imports with 1,136kg. Guinea remained in between both countries on the relative imports as well, with a relative increase in total imports by 1,006kg falling between China and Japan.

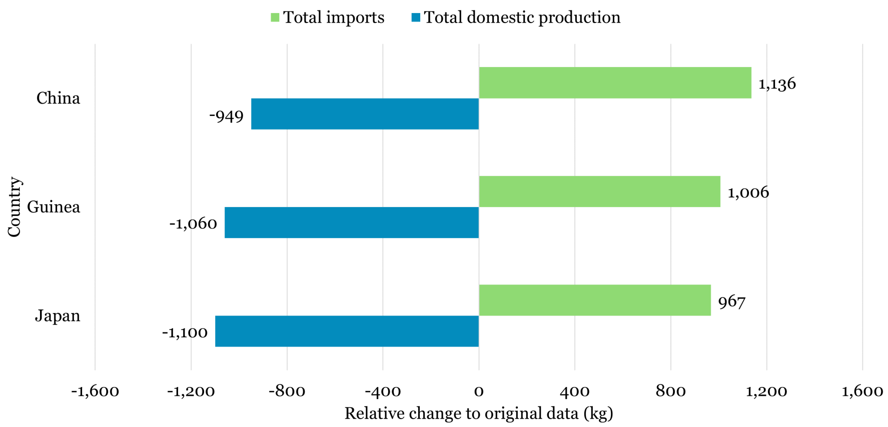

Figure 3.4: Labour union scenario run of model relative to the original data for each country with a labour union in only China.

Across the three scenarios, Japan had both the relatively largest increase in imports and decrease in domestic production when China had a labour union, with much smaller increases and decreases in the other scenarios. Guinea had the relatively largest increase in imports when Japan had a labour union and the largest decrease in domestic production when China had a labour union. China had the relatively largest increase in imports when it was considered to have a labour union and the largest reduction in domestic production when Japan had a labour union. Moreover, the scenario with Japan having a labour union was the only scenario to not see both an increase in imports and a decrease in domestic production for each country.

3.2.3. Labour union scenarios relative to base case scenario

The same three labour union scenarios were tested as above, but here were instead compared to the base case scenario data. In the first scenario with Japan having increased labour union bargaining power, the results followed a similar trend to those compared to the original data, but had some differences as seen in Figure 3.5. For instance, the relative imports decreased for Japan by -610kg rather than increasing as when compared to the original data. There were also very small increases in the domestic production for Japan and Guinea along with a small decrease for China, which were not as present relative to the original data. Otherwise, compared to the previous section relative to the original data, the relative imports increased for Guinea by a smaller amount of 940kg and reduced for China by a smaller amount of -330kg.

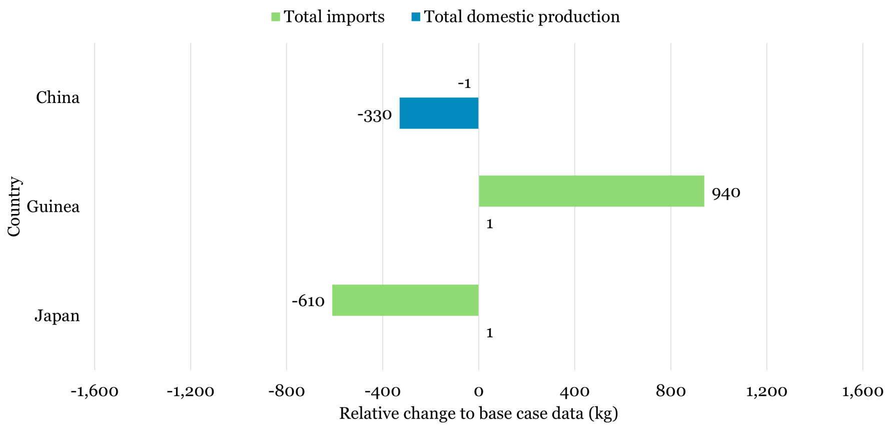

Figure 3.5: Labour union scenario run of model relative to the base case data for each country with a labour union in only Japan.

In the second scenario in Figure 3.6 with Guinea having increased labour union bargaining power, the results followed a similar trend for Guinea itself with slightly less sensitive changes than in the comparison to base case data, with domestic production reducing by a smaller amount of -893kg and increasing imports by a smaller amount of 494kg. Conversely, for Japan the imports reduced by -717kg which is quite different from the increase in the comparison with the original data, while the domestic production remained quite similar with -1kg. China had a similar trend with its imports increasing 781kg, while there was different result from the comparison with original data as here domestic production increased rather than decreased by 337kg.

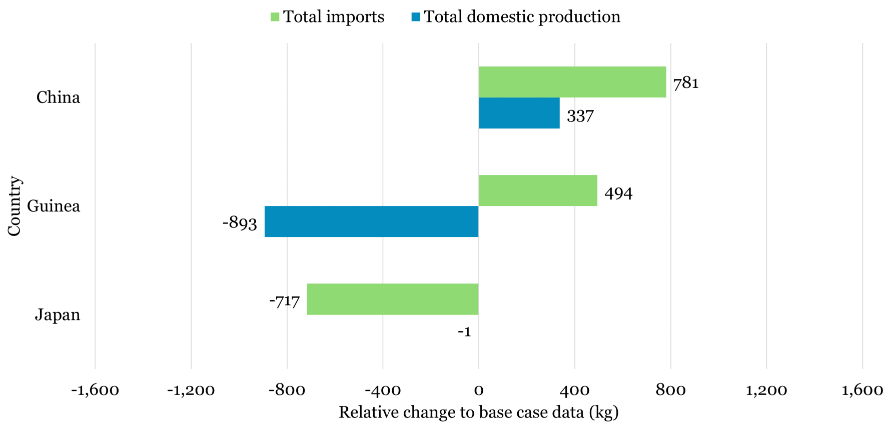

Figure 3.6: Labour union scenario run of model relative to the base case data for each country with a labour union in only Guinea.

With China having increased labour union bargaining power in Figure 3.7, the results were overall less sensitive than in the comparison to the base case data. China, itself, had a similar trend with its imports increasing by 1,134kg, while the domestic production had a different relative change of increasing 292kg while it decreased in the comparison with the base case data. Otherwise, Japan and Guinea had similar but slightly smaller decreases in domestic production by -1,099kg and -1,059kg respectively. The increases in imports were much smaller than in the comparison with the original data, with 107kg for Japan and 626kg for Guinea.

