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Modelling the Endogenous Feedback Structure of a Food System using a Qualitative System Dynamics Approach:

Informing Policy Design and Supporting Sustainability Transitions in the Salmon Aquaculture Industry

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FACULTY OF INDUSTRIAL ENGINEERING, MECHANICAL ENGINEERING AND COMPUTER SCIENCE

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Abstract

Food systems face urgent sustainability challenges that are set to escalate as the world population expands, becomes more affluent, and urbanizes at a fast rate. These challenges are deeply rooted in food systems; the technology, ways of working, interorganizational relationships and interdependencies, and the wider societal structure and culture. Therefore, their solution calls for radical, non-linear, and structural system changes (i.e., sustainability transitions). Transitions require an understanding of the dynamics of the system, including drivers of change and structural inertia, especially as food systems are characterised by concentration of power in the hands of large, profit driven businesses with vested interest in maintaining the status quo. Given the urgency of food system sustainability transitions, and the potential for using modelling to design policy to guide such transitions, the aim of this research is to map the endogenous feedback structure of the Norwegian salmon aquaculture industry, to determine if the modelling of a food system's endogenous feedback structure using a system dynamics approach can support the system's transition towards sustainability. The findings indicate that the endogenous structure of the Norwegian salmon aquaculture industry has impacted its development and in particular policy outcomes and thus potentially maintained resistance to change. This implies that new policy design will be important to guide transitions towards sustainability and would benefit from considering the system's endogenous structure. These findings underscore the relevance of a systems perspective in policy design and transitions modelling.

Útdráttur

Matvælakerfi standa frammi fyrir brýnum sjálfbærniáskorunum sem eiga sér djúpar rætur í tækni og aðferðum við frumframleiðslu, vinnslu og dreifingu matvæla, viðskiptasamböndum, stjórnkerfinu, samfélagsgerðinni og menningunni. Lausn þeirra krefst því róttækra kerfisbreytinga sem kallast sjálfbærniumskipti (e. sustainability transitions). Þar sem matvælakerfi einkennast af samþjöppun valds í höndum stórra, hagnaðardrifinna fyrirtækja sem hafa hagsmuni af óbreyttu ástandi krefjast umskipti þeirra skilnings á innri byggingu (e. endogenous structure) þeirra, og drifkröftum breytinga og tregðu innan slíkra kerfa. Í ljósi þess hve brýnt er að auka sjálfbærni matvælakerfa og þeirra tækifæra sem felast í notkun líkana við stefnumótun sjálfbærniumskipta er markmið þessarar rannsóknar að kortleggja innri byggingu norska fiskeldisiðnaðarins til að ákvarða hvort kvikt kerfislíkan (e. system dynamics model) af innri byggingu matvælakerfis geti stutt sjálfbærniumskipti kerfisins. Niðurstöðurnar benda til þess að innri bygging norska laxeldisiðnaðarins hafi áhrif á þróun hans og viðbrög við stefnumörkun stjórnvalda og viðhaldi þannig viðnámi gegn sjálfbærniumskiptum. Þessar niðurstöður fela í sér að stefnumörkun verður mikilvægt tæki til að leiða sjálfbærniumskipti í framtíðinni og að skilningur á innri byggingu matvælakerfa mun vera forsenda slíkrar stefnumörkunar. Þetta undirstrikar mikilvægi kerfissjónarmiða (e. systems perspective) í stefnumótun og sjálfbærniumskiptum.

To my daughters, Freyja, Edda, and Embla.

May you believe you can.

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List of Publications

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Paper II: Conceptualization, Investigation, Data curation, Formal analysis, Methodology, Visualization, Writing of original draft.

Paper III: Conceptualization, Investigation, Methodology, Visualization, Writing of original draft.

Paper IV: Conceptualization, Investigation, Methodology, Visualization, Writing of original draft.

Abbreviations

CLD	Causal loop diagram
DR	Density restriction
FQ	Feed quota
GVC	Global value chain
IOF	Interorganizational fairness
LL	Lice limit
MAB	Maximum allowable biomass
MLP	Multi-Level Perspective
NPV	Net pen volume restriction
OMOL	“One man, one license”
RQ	Research question
RQ IV.1	Research question 1 in Paper IV
RQ IV.2	Research question 2 in Paper IV
SD	System dynamics
SL	Social license
SNM	Strategic Niche Management
SQ	Smolt quota
STF	Stock and flow
TIS	Technological Innovation System
TL	Technological limit
TLS	Traffic light system
TM	Transition Management

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1 Introduction

Well-functioning food systems are vital, both due to their positive impact as providers of nutrition and jobs but not least due to their potential negative impacts. Global food systems face several sustainability challenges (e.g., erosion, resource depletion, concentration of power, unfair trading practices) and as the world population is getting larger, more affluent, and urbanizing at a fast rate, the urgency of those issues will only increase. There will be a need to produce more food, using fewer resources, with less environmental impact (Béné et al., 2019). As sustainability challenges are deeply rooted in food industries; the technology, the ways of working, interorganizational relationships and interdependencies, and the wider societal structure and culture (e.g., laws, institutions, education), their solution is not straight-forward. Solving them calls for an understanding of the dynamics of food systems, including drivers of change and sources of structural inertia. Indeed, there is growing consensus within the scientific community that while "[…] global food systems can provide win-win diets to everyone by 2050 and beyond […] achieving this goal will require […] nothing less than a Great Food Transformation." (Willett et al., 2019).

1.1 Sustainability transitions

The concepts "transformation" and "transition" have been applied, within different fields of research, in seemingly interchangeable ways (Hölscher et al., 2018), to refer to radical, non-linear, and structural changes to complex systems that have been "deemed necessary to solve grand societal challenges" (Loorbach et al., 2017). Sustainability transition research (hereafter transition research), with the central aim to "conceptualise and explain how radical changes come about in the way societal functions are fulfilled" (Köhler & Holtz, 2019, p. 10), originated within two distinct research clusters, innovation studies and environmental studies, in the early 2000s (de Gooyert, Awan, et al., 2024). They have since evolved into what today is a distinct, multi-disciplinary research field (Truffer et al., 2022), that uses various methods to study radical changes to socio-technical systems. Socio-technical systems are defined as complex systems consisting of various elements (e.g., artifacts, knowledge, capital, labour, cultural meaning) that combine to fulfil societal functions (e.g., transport, communication, nutrition) through the production, diffusion, and use of technology (Geels, 2002).

1.1.1 Transition research

Transition scholars depart from the idea that grand sustainability challenges, brought on by unsustainable patterns of production and consumption, call for system-level changes as they are not just concerned with the development of individual (green) technologies, but also by how these technologies co-evolve with cultural and social aspects in the broader socio-technical system (de Gooyert, Awan, et al., 2024; Holtz et al., 2015). Furthermore, unlike studies focused on either addressing sustainability issues at the macro-level (e.g., global, national), or the micro-level (e.g., individuals), the analysis of socio-technical systems, brings the focus to the meso-level of organizations and sectors, and inter-level interactions (Köhler et al., 2019).

While transition research comprises diverse approaches and perspectives, research efforts can largely be divided into two interrelated research agendas: one *retrospective*, focused on understanding how transitions come about by studying past transitions, and the other *foresighted*, focused on how to make (desirable) future transitions happen by analysing contemporary socio-technical systems and proposing e.g., policy interventions or business strategies (Alkemade & Papachristos, 2025a; Holtz et al., 2015). To these ends, various transition theory frameworks and approaches have been developed and successfully applied to different systems (e.g., The Multi-Level Perspective (MLP), The Technological Innovation systems (TIS) framework, the Transition Management (TM) approach and, the Strategic Niche Management (SNM) framework). Turnheim et al. (2015) distinguished three transition research approaches: (1) *quantitative systems modelling*, (2) *socio-technical analysis,* and (3) *initiative-based learning*. Similarly, Tomai et al. (2024), divides methods for studying transitions into (1) *frameworks for analysing innovation and transformation processes* (e.g., MLP, TIS), and (2) *methods and approaches for sustainability transition governance* (e.g., TM, SNM, modelling methods).