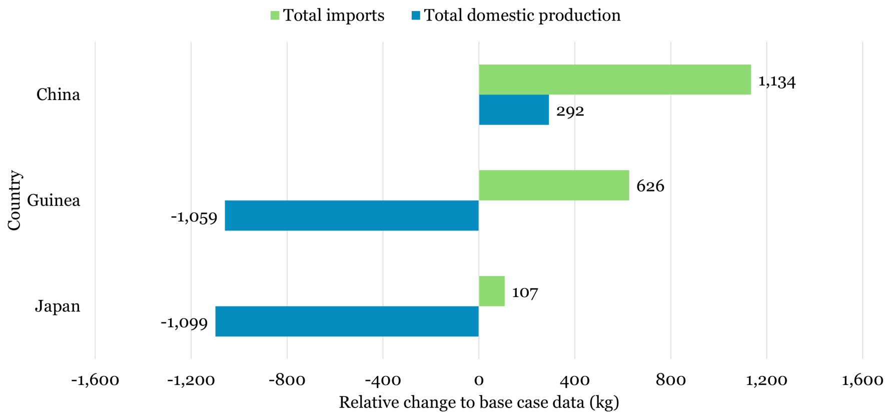

Figure 3.7: Labour union scenario run of model relative to the base case data for each country with a labour union in only China.

Across the three scenarios, Japan had only one case with an increase in imports when China had a labour union, and this was quite small relative to the comparison with the original data. Japan also had its largest decrease in domestic production in the case when China had a labour union, but to a similar amount as in the comparison with the original data. Guinea had its relatively largest reduction in domestic production when China had a labour union and largest increase in imports when Japan had a labour union. China had its relatively largest change in domestic production with an increase in the case when Guinea had a labour union. China also had its largest change in imports in the case where it has a labour union itself.

In terms of general trends across both the comparison with the original data and base case data, relative domestic production reduce and imports increase with a few exceptions. Also, in the scenario with China having a labour union, the sensitivity is generally higher from all countries including China to having larger increases and decreases.

4
Discussion

The integration of power dynamics within socio-economic and environmental models is lacking. This omission limits how representative such models can be of the economy and its interactions with the environment. Without considering power dynamics, policies designed from these models may not fully address root causes of these power imbalances, potentially leading to unaddressed resistance from more powerful actors. This exclusion from integrated models is in part because power dynamics are difficult to quantify as they involve complex and context-specific relationships between actors that are not easily captured in numerical data. Nevertheless, this paper attempts to show an illustration of how one type of power dynamic can be modelled with the aim to encourage more research in this field. After interpreting these results, this discussion thereafter provides a strategy for future research that should be pursued by other natural and social scientists.

4.1. Illustrative model

4.1.1. Interpretation

Across all the scenarios, changes to the data for China has facilitated much more sensitive results with relatively larger increases and decreases across all countries. This implies that the global supply chain is much more reliant on China than for example on Japan, potentially guided by the model inputs where there are higher production capabilities and low costs for the technologies in China [52], [53]. Although a clear link to this dynamic being representative of the world at large is not sufficient, some validity of the model assumptions could be noted with some preliminary representation of real world dynamics. For instance, with the underlying assumption that some production capabilities relative to costs of China are more efficient, and that the global supply chain is indeed quite reliant on China and sensitive to changes within it. Much more granularity by industry, experimentation with the inputs, and real world data would be required before empirical results from this can be reaped. There has been no application of power dynamics in general, or of labour union bargaining power more specifically, to the WTM. Therefore, comparing the results with current papers beyond the more general aforementioned global dynamics to validate some of the assumptions and outcome trends of the model is not possible.

When assessing the comparisons of all the scenarios relative to the base case data and the original data, relative domestic production would reduce and imports would increase with only some exceptions. Part of the justification for these dynamics is because the base case data after being run has no imports across all technologies, which is based on the source data from Duchin. Therefore, any change is shown to be increasing, which in turn creates a reduction in relative domestic production to ensure final demand is being met. Future research could address this by running additional base case scenarios that already consider there to be imports, and adjusting constraints to also include information on exports through allowing imports to be negative. There were some anomalies in this trend as well, but not many. In general, when there was a labour union there was not distinct enough of a trend to explain all the cases. The scope of the model is more to show how this can be included as an input and what general trends in relative differences can be observed, rather than making conclusions about the real impact of labour union bargaining power.

With first the identification of the research gap through literature reviews of the integration of power dynamics in macroeconomic modelling, the applications of the WTM, and the uses of labour union bargaining power as a mechanism, this research addressed a key literature gap of adding to the discussion on the drivers of these power dynamics. This illustration has also contributed to this gap by showing a potential way to integrate labour union bargaining power as an input within the WTM, which has not ever had power dynamics included within it. This research has gone further to provide a well-documented version of the WTM code in hopes of making it more accessible and applicable for additional power dynamics research. A contribution is also made with the code itself through its adjustment to the more accessible MATLAB format from the original LINGO code, along with its into MRIO compatible layout.

4.1.2. Limitations

Even with the aforementioned contributions of this illustration, there are some limitations to consider. With the literature review on the influences on labour union bargaining power, a more detailed systematic review should be conducted. Additionally, the most significant limitation as of yet with the illustrative case study is that this is not empirically proven and rather aims to illustrate the model dynamics. The nature of the model is quite deterministic based on the inputs, which should be expanded upon in future research to add more variability. In addition, even if empirically proven, a significant amount of qualitative research is needed on these dynamics before they can be modelled adequately and used for policy making. Moreover, the source data used has limited transparency and future research should consider making this real world data. In turn, additional sensitivity must be conducted on the inputs, the optimisation algorithm used, and the constraints. In particular, with the results that are in this paper already it would be beneficial to run sensitivity on these factors for the base case data, as there were notable discrepancies in the results comparing the scenarios with the original data, and the comparison with the base case model run data. This requires making adjustments to the underlying data itself and the base case model run in order to observe by how much the results change relative to the original data. Currently, the illustrative data is only for three sectors, three countries, and three technologies that are aggregated to show the production differences. However, much of this data required is quite nuanced, such as factor endowments in physical units required for specific industries, and would be difficult to obtain for a global database without standardisation around reporting this data.