Early on case study research using various transition frameworks, mainly the MLP and later also the TIS framework, dominated transition research (Köhler et al., 2019; Truffer et al., 2022). As the field has progressed new disciplinary topics (e.g., business administration, power and politics) have entered the domain, with foundational concepts like the MLP and TIS remaining important, although over time increasingly as supporting background references (Truffer et al., 2022). The field has an increasingly wide geographical scope and covers various sectors (Loorbach et al., 2017), including energy (e.g., Gürsan & de Gooyert (2021)), mobility (e.g., Köhler et al. (2009)), and food (e.g., Mylan et al. (2023), Lamine & Marsden (2023), Bush & Marschke (2014)).

1.1.2 The Multi-Level Perspective

The MLP is particularly suitable for analysing transitions in production systems as it emphasizes the embeddedness of technological innovations in social systems (Geels, 2002). The framework distinguishes three analytical levels: (1) *socio-technical landscape*, (2) *socio-technical regime,* and (3*) niche innovations* (Geels & Schot, 2007). The socio-technical landscape is the external macro-level context of socio-technical systems and the backdrop of system developments. The socio-technical regime consists of a set of interrelated, shared rules (e.g., laws, shared values, bodies of knowledge) that coordinate the activities of interdependent actors (e.g., firms, policymakers, civil society actors, etc.) and promote stability (Grin et al., 2010). Radical innovations are developed in niches protected from market selection within the regime (Geels & Schot, 2007). Niche-innovations in food systems range in radicality from technical innovations (e.g. agroecology, plant-based meat), social innovations (e.g. urban farming), and business model innovations (e.g., organic food, aquaponics), to infrastructural innovations (e.g., agroforestry, offshore aquaculture) (Geels, 2019).

The MLP posits that transitions take place through interactions that occur in and between the three levels. Landscape developments put pressure on the existing system, thus opening opportunities for niche-innovations that can, if sufficiently developed (e.g., technologically, economically), break through and replace the existing regime. The regime has vested interest in maintaining the status quo and hampering radical innovation and therefore resists change and responds to landscape pressures with incremental innovations if needed (Geels, 2002). Geels & Schot (2007) differentiated four transition pathways towards sustainability based on temporality and MLP-alignments: (1) *Technological substitution*, where a competing niche-innovation replaces the regime after it is destabilized by landscape pressure; (2), *Regime transformation*, where incumbent actors reorient in response to landscape pressure; (3) *Regime reconfiguration*, where symbiotic niche innovation is incorporated in the regime, gradually altering system architecture; and (4) *De-alignment/re-alignment*, where rapid landscape pressure destabilizes the regime, making room for multiple emerging niche-innovations, followed by re-alignment of a regime around one of them.

Two decades worth of MLP case study research has resulted in large amounts of case study data on multiple socio-technical systems, located across the world (Köhler et al., 2019), and adjustments and improvements to the framework in response to criticism (Papachristos, 2018). However, although frameworks like the MLP have proved useful for studying past transitions and informing research on future transitions, transition research faces considerable challenges due to the complexity of the subject. Advancement of the field will be contingent on solving those challenges, through the development of its methodologies and/or adoption of methodologies from other fields of research. In the next section the key challenges of transition research will be elaborated on, before diving into the developing field of transition modelling which has potential to solve at least some of these challenges.

1.2 Challenges of transition research

Several characteristics of socio-technical systems, and transition processes, pose challenges to understanding and, more importantly, shaping sustainability transitions. These characteristics and their consequences have been described by many scholars (see e.g., Holtz et al. 2015; Köhler et al., 2018; Tomai et al., 2024; Turnheim et al., 2015). In addition to challenges related to the general characteristics of socio-technical systems, a foresighted perspective, and the specific characteristics of food systems, pose additional challenges, to transition research.

1.2.1 Challenging characteristics of socio-technical systems and transitions

Socio-technical systems are multi-dimensional and complex, which has major implications for our ability to understand and guide their transitions. They are made up of multiple interlinked components that is helpful to distinguish along three dimensions: (1) *technical* (e.g., technologies, supply chains, infrastructures, markets), (2) *governance* (e.g., policy, rules and regulations, standards, norms), and (3) *social* (e.g., multiple actors, networks of actors, and social groups with diverse preferences, cultural meanings, goals and strategies). These interlinked components form endogenous system structures that are maintained and reinforced by e.g., institutionalized practices, vested interests, and established rules. This complex internal structure of socio-technical systems produces patterns of self-organization, emergence, and co-evolution, which often results in structural system inertia, path dependence, and system lock-ins (Tomai et al., 2024). Due to the inherent complexities of socio-technical systems, their transition demands changes involving co-evolutionary, non-linear processes across scales (e.g., geographical, jurisdictional, organizational, cultural), dimensions (i.e., technical, social, political), and levels (i.e., micro, meso, macro). Further adding to the complexity of transition processes, is that they typically extend beyond the boundaries of single socio-technical systems and thus involve alignment, not just within a single system but across systems, which can be a source of conflicting goals calling for trade-offs. Finally, a major complication of transitions is that they inherently involve a re-design and/or re-ordering of the system involving the emergence of e.g., new actors, connections, norms and values. This is less of a problem in retrospective transition research but adds complication to efforts aimed at guiding future transitions (Turnheim et al., 2015).

1.2.2 Challenges of foresighted transition research

The complex endogenous structure of socio-technical systems and the inherent uncertainty of transitions pose challenges to efforts aimed at moving from describing (past) transitions to guiding ongoing and future transitions. Despite being a vibrant, inter-disciplinary field, transition research has primarily focused on increasing understanding of innovation and transition processes, mostly using qualitative frameworks, and often by studying past transitions as single case studies (Köhler et al., 2019). A major challenge within the field relates to finding ways of using the accumulated understanding of transitions (mainly from case study data) to build theory, inform policy, and preferably steer contemporary socio-technical systems towards desirable futures (Köhler et al., 2019; Papachristos & Adamides, 2016). A key difference between past and ongoing/future transitions is that the latter require a shift to a system that is not necessarily aligned with economic growth (Papachristos, 2018). This is a source of major system inertia, due to path dependencies and lock-ins, as it requires revolutionizing not just business models but also culture, values and performance metrics. Geels (2019) identified three types of lock-in mechanisms in socio-technical systems that reinforce and support the current regime: (1) *Techno-economic lock-ins*, due to e.g., sunk investments, low-cost and high-performance existing technologies; (2) *Social- and cognitive lock-ins*, due to e.g., routines, shared mindsets, and life-styles shaped around existing technologies, and (3) *Institutional- and political lock-ins*, due to e.g., existing regulations, standards and policies favouring incumbents.

Institutional and political lock-ins relate to a further limitation to foresighted transition research. As most traditional transition theory frameworks originate within the field of innovation studies, they focus heavily on the role of niche innovations in transitions while the role of resistance to change within the regime has been undertheorized (Köhler et al., 2019). Increasingly, scholars are pointing out that the challenges related to transitions towards sustainability within complex systems are not just related to the necessary technological innovations but also the resistance to change inherent to the systems' governance structures (Béné, 2022; Béné et al., 2020; Köhler et al., 2019). Due to their vested interest in the status quo, private actors also often lack incentives to support transitions towards new, possibly more sustainable, systems. This is the case in food systems where the concentration of power in the hands of very few, powerful, international corporations in the agri-food industry and the interdependencies between private actors and public institutions creates very strong incentives to maintain the current situation (Béné, 2022; Clapp, 2021), thus reinforcing system lock-ins. This opposition to change indicates that policy might have to play an important role in guiding and accelerating sustainability transitions (Köhler & Holtz, 2019; Schøning et al., 2023).

The leap from describing past transitions towards guiding future transitions entails understanding the system's endogenous feedback structure and identifying system drivers and actors' incentives as these impact how the system responds to external factors like policy instruments (Papachristos & Adamides, 2016). Understanding system drivers and incentives helps identifying leverage points to better guide system transition trajectories (Papachristos, 2018). In food industries, which are for the most part made up of profit-driven businesses, profit maximization is a prominent system driver. While making profit is not the only objective of doing business it is necessary for long-term survival of the operation and thus an important factor in organizational decision making.