Certain assumptions in the WTM itself could also be challenged. For example, the WTM has a constraint that no region enters into trade unless it benefits economically [25], but that is not necessarily realistic as some regions are ’forced’ with power to enter into certain types of trade agreements. The current state of this model has implemented scenarios, but has not included dynamic change over time which is a significant limitation for modelling power dynamics as wages and unions are likely to experience large changes over time. Additionally, the WTM falls under the umbrella of CGE based models which inherently have many limitations for evaluating power dynamics, such as assuming that perfectly competitive markets exist where minimised costs are the underlying driver of the most optimal solution, which omits other considerations such as evaluating the differences between the market participants and other actors that perpetuate this dynamic [54]. Alternatively, other newer economic models such as Kaleckian ones could be better suited to highlight the role of power relations and income shares in shaping macroeconomic dynamics [14]. This model is not at the point where implications around how strength of labour unions can be impacting wages for country- and industry-specific scenarios can be derived for aforementioned reasons such as lack of data. Instead, the discussion can currently revolve around the dynamics that are observed in the results without drawing implications for the real world. However, even with these limitations, there is still value in describing these dynamics at this point since the research on power dynamics in integrated modelling is lacking and the purpose of the research is to serve as an illustration of how one of these dynamics could be included.

4.2. Strategy and future research

This intention of the illustration is to serve as a preliminary example for future research. For this, a strategy is proposed around how to facilitate this, with two main components. First, directions for future research on how power dynamics should be included as an input within socio-economic and environmental models and the WTM illustration are elaborated upon. An example of this first direction was shown through the illustration. Second, in contrast to the WTM illustration, a proposal on a future direction for research which distinguishes between the actors themselves is provided, as doing so could help to provide more granular differences in the power resources that different actors hold.

4.2.1. Power dynamics as inputs

The first direction was partly taken by the WTM illustration, where forms of power dynamics are included as inputs to a model to analyse scenarios, and thereafter explicitly reported upon. In terms of wage adjustments, although there is plentiful macroeconomic research, there is none with the WTM that explores the impacts of changing minimum wages on economic outputs. The gap lies in explaining the power dynamics that drive wages higher, such as increased labour union bargaining power, which the illustration did cover. However, there is no explanation of the underlying power dynamics that cause this power mechanism to either be higher or lower.

Additionally, there is a gap in the review of what causes labour union bargaining power to vary, which is largely qualitative and draws from fields such as sociology and political economy. The literature review on labour union bargaining power in this paper began to address this. Therefore, a specific layout is recommended, which was also used in this paper. Ultimately, following a similar format in future models as was done here, namely with a literature review analysing the underlying power dynamics, then integrating that power mechanism as an input into the model, and then running scenarios to evaluate the impacts on the model outcomes whether social, environmental, or economic. This is a structure that would be beneficial to replicate. This paper's general structure includes these components: first, the literature review on labor union bargaining power mechanisms, then integrating that as an input in the WTM, and finally evaluating the impacts on production, whether domestic or outsourced. With this proposed layout, there are many areas to continue with this in future research, but there are a few recommended focus areas to begin with.

Improving the link between the literature review on the bargaining power mechanism and the WTM

To improve the link between the literature review on the bargaining power mechanism and the WTM, future research should address the current limitations in clearly connecting the causes of varying levels of labour union bargaining power with the inputs of the model. While this research includes both components, it presently lacks a nuanced integration between the literature on bargaining power and the WTM's inputs. The model currently treats changes in bargaining power as binary, either there is a static increase or there is not. This is contrary to real-world scenarios which involve a complex array of factors. In practice, labour unions are not uniformly strong across regions but exhibit varying levels of influence. Future work should aim to capture these subtleties and variations in union strength, providing a more accurate and dynamic representation of labour union power within the model.

Additional types of factor inputs

The illustrative case study has shown one potential example of how to include power dynamics within integrated modelling as an input in order to evaluate the impact on certain outputs, which was domestic production in this case. However, future research should consider including more complex factor inputs within the scenarios that could be influenced by the level of bargaining power which labour unions have beyond wages being adjusted. Doing so would create a better picture of real world dynamics, as wages are not the only factor being influenced by higher or lower labour union bargaining power. Moreover, beyond the inputs themselves, additional qualitative research should be conducted on the underlying power dynamics which either cause higher or lower labour union bargaining power. Then, the scenarios could reflect a more comprehensive range of socio-economic variables and interactions, potentially leading to more accurate policy recommendations that reflect the underlying power dynamics.

Localisation of dynamics:

It would be useful to localise this demonstration of power dynamics to consider specific industries and countries in how they operated within the real world. For example, comparing the strength of labour unions within the automotive industry across different countries and using real world data can be a way to expand this model in order to see if within this context it can be empirically proven.

Extension to environmental impacts

Future research should also focus on highlighting the links between these power mechanisms and their influence on the environment, as understanding these connections is crucial for developing effective policies and strategies for sustainable environmental management. In continuing with the labour unions scenarios with the WTM, adding the environmental extension used in MRIO format could be interesting to later analyse how shifts in labour union bargaining power across different countries and regions affect environmental impacts in those regions and abroad. Additionally, evaluating the distributional environmental impacts on various income groups could be interesting to evaluate how power dynamics influence the burden of environmental degradation across different regions and socio-economic groups.

Adding supplementary qualitative sections on power dynamics to quantitative models

Including qualitative sections on power dynamics into quantitative models can greatly enhance their depth and accuracy. While quantitative models offer valuable numerical data, they often miss the nuanced power structures behind the numbers. By adding qualitative analyses, such as case studies, interviews, and historical context, researchers can provide a richer understanding of how factors including labour union influence, political pressures, and social movements impact quantitative outcomes.

Continuing to improve the WTM

Even though this research used scenarios in an attempt to make the WTM more dynamic, additional research should be done to test this empirically with real data and to attempt to compare the results against historical data when input conditions match actual conditions of the model.

4.2.2. Distinguishing power dynamics between actors

A very brief and high level explanation is provided about another direction that future researchers should consider. The illustrative case study and background research in the aforementioned sections are one facet of how research could include power dynamics. However, another important facet is to consider how the underlying data requirements of IOA set by the SNA could play a role in these modelling efforts, in particular by focusing more on evaluating the differences in power dynamics between actors rather than only using variables to represent this as an input, as was illustrated in the WTM case study.