1.2.3 Food systems

Food systems have traditionally been conceptualized as supply systems or networks of businesses that use value adding activities ranging from production to consumption to transform raw materials into food products (Nguyen, 2018). However, their complexity is far greater as they involve interactions between human (e.g., social, economic) and natural (e.g., biophysical, ecological, environmental) systems (Berkes et al., 2000) resulting in researchers defining them and studying as social-ecological systems (e.g., Allen & Prosperi (2016) and Ericksen (2008)). Social-ecological systems, sometimes referred to as socio-ecological systems[1], are "integrated complex adaptive systems in which social and ecological subsystems are coupled and interdependent, each a function of the other, expressed in a series of mutual feedback relationships" (Berkes, 2017). It is particularly difficult to grasp the dynamics of such systems as they are characterized by many interactions and interdependencies and often exhibit nonlinear and unpredictable dynamics resulting from the feedback between social and ecological processes (Liu et al., 2007). Governance has a role in providing an important link between the social and ecological subsystems of social-ecological systems (Berkes, 2017). This has, however, proved problematic as for policy makers a lack of whole-system overview makes it difficult to predict policy outcomes (Stave & Kopainsky, 2015).

In the context of sustainability transitions, which are focused on technological innovations, the view of food systems as social-ecological systems may be extended to social-technical-ecological systems (Köhler & Holtz, 2019). Social-ecological systems research and transition research are two research communities, driven by similar concern about environmental problems, but study sustainable development from different perspectives. These schools of thought could therefore presumably benefit from some form of integration or exchange of ideas. This has been done to some extent within the field of social-ecological research but less so in transition research. Indeed, Andersson et al. (2024) argued that transition research should better address ecological elements of socio-technical

[1] Berkes (2017) who developed the concept of social-ecological systems into a framework (Berkes & Folke, 1998) argued that the term social-ecological was more suitable than socio-ecological as it "emphasizes that the two subsystems are equally important, whereas socio- is a modifier, implying a less than equal status of the social subsystem" (Berkes, 2017, p.3).

systems by adopting a socio-techno-ecological approach as nature influences sustainability transitions and vice versa. Specifically, he posits that transition research would benefit from including ecological factors and dynamics in their transition analyses. This is particularly relevant for food industries.

As transitions take place in complex systems involving multiple actors with diverse interests and refer to changes to system structures, values and technologies across sectors and scales, scholars have highlighted the benefit that modelling approaches could have to transition research (Holtz et al., 2015; Köhler & Holtz, 2019). This work is ongoing within the transition research community through an expansion of the methodological reach to include quantitative, qualitative, and mixed method modelling approaches, and their "bridging" (Köhler et al., 2018; Turnheim et al., 2015) or "linking" (Trutnevyte et al., 2014) to qualitative narrative case study research. However, the characteristics of complex systems like food systems poses challenges to model building. These include challenges related to the often-transdisciplinary nature of the research, the combination of qualitative and quantitative methods and data sources, the multiscale nature of the systems under study, the inherent uncertainty of such systems and the challenges involved in representing intangible social aspects in model operational terms (Elsawah et al., 2020). The interdependencies between social and ecological subsystems within in food systems adds another layer of complexity. In the next section the benefits and challenges of modelling food system transitions will be elaborated on.

1.3 Transition modelling

Model building offers numerous benefits to the study of complex systems but also has some drawbacks that need to be considered. Models are an explicit, clear, and systematic representation of reality. Modelling thus helps clarifying assumptions, formalizing system variables and the relationships between them. This process facilitates learning about the system and helps bridge disciplinary boundaries. Perhaps most importantly, in relation to transitions, models facilitate inferences of dynamics in complex systems and thus systematic experiments (Holtz et al., 2015).

Understanding and predicting co-evolutionary, non-linear transition processes across scales (e.g., geographical, jurisdictional, organizational, cultural), dimensions (i.e., technical, social, political), and levels (i.e., micro, meso, macro), involving multiple heterogenous actors with divergent goals, calls for a systems approach (Halbe et al., 2015). Traditional transition research approaches are to some extent able to represent transition dynamics of historic transitions as the changes are known (Holtz et al., 2015). Guiding future transitions requires the ability to address the uncertainty and open-endedness of transitions (Hafner et al., 2024). Dynamic models are useful to understand and explore emergent phenomena by taking an endogenous perspective, identifying feedback loops, system drivers and leverage points (Holtz et al., 2015). Indeed, sustainability transitions succeed or stall due to underlying feedback dynamics, path dependencies, and lock-ins (e.g., regime resistance). Thus, modelling can support the goal of guiding transitions by elucidating an explicit, clear representation of the socio-technical system's endogenous structure (de Gooyert, Awan, et al., 2024).

Modelling transitions comes with challenges. The complexity of socio-technical systems and sustainability transitions can lead to overly complicated models, that are too complex to infer any valuable information from or validate, or models that are either too abstract or limited in scope and thus provide limited insights. Specifically, capturing social processes in models poses challenges due to lack of data and issues related to the operationalization of intangible social phenomena (e.g., cultural aspects). However, both including and omitting these processes and phenomena can cause rigor issues (Holtz et al., 2015). Another transition modelling challenge relates to the broad time scales (e.g., linking short-term and long-term dynamics) and variable aggregation levels (e.g., linking developments at the macro-, meso-, and micro levels) of transition dynamics (Alkemade & Papachristos, 2025b). However, different modelling methods can solve different transition modelling challenges. Furthermore, the model requirements depend on the purpose of the model. In the next section transition modelling approaches and model types will be elaborated on.

1.3.1 Transition models

Although transition studies share the common objective of facilitating sustainability transitions, either through increasing understanding of such processes or using that understanding to steer them, individual models serve different purposes (e.g., understanding, changing, projecting), and this influences the model scope and modelling method of choice. This is important as models and their outcomes can only be properly assessed with consideration to their intended purpose (de Gooyert, Awan, et al., 2024).

Halbe et al. (2015) sorted transition models into three types based on their intended use; (1) *Models for understanding transitions*, used to develop general insights, support theory building and usually not expected to predict system behavior; (2) *Models for providing case-specific policy advise*, problem-driven, with a practical purpose (i.e., inform policy) and can be used to explore the influence of different underlying assumptions on system behavior; and (3) *Models for facilitating stakeholder processes*, with the purpose of engaging with stakeholders to facilitate learning and communication. The purpose of a model influences its scope. van den Broek et al. (2024) identified three types of transition mental models: (1) *Models of the system,* which model system components and the interactions between them; (2) *Models of transition pathways,* which model current or envisioned transitions; and (3) *Models of behavior,* which model the drivers of a decision-making process or behavior. This categorization is also helpful for distinguishing between different types of general, not just mental, transition models. Research is not always strictly theoretical or strictly applied. Therefore, models can be a combination of more than one type.

Köhler et al. (2018) identified several simulation and modelling approaches, from other fields of research, that can contribute to the study of transitions (e.g., system dynamics (SD) models, agent-based models (ABM), social-ecological systems models, evolutionary economics models, integrative environmental assessment models). They found that many of these can represent non-linearity and path dependency due to their systems approach but struggle more, although to different extents, with modelling processes across scales, representing normative aspects, and handling uncertainty. They further concluded that no modelling approach can represent qualitatively different states (e.g., not just changes towards more or less of the same but also the emergence of new elements) which is an important aspect of modelling future transitions (Köhler et al., 2018).

1.3.2 Simulation modelling in transition research

Köhler & Holtz (2019) stated, in their overview of the transition modelling field, that "The use of simulation modelling methods in research on (sustainability) transitions is still in an early stage of development" (Köhler & Holtz, 2019, p. 11). Still, the specific benefits of simulation modelling approaches (e.g., ABM and SD) to transition research has been highlighted by scholars (de Gooyert, Awan, et al., 2024; Köhler & Holtz, 2019; Papachristos, 2014), and demonstrated through various modelling efforts (Köhler et al., 2009; Papachristos & Adamides, 2016). According to Tomai et al. (2024) these benefits include the way in which simulation modelling helps untangle multi-system interactions, how it forces the quantification of intangible factors and the clarification of assumptions, and how it facilitates stakeholder engagement.

While ABMs stand out for their ability to model diversity and heterogeneity in actors' behavior (Köhler et al., 2018), a key benefit to transition research offered by SD models is their inherent endogenous perspective, which enables the identification of the causal relations, drivers and feedback loops that offer leverage for guiding future transitions (Alkemade & Papachristos, 2025a; Tomai et al., 2024). Papachristos & Adamides (2016) listed further benefits of SD modelling for transition research including its compatibility to narrative style case study research and middle-range theory building (Kopainsky & Luna-Reyes, 2008; Schwaninger & Grösser, 2008), and its ability to address the limitations of the human mind in assessing system features like feedback, delays and accumulation (Forrester, 1993).