First, a description of the IOTs and SUTs in connection with the SNA is important to understand, along with how this can be used for EEIOA. IOTs are constructed in accordance with the SNA standards which show the intermediate consumption of outputs with either product by product or industry by industry within an economy [55]. These tables are well-suited for analyses which enable estimates such as changing relative prices, labour and capital requirements based on changing output levels, consequences of changing demand patterns, and expanded upon to estimate the demands made by the economy upon the environment [55]. The IOTs are also originally derived from SUTs, which allows for a transformation from tables showing product to industries, and towards tables relating either products to products or industries to industries [55]. Social Accounting Matrices have also been developed which capture the interdependencies of institutional groups, but still do not fully capture the proposed data which would assist power dynamics research [56].

As the SNA has widespread impact on economic analyses and policy formulation, this paper advocates for the inclusion of more detailed data which can support in-depth analyses about power relations, and to reduce the required manual data retrieval. The efforts made to include environmental extensions within the SNA standards are commendable, but power relations are now also critical to analyse in order to understand how to effectively reduce environmental impacts and other inequalities with targeting more refined groups, rather than the broader institutional groups currently used [55].

The structure of the SNA and IO frameworks presents a valuable opportunity for advancing research on power dynamics. The SNA already categorises different actor groups, including households, governments, and non-profit institutions, each of which exhibits varying levels of power. For instance, institutions may generally possess more resources compared to households. However, there is currently a lack of detailed analysis on the power held by these different groupings, marking a crucial area for future research.

The SNA's strength lies not only in identifying these groups but also in linking them to monetary data, which can serve as a proxy for assessing power dynamics. This linkage allows for an exploration of how different types of power, such as financial and resource-based power, affect these groups. Future research should focus on more explicitly defining and measuring the types of power each group holds, including variations within groups, such as differences in power between men and women in the labour market. This detailed understanding can then be integrated into EEIOA to examine how these power dynamics influence emissions levels.

Identifying relevant statistical units based on the SNA and ascribing power to these accounts is useful to reap a more holistic picture of how these actors interact. More research is required for how exactly to achieve this, but some ideas for case studies are defined as follows. For instance, upcoming research can focus on the relationship between farmers who are often squeezed by investors. If the market is then highly concentrated or monopolised, the power mechanism revolves around market freedom to price food. High food prices resulting from such market conditions feed into the IOTs. Similarly, supermarkets wield significant power over farmers, which can be further explored.

Another example of a case study that should be considered is around the resource curse and institutional quality. According to Acemoglu and Robinson (2012), countries with higher institutional quality and effective redistribution mechanisms tend to retain more wealth from their natural resources, leading to higher wages and improved public services [22]. Conversely, countries with lower institutional quality often suffer from capital leakage [22]. Further examination of how this relationship feeds into the IOTs would be useful. Including power dynamics in the SNA is not merely philosophical but offers practical solutions to real issues. Highlighting how power dynamics influence economic outcomes can guide methodologies for effective integration.

The most significant limitation is that these ideas are still quite general and require iteration over time as they are applied. The hope is that with time the SNA would include more relevant data in the standards, but this of course may not occur. A limitation of this is that there are inequalities in statistical capacity if additional SNA reporting is to be implemented [57].

5 Conclusion

5.1. Research questions addressed

There are a plethora of ways that this research field could be continued as discussed in Chapter 4. However, this research provides a preliminary attempt at answering the exploratory research question: *How can power dynamics be incorporated within integrated models which deal with socio-economic and environmental problems?*

The study addressed this question with both an illustrative proof of concept combining both a qualitative literature review and by using the labour union bargaining power variable reviewed as an input for the WTM. Additionally, a strategy containing ideas on how power dynamics could be included within integrated models going forward was included.

The sub-research questions have also been addressed. The first SRQ asks *”What proof of concept can be used as an illustration for how power dynamics could be implemented into modelling?”* This was shown with the WTM which included labour union bargaining power. In addition, a supplementary qualitative literature review was used to provide background on the drivers of the power dynamic at hand.

The second SRQ asks *”2. What overall strategy could be used to integrate power dynamics into modelling?”* This question was addressed primarily within the discussion, which provided two main areas of research that should be focused on, namely by using power dynamic mechanisms as inputs to models in combination with research on why these dynamics exist, along with distinguishing the power dynamics between different actors by leveraging existing frameworks such as the SNA. There are also many subsections which point to future research in each of these main areas.

This paper addresses the literature gap of not having integrated models include power dynamics in a way which includes both the dynamics as an input and also addresses the drivers of these dynamics. In turn, the paper has several contributions. With first the identification of the research gap through literature reviews of the integration of power dynamics in macroeconomic modelling and the uses of labour union bargaining power as a mechanism, this research addressed a key literature gap of adding to the discussion on the drivers of these power dynamics. This illustration has also contributed to this gap by showing a potential way to integrate labour union bargaining power as an input within the WTM, which has not ever had power dynamics included within it. This research has gone further to provide a well-documented version of the WTM code in hopes of making it more accessible and applicable for additional power dynamics research. A contribution is also made with the code itself through its adjustment to the more accessible MATLAB format from the original LINGO code, along with its into MRIO compatible layout.

5.2. Implications

Integrating power dynamics within integrated modelling in a way which addresses the research gap to also consider what is causing these dynamics to exist is crucial for addressing environmental issues and inequalities comprehensively. Ignoring power dynamics means overlooking a fundamental aspect of how systems operate, which is vital for effective policy making and understanding the root causes of both environmental degradation and social inequality.

This research calls upon two primary groups: researchers and the SNA developers. Researchers should integrate power dynamics into their models, using qualitative and quantitative methods to capture the complexities of power relationships. This integration will lead to a more nuanced understanding of how economic and environmental outcomes are influenced by power structures. Similarly, the SNA should revise its requirements to include information and guidelines on measuring the power of actors within institutional groups and their interactions, ensuring a holistic approach to economic and environmental analysis.

In conclusion, acknowledging and addressing power dynamics is essential to have more representative models and to address the power structures in place which inhibit certain policies from being pushed through or rapidly advance others.

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A

Appendix A: Documentation

The following formulas are from Duchin's RCOT/WTM [36]. A.1 and A.2 consider a one region model, while A.3 and A.4 consider a world model with more than one region. Figure 2.1, Figure 2.2, and Figure 2.3 show the variables and their meanings.