1.3.3 System dynamics modelling in transition research

A key characteristic of the SD modelling approach is that it assumes that it is the endogenous feedback structure of a system that determines its dynamic behaviour over time and how it responds to disturbances (e.g., policy instruments, environmental shocks) (Sterman, 2000). Traditionally, SD models have served practical purposes (e.g., problem solving), often in relation to management. However, the methodology is increasingly used for building and testing theory, thus shifting the focus from solving single problems to expanding knowledge and understanding of systems (de Gooyert, 2019).

A fundamental part of SD modelling is analysing the internal structure of a system as a collection of feedback loops that interact to generate dynamic patterns of behaviour, using SD structural thinking and diagramming tools (e.g., causal loop diagrams (CLD), stock and flow diagrams (STF)) (Sterman, 2000). Structural thinking and diagramming tools are very useful for describing complex systems in a way that can improve and consolidate understanding of the relationships between system variables and based on that make inferences about system behaviour. While the creation of such diagrams is typically associated with a single step in the process of building a quantitative (computer) simulation model, they are also useful, on their own, to qualitatively analyse complex systems and thus potentially aid in policy analysis and design (Stave & Kopainsky, 2015). Using diagrams adds clarity, especially about circular causality like feedback loops, and helps integrating various strands of information in a meaningful, visually recognizable way (de Gooyert, Awan, et al., 2024).

This type of SD modelling is often referred to as qualitative SD (Coyle, 2000; de Gooyert, 2019; Größler, 2008; Lane, 2008). While quantitative simulation has some advantages over qualitative diagrammatic reasoning with tools like CLDs (e.g., ability to test the system's response to different kinds and magnitudes of disturbance) (Lane, 2008; Schwaninger & Grösser, 2008), the latter have numerous benefits when used on their own. Indeed, for highly complex systems (e.g., food systems) where concrete data about many variables are scarce, imperfect, or time-consuming to gather, a simulation model could end up being misleading and thus a qualitative SD approach might be more appropriate as a basis for reasoning (Coyle, 2000; Größler, 2008). The applicability of qualitative SD for studying the dynamics of a system is determined by the purpose of the model building, the complexity of the system under study, and the availability of data (Größler, 2008). Qualitative SD modelling is especially applicable in theoretical studies focused on advancing knowledge of a system through mapping the causal relationships between variables and can be based on primary data (e.g., interviews, group model building) and secondary data (e.g., literature review) (de Gooyert, Awan, et al., 2024).

de Gooyert, Awan, et al. (2024) reviewed qualitative SD contributions and concluded that, in addition to the benefits of SD in general, qualitative SD approaches complement transition research by allowing for a broader system boundary, visualizing and communicating complex feedback structures in a way that is approachable for stakeholders of different backgrounds, and bridging the gap between more positivistic simulation approaches (e.g., quantitative SD) and more interpretivist narrative transition research approaches (e.g. MLP case study research).

1.3.4 System dynamics transition models

Given the overlaps between transition research and SD modelling, studies have used SD to model past transitions (e.g., Yücel & Chiong Meza (2008)), to test scenarios for future transitions (e.g., Papachristos & Adamides (2016), Purvis et al. (2022)), for theory building (e.g., Papachristos (2011)), and to complement qualitative transition frameworks (e.g., Hafner et al. (2024), and Walrave & Raven (2016)). Most SD transition studies have applied a quantitative approach or a combination of a qualitative and quantitative approach (de Gooyert, Awan, et al., 2024). However, some recent studies have applied strictly qualitative SD in the context of sustainability transitions using both primary data (e.g., interviews, participatory modelling) and secondary data (e.g., literature review) to elicit the system's structure.

de Gooyert, de Coninck, et al. (2024) and Gürsan et al. (2024) used CLDs constructed using a participative modelling approach to identify policy intervention points (de Gooyert, de Coninck, et al., 2024), and potential unintended policy consequences (Gürsan et al., 2024), related to the transition towards a climate-neutral energy system in the Netherlands in 2050. They found that using a participatory modelling approach led to a shared understanding of a complex problem and thus new perspectives and recommendations that differ from those that can be derived from narrower perspectives. Also eliciting causal relationships from primary data, this time expert interviews, Janipour et al. (2021), developed STF diagrams related to carbon dioxide capture and storage in the Netherlands and used it to analyse contrasting narratives and suggest ways of alignment. Later, combining expert interviews and group model building, Janipour et al. (2022), used a qualitative SD approach to study how industrial clustering in an energy-intensive industry may impact the ability to reach emission targets. Finally, Swennenhuis et al. (2024) used literature, expert interviews, and group model building to study the enablers for, and barriers to, the implementation of carbon dioxide capture and storage in an industrial cluster. The authors highlighted as an important implication of the study, the insights brought to, not just the researchers, but also the participants.