Primal:

$$\mathrm{Min}\,\mathrm{Z} = \boldsymbol{\pi}^T \mathbf{F}^* \mathbf{x}^* \tag{A.1}$$

subject to:

$$(\mathbf{I}^* - \mathbf{A}^*)\,\mathbf{x}^* \geq \mathbf{y}$$

$$\mathbf{F}^* \mathbf{x}^* \leq \mathbf{f}$$

$$\mathbf{x}^* \geq \mathbf{o}$$

Dual:

$$\mathrm{Max}\,\mathrm{W} = \mathbf{p}^T \mathbf{y} - \mathbf{r}^T \mathbf{f} \tag{A.2}$$

subject to:

$$\mathbf{p} \leq \left[(\mathbf{I}^* - \mathbf{A}^*)^T\right]^{-1} \mathbf{F}^{*T}(\boldsymbol{\pi} + \mathbf{r})$$

$$\mathbf{p}, \mathbf{r} \geq \mathbf{o}$$

Primal:

$$\mathrm{Min}\, Z = \Sigma_{\mathrm{i}} \pi_{\mathrm{i}}^T \mathbf{F}_{\mathrm{i}}{}^* \mathbf{x}_{\mathrm{i}}{}^* \tag{A.3}$$

subject to:

$$\Sigma_i \left(\mathbf{I}_{\mathbf{i}}^* - \mathbf{A}_{\mathbf{i}}^*\right) \mathbf{x}_{\mathbf{i}}^* \geq \Sigma_{\mathrm{i}} \mathbf{y}_{\mathbf{i}}$$

$$\mathbf{F}_{\mathrm{i}}{}^* \mathbf{x}_{\mathbf{i}}{}^* \leq \mathbf{f}_{\mathbf{i}}, \mathrm{i} = 1, \ldots, \mathrm{m}$$

$$\mathbf{x}_{\mathbf{i}}{}^* \geq \mathbf{o}, \mathrm{i} = 1, .., \mathrm{m}$$

Dual:

$$\mathrm{Max}\,\mathrm{W} = \Sigma_{\mathrm{i}} \left(\mathbf{p}^T \mathbf{y}_{\mathbf{i}} - \mathbf{r}_{\mathbf{i}}^T \mathbf{f}_{\mathbf{i}}\right) \tag{A.4}$$

subject to:

$$\mathbf{p} \leq \Sigma_{\mathrm{i}} \left[\left(\mathbf{I_i}^* - \mathbf{A_i}^* \right)^T \right]^{-1} \mathbf{F_i}^{TT} \left(\boldsymbol{\pi}_\mathbf{i} + \mathbf{r_i} \right)$$

$$\mathbf{p} \geq \mathbf{0}, \mathbf{r_i} \geq \mathbf{0}, \mathrm{i} = 1, .., \mathrm{m}$$

B

Appendix B: Model inputs

The tables below illustrate the inputs for the WTM model runs. The A matrices, final demand matrix, unit factor requirement matrices, factor price matrix, and the factor endowments matrix are shown. The only table being changed in the scenarios was the factor price table. The unit for the inputs is tonnes.

Japan	Technology		
Industry	virgin metals	new computers	other machines
metals	0.05	0.15	0.3
computers	0.1	0.2	0.22
other machineries	0.2	0.15	0.31

Guinea	Technology		
Industry	virgin metals	new computers	other machines
metals	0.01	0.25	0.3
computers	0.01	0.35	0.15
other machineries	0.1	0.26	0.25

China	Technology		
Industry	virgin metals	new computers	other machines
metals	0.03	0.25	0.3
computers	0.05	0.35	0.15
other machineries	0.15	0.26	0.31

Figure B.1: A matrices showing the industries by technologies for all countries used as inputs.

	Country		
Industry	**Japan**	**Guinea**	**China**
metals	0	0	0
computers	50,000	1,000	100,000
other machineries	6,000	500	10,000

Figure B.2: Final demand matrix across all industries and countries that were used as inputs.

Japan	Technology		
Unit factors	**virgin metals**	**new computers**	**other machines**
labour	3.2	1.5	1.2
ore	2.0	0.0	0.0
used computers	0.0	0.0	0.0

Guinea	Technology		
Unit factors	**virgin metals**	**new computers**	**other machines**
labour	8.0	2.1	3.0
ore	1.0	0.0	0.0
used computers	0.0	0.0	0.0

China	Technology		
Unit factors	**virgin metals**	**new computers**	**other machines**
labour	6.0	4.0	2.0
ore	1.5	0.0	0.0
used computers	0.0	0.0	0.0

Figure B.3: Unit factor requirements across all technologies for all countries that were used as inputs.

	Country		
Unit factors	**Japan**	**Guinea**	**China**
Labour	12.0	1.2	3.0
Ore	7.0	7.0	7.0
Used computers	0.0	0.0	0.0

Figure B.4: Factor prices across all countries that were used as inputs. This table was later adjusted within the 'labour' row to adjust for the labour union bargaining power assumption.

	Country		
Unit factors	**Japan**	**Guinea**	**China**
Labour	250,000	150,000	1,000,000
Ore	50,000	50,000	80,000
Used computers	30,000	100	70,000

Figure B.5: Factor endowments across all countries that were used as inputs.

C

Appendix C: Scenario inputs

The scenario inputs for the factor prices table are below. The units used are in tonnes.

	Country		
Unit factors	**Japan**	**Guinea**	**China**
Labour	14.4	1.2	3.0
Ore	7.0	7.0	7.0
Used computers	0.0	0.0	0.0

Figure C.1: Factor price table for scenario in which only Japan has a labour union, implying that the labour factor price is increased by 20% and driven by higher bargaining power.

	Country		
Unit factors	**Japan**	**Guinea**	**China**
Labour	12.0	1.44	3.0
Ore	7.0	7.0	7.0
Used computers	0.0	0.0	0.0

Figure C.2: Factor price table for scenario in which only Guinea has a labour union, implying that the labour factor price is increased by 20% and driven by higher bargaining power.

	Country		
Unit factors	**Japan**	**Guinea**	**China**
Labour	12.0	1.20	3.6
Ore	7.0	7.0	7.0
Used computers	0.0	0.0	0.0

Figure C.3: Factor price table for scenario in which only China has a labour union, implying that the labour factor price is increased by 20% and driven by higher bargaining power.

D

Appendix D: Model results

Note that the following data is rounded into whole numbers. The inputs used for the model also in the excel input file are in tonnes since this is how this data was originally presented by Duchin, but are converted from tonnes into kg in the final presentation for improved readability. This was simply achieved by multiplying the data points in the tables below all by 1000.

D.0.1. Original data

	Unit: kg		**Technologies**								
			Japan virgin metals	**Japan new computers**	**Japan other machines**	**Guinea virgin metals**	**Guinea new computers**	**Guinea other machines**	**China virgin metals**	**China new computers**	**China other machines**
Industries	**Japan**	**metals**	50	150	300	0	0	0	0	0	0
	Japan	**computers**	100	200	220	0	0	0	0	0	0
	Japan	**other machineries**	200	150	310	0	0	0	0	0	0
	Guinea	**metals**	0	0	0	10	250	300	0	0	0
	Guinea	**computers**	0	0	0	10	350	150	0	0	0
	Guinea	**other machineries**	0	0	0	100	260	250	0	0	0
	China	**metals**	0	0	0	0	0	0	30	250	300
	China	**computers**	0	0	0	0	0	0	50	350	150
	China	**other machineries**	0	0	0	0	0	0	150	260	310

Figure D.1: Full raw original data used in the format of the Am matrix across industries and technologies for all countries.

	Unit: kg		**Technologies**		
			Japan all technologies	**Guinea all technologies**	**China all technologies**
Industries	**Japan**	**metals**	500	0	0
	Japan	**computers**	520	0	0
	Japan	**other machineries**	660	0	0
	Guinea	**metals**	0	560	0
	Guinea	**computers**	0	510	0
	Guinea	**other machineries**	0	610	0
	China	**metals**	0	0	580
	China	**computers**	0	0	550
	China	**other machineries**	0	0	720

Figure D.2: Condensed raw original data used in the format of the Am matrix across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	1,680	0
Guinea	1,680	0
China	1,850	0

Figure D.3: Comparison of domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.2. Base case run data

	Unit: kg		Technologies								
			Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Industries	Japan	metals	50	150	300	0	0	0	0	250	0
	Japan	computers	100	200	220	0	0	0	0	350	0
	Japan	other machineries	200	150	310	0	0	0	0	260	0
	Guinea	metals	0	0	0	10	250	299	30	0	0
	Guinea	computers	0	0	0	10	350	150	50	0	149
	Guinea	other machineries	0	0	0	100	260	250	150	0	1
	China	metals	0	0	0	0	0	1	0	0	300
	China	computers	0	0	0	0	0	0	0	0	0
	China	other machineries	0	0	0	0	0	0	0	0	309

Figure D.4: Full base can run data used in the format of the Am matrix across industries and technologies for all countries. These are the results after running the model with the inputs outlined in Appendix B.

	Unit: kg		Technologies		
			Japan all technologies	Guinea all technologies	China all technologies
Industries	Japan	metals	500	0	250
	Japan	computers	519	0	350
	Japan	other machineries	660	0	260
	Guinea	metals	0	559	30
	Guinea	computers	0	510	199
	Guinea	other machineries	0	610	151
	China	metals	0	1	300
	China	computers	1	0	0
	China	other machineries	0	0	309

Figure D.5: Condensed base case run data used in the format of the Am matrix across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	1,679	860
Guinea	1,679	381
China	609	1

Figure D.6: Comparison of domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.3. Japan labour union model run data

	Unit: kg		Technologies								
			Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Industries	Japan	metals	50	150	300	0	0	0	0	250	0
	Japan	computers	100	200	220	0	0	0	0	0	0
	Japan	other machineries	200	150	310	0	0	0	0	0	0
	Guinea	metals	0	0	0	10	250	300	0	0	300
	Guinea	computers	0	0	0	10	350	150	50	350	150
	Guinea	other machineries	0	0	0	100	260	250	150	256	65
	China	metals	0	0	0	0	0	0	30	0	0
	China	computers	0	0	0	0	0	0	0	0	0
	China	other machineries	0	0	0	0	0	0	0	4	245

Figure D.7: Full data from the run where Japan has a labour union used in the format of the Am matrix across industries and technologies for all countries. These are the results after running the model with the inputs outlined in Appendix B and the relevant scenario in Appendix C.

Industries	Unit: kg		Technologies: Japan all technologies	Guinea all technologies	China all technologies
	Japan	metals	500	0	250
	Japan	computers	520	0	0
	Japan	other machineries	660	0	0
	Guinea	metals	0	560	300
	Guinea	computers	0	510	550
	Guinea	other machineries	0	610	471
	China	metals	0	0	30
	China	computers	0	0	0
	China	other machineries	0	0	249

Figure D.8: Condensed base case run data from the run where Japan has a labour union used in the format of the Am matrix across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	1680	250
Guinea	1680	1321
China	279	0

Figure D.9: Comparison of domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.4. Guinea labour union model run data

Industries	Unit: kg		Technologies: Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
	Japan	metals	50	150	300	0	0	101	11	8	0
	Japan	computers	100	200	220	0	0	2	1	6	0
	Japan	other machineries	200	150	310	0	0	10	2	2	0
	Guinea	metals	0	0	0	10	250	104	7	19	300
	Guinea	computers	0	0	0	10	350	59	45	338	150
	Guinea	other machineries	0	0	0	0	0	3	7	8	0
	China	metals	0	0	0	0	0	96	13	223	0
	China	computers	0	0	0	0	0	88	3	6	0
	China	other machineries	0	0	0	100	260	237	141	250	310

Figure D.10: Full data from the run where Guinea has a labour union used in the format of the Am matrix across industries and technologies for all countries. These are the results after running the model with the inputs outlined in Appendix B and the relevant scenario in Appendix C.