Three noteworthy recent qualitative SD contributions adopted an integrated literature review and qualitative SD diagramming approach. Gonella & de Gooyert (2024) studied the plastics sustainability transition by constructing STF diagrams and CLDs based on a literature review and using them to qualitatively explore the impact of select interventions. Using a grounded theory approach, Buzogany et al. (2024) elicited the causal relationships of poverty and hunger from a review of the literature and constructed a comprehensive CLD. They then used this CLD to assess the effectiveness of existing (or proposed) policy narratives. They argued that developing a qualitative causal map can highlight potential policy weaknesses and should thus precede eventual policy analysis using quantitative simulation. Also using an integrated literature review and qualitative SD diagramming approach, Gürsan & de Gooyert (2021) studied how various positive and negative effects of natural gas interrelate. Based on this analysis they suggested policy interventions aimed at supporting the energy transition.

Although this review of qualitative SD transition studies in transition research is not exhaustive, the adoption of qualitative SD approaches in transition research is surely still limited and many contributions seem to originate within a small group of scholars in the Netherlands. Their contributions are still important, especially as they highlight how qualitative approaches using structural thinking and diagramming tools facilitate the revealing of conflicting views, the building of shared understanding, and thus perhaps the changing of perspectives. This is indeed important as stated by the founder of the SD modelling paradigm, Forrester, p. (1993, p. 15): “In general, influential system dynamics projects are those that change the way people think about a system”.

1.3.5 System dynamics modelling of food systems

Modelling food systems adds another layer of complexity, on top of the intricacies of transitions and socio-technical systems, in the form of ecological feedback. SD modelling has been used extensively to model food systems. These models range from simple supply chain models focused on the flow of products (e.g., Azizsafaei et al. (2022) and Vanany et al. (2021)) to more complex models that include the dynamics between the social, economic, and ecological aspects of food systems (e.g., Stave & Kopainsky (2015), Shamsuddoha et al. (2023), Kopainsky et al. (2015), and Queenan et al. (2022)). Noticeably, the role of profitability as a system driver is undertheorized and lacking from many food system models (e.g., Esteso et al. (2023), Odoemena et al. (2020), Shamsuddoha et al. (2023)). Notable exceptions are Ouma et al. (2018) who showed how considering farmers’ incentives in policy design aimed at reducing AFS outbreaks led to better policy outcomes, Herrera de Leon & Kopainsky (2019) who included a reinforcing investment loop and a balancing “market invisible hand” loop in their model of subsistence farming in Guatemala, Brzezina et al. (2017) who included reinforcing profit driven mechanization and intensification loops in their model of organic farming, and Lie et al. (2018) who modelled the impact of different policy instruments in a dairy supply chain in Nicaragua.

A similar gap seems to exist in transition models. As an example, Papachristos & Adamides (2016) used a combined MLP and SD modelling approach to study the emergence of functional foods as a niche-innovation in the food/nutrition socio-technical system. Their model, although including the component "business opportunity" (related to niche-innovations), does not consider profitability or any economic factors for that matter as drivers of niche development. Béné (2022) pointed out that the fact that technological innovation is by nature driven by profit and not (just) sustainability, is to an extent standing in the way of the transition of food systems. As the profit driven nature of industries also plays an important role in regime resistance, it seems important to consider the driver of profitability when modelling transitions.

Food systems are made up of profit driven businesses each striving to maximize their outcomes. Therefore, neglecting this profit driven nature in food system models is problematic. Regardless of whether the policy objective is guiding a sustainability transition, food security, or improved labour conditions, there is need to consider how system actors will respond. This entails understanding their incentives, the drivers that are embedded in the systems' endogenous feedback structures. If not, the result can be policy failure and, worse yet, unintended policy consequences.

Over two decades of transition research has resulted in multiple in-depth descriptions of various historical transitions