Industries	Unit: kg		Technologies: Japan all technologies	Guinea all technologies	China all technologies
	Japan	metals	499	101	19
	Japan	computers	519	2	7
	Japan	other machineries	660	10	5
	Guinea	metals	0	364	326
	Guinea	computers	0	419	534
	Guinea	other machineries	0	3	15
	China	metals	0	96	235
	China	computers	0	88	10
	China	other machineries	0	597	701

Figure D.11: Condensed base case run data from the run where Guinea has a labour union used in the format of the Am matrix across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	1678	143
Guinea	786	875
China	946	782

Figure D.12: Comparison of domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.5. China labour union model run data

Unit: kg		Technologies								
		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Industries Japan	metals	0	35	43	0	0	300	30	0	0
Japan	computers	0	0	0	0	0	150	50	37	0
Japan	other machineries	42	150	310	0	0	250	150	0	0
Guinea	metals	50	115	38	10	250	0	0	232	300
Guinea	computers	100	0	20	10	350	0	0	0	150
Guinea	other machineries	0	0	0	0	0	0	0	0	0
China	metals	0	0	218	0	0	0	0	18	0
China	computers	0	200	200	0	0	0	0	313	0
China	other machineries	158	0	0	100	260	0	0	260	310

Figure D.13: Full data from the run where China has a labour union used in the format of the Am matrix across industries and technologies for all countries. These are the results after running the model with the inputs outlined in Appendix B and the relevant scenario in Appendix C.

Unit: kg		Technologies		
		Japan all technologies	Guinea all technologies	China all technologies
Industries Japan	metals	78	300	30
Japan	computers	0	150	87
Japan	other machineries	502	250	150
Guinea	metals	204	260	532
Guinea	computers	120	360	150
Guinea	other machineries	0	0	0
China	metals	218	0	18
China	computers	400	0	313
China	other machineries	158	360	570

Figure D.14: Condensed base case run data from the run where China has a labour union used in the format of the Am matrix across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	580	967
Guinea	620	1006
China	901	1136

Figure D.15: Comparison of domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.6. Relative change of base case data compared to original data

Unit: kg		Technologies								
		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Industries Japan	metals	0	0	0	0	0	0	0	250	0
Japan	computers	0	0	0	0	0	0	0	350	0
Japan	other machineries	0	0	0	0	0	0	0	260	0
Guinea	metals	0	0	0	0	0	-1	30	0	0
Guinea	computers	0	0	0	0	0	0	50	0	149
Guinea	other machineries	0	0	0	0	0	0	150	0	1
China	metals	0	0	0	0	0	1	-30	-250	0
China	computers	0	0	0	0	0	0	-50	-350	-150
China	other machineries	0	0	0	0	0	0	-150	-260	-1

Figure D.16: Relative percentage change of the full base case run data compared to the original data inputs across all industries and technologies for all countries. The original data is subtracted from the base case run data to see the relative change.

Unit: kg		Technologies		
Industries		Japan all technologies	Guinea all technologies	China all technologies
Japan	metals	0	0	250
Japan	computers	-1	0	350
Japan	other machineries	0	0	260
Guinea	metals	0	-1	30
Guinea	computers	0	0	199
Guinea	other machineries	0	0	151
China	metals	0	1	-280
China	computers	1	0	-550
China	other machineries	0	0	-411

Figure D.17: Condensed version of the table above showing the relative percentage change of the full base case run data compared to the original data inputs across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	-1	860
Guinea	-1	381
China	-1,241	1

Figure D.18: Comparison of the relative changes of the domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.7. Relative change of Japan labour union compared to original data

Unit: kg		Technologies								
Industries		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Japan	metals	0	0	0	0	0	0	0	250	0
Japan	computers	0	0	0	0	0	0	0	0	0
Japan	other machineries	0	0	0	0	0	0	0	0	0
Guinea	metals	0	0	0	0	0	0	0	0	300
Guinea	computers	0	0	0	0	0	0	50	350	150
Guinea	other machineries	0	0	0	0	0	0	150	256	65
China	metals	0	0	0	0	0	0	0	-250	-300
China	computers	0	0	0	0	0	0	-50	-350	-150
China	other machineries	0	0	0	0	0	0	-150	-256	-65

Figure D.19: Relative percentage change of the full data from the run with Japan having a labour union compared to the original data inputs across all industries and technologies for all countries. The original data is subtracted from the labour union run data to see the relative change.

Unit: kg		Technologies		
Industries		Japan all technologies	Guinea all technologies	China all technologies
Japan	metals	0	0	250
Japan	computers	0	0	0
Japan	other machineries	0	0	0
Guinea	metals	0	0	300
Guinea	computers	0	0	550
Guinea	other machineries	0	0	471
China	metals	0	0	-550
China	computers	0	0	-550
China	other machineries	0	0	-471

Figure D.20: Condensed version of the table above showing the relative percentage change of the full data from the run with Japan having a labour union compared to the original data inputs across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	0	250
Guinea	0	1,321
China	-1,571	0

Figure D.21: Comparison of the relative changes of the domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.8. Relative change of Guinea labour union compared to original data

Unit: kg		Technologies								
Industries		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Japan	metals	0	0	0	0	0	101	11	8	0
Japan	computers	0	0	0	0	0	2	1	6	0
Japan	other machineries	0	0	0	0	0	10	2	2	0
Guinea	metals	0	0	0	0	0	-196	7	19	300
Guinea	computers	0	0	0	0	0	-91	45	338	150
Guinea	other machineries	0	0	0	-100	-260	-247	7	8	0
China	metals	0	0	0	0	0	96	-17	-27	-300
China	computers	0	0	0	0	0	88	-47	-344	-150
China	other machineries	0	0	0	100	260	237	-9	-10	0

Figure D.22: Relative percentage change of the full data from the run with Guinea having a labour union compared to the original data inputs across all industries and technologies for all countries. The original data is subtracted from the labour union run data to see the relative change.

Unit: kg		Technologies		
Industries		Japan all technologies	Guinea all technologies	China all technologies
Japan	metals	-1	101	19
Japan	computers	-1	2	7
Japan	other machineries	0	10	5
Guinea	metals	0	-196	326
Guinea	computers	0	-91	534
Guinea	other machineries	0	-607	15
China	metals	0	96	-345
China	computers	0	88	-540
China	other machineries	0	597	-19

Figure D.23: Condensed version of the table above showing the relative percentage change of the full data from the run with Guinea having a labour union compared to the original data inputs across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	-2	143
Guinea	-894	875
China	-904	782

Figure D.24: Comparison of the relative changes of the domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.9. Relative change of China labour union compared to original data

Unit: kg		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Japan	metals	-50	-115	-257	0	0	300	30	0	0
Japan	computers	-100	-200	-220	0	0	150	50	37	0
Japan	other machineries	-158	0	0	0	0	250	150	0	0
Guinea	metals	50	115	38	0	0	-300	0	232	300
Guinea	computers	100	0	20	0	0	-150	0	0	150
Guinea	other machineries	0	0	0	-100	-260	-250	0	0	0
China	metals	0	0	218	0	0	0	-30	-232	-300
China	computers	0	200	200	0	0	0	-50	-37	-150
China	other machineries	158	0	0	100	260	0	-150	0	0

Figure D.25: Relative percentage change of the full data from the run with China having a labour union compared to the original data inputs across all industries and technologies for all countries. The original data is subtracted from the labour union run data to see the relative change.

Unit: kg		Japan all technologies	Guinea all technologies	China all technologies
Japan	metals	-422	300	30
Japan	computers	-520	150	87
Japan	other machineries	-158	250	150
Guinea	metals	204	-300	532
Guinea	computers	120	-150	150
Guinea	other machineries	0	-610	0
China	metals	218	0	-562
China	computers	400	0	-237
China	other machineries	158	360	-150

Figure D.26: Condensed version of the table above showing the relative percentage change of the full data from the run with China having a labour union compared to the original data inputs across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	-1,100	967
Guinea	-1,060	1,006
China	-949	1,136

Figure D.27: Comparison of the relative changes of the domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.10. Relative change of Japan labour union compared to base case run data

Unit: kg		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Japan	metals	0	0	0	0	0	0	0	0	0
Japan	computers	0	0	0	0	0	0	0	-350	0
Japan	other machineries	0	0	0	0	0	0	0	-260	0
Guinea	metals	0	0	0	0	0	1	-30	0	300
Guinea	computers	0	0	0	0	0	0	0	350	1
Guinea	other machineries	0	0	0	0	0	0	0	256	64
China	metals	0	0	0	0	0	-1	30	0	-300
China	computers	0	0	0	0	0	0	0	0	0
China	other machineries	0	0	0	0	0	0	0	4	-63

Figure D.28: Relative percentage change of the full data from the run with Japan having a labour union compared to the base case run data inputs across all industries and technologies for all countries. The base case run data is subtracted from the labour union run data to see the relative change.

Unit: kg		Technologies		
Industries		Japan all technologies	Guinea all technologies	China all technologies
Japan	metals	0	0	0
Japan	computers	1	0	-350
Japan	other machineries	0	0	-260
Guinea	metals	0	1	270
Guinea	computers	0	0	351
Guinea	other machineries	0	0	319
China	metals	0	-1	-270
China	computers	-1	0	0
China	other machineries	0	0	-59

Figure D.29: Condensed version of the table above showing the relative percentage change of the full data from the run with Japan having a labour union compared to the base case run data inputs across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	1	-610
Guinea	1	940
China	-330	-1

Figure D.30: Comparison of the relative changes of the domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.11. Relative change of Guinea labour union compared to base case run data

Unit: kg		Technologies								
Industries		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Japan	metals	0	0	0	0	0	101	11	-242	0
Japan	computers	0	0	0	0	0	2	1	-344	0
Japan	other machineries	0	0	0	0	0	10	2	-257	0
Guinea	metals	0	0	0	0	0	-195	-23	19	300
Guinea	computers	0	0	0	0	0	-91	-5	338	1
Guinea	other machineries	0	0	0	-100	-260	-247	-143	8	-1
China	metals	0	0	0	0	0	95	13	223	-300
China	computers	0	0	0	0	0	88	3	6	0
China	other machineries	0	0	0	100	260	237	141	250	1

Figure D.31: Relative percentage change of the full data from the run with Guinea having a labour union compared to the base case run data inputs across all industries and technologies for all countries. The base case run data is subtracted from the labour union run data to see the relative change.

Unit: kg		Technologies		
Industries		Japan all technologies	Guinea all technologies	China all technologies
Japan	metals	-1	101	-231
Japan	computers	0	2	-343
Japan	other machineries	0	10	-255
Guinea	metals	0	-195	296
Guinea	computers	0	-91	334
Guinea	other machineries	0	-607	-137
China	metals	0	95	-64
China	computers	0	88	9
China	other machineries	0	597	392

Figure D.32: Condensed version of the table above showing the relative percentage change of the full data from the run with Guinea having a labour union compared to the base case run data inputs across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	-1	-717
Guinea	-893	494
China	337	781

Figure D.33: Comparison of the relative changes of the domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.

D.0.12. Relative change of China labour union compared to base case run data

Unit: kg		Technologies								
Industries		Japan virgin metals	Japan new computers	Japan other machines	Guinea virgin metals	Guinea new computers	Guinea other machines	China virgin metals	China new computers	China other machines
Japan	metals	-50	-115	-257	0	0	300	30	-250	0
Japan	computers	-100	-200	-220	0	0	150	50	-313	0
Japan	other machineries	-158	0	0	0	0	250	150	-260	0
Guinea	metals	50	115	38	0	0	-299	-30	232	300
Guinea	computers	100	0	20	0	0	-150	-50	0	1
Guinea	other machineries	0	0	0	-100	-260	-250	-150	0	-1
China	metals	0	0	218	0	0	-1	0	18	-300
China	computers	0	200	200	0	0	0	0	313	0
China	other machineries	158	0	0	100	260	0	0	260	1

Figure D.34: Relative percentage change of the full data from the run with China having a labour union compared to the base case run data inputs across all industries and technologies for all countries. The base case run data is subtracted from the labour union run data to see the relative change.

Unit: kg		Technologies		
Industries		Japan all technologies	Guinea all technologies	China all technologies
Japan	metals	-422	300	-220
Japan	computers	-519	150	-263
Japan	other machineries	-158	250	-110
Guinea	metals	204	-299	502
Guinea	computers	120	-150	-49
Guinea	other machineries	0	-610	-151
China	metals	218	-1	-282
China	computers	399	0	313
China	other machineries	158	360	261

Figure D.35: Condensed version of the table above showing the relative percentage change of the full data from the run with China having a labour union compared to the base case run data inputs across industries and combined technologies for all countries. For each row, the values across all the columns for one country were summed in order to combine the technologies into one value, as the focus of the research is not on distinguishing between the technologies.

Unit: kg	Total domestic production	Total imports
Japan	-1,099	107
Guinea	-1,059	626
China	292	1,134

Figure D.36: Comparison of the relative changes of the domestic production and imports for each country from the table above. For each country, the relevant three rows for the technologies column for that country are summed to calculate the total domestic production. Then, the other two columns have the relevant three rows for that country summed to calculate the total imports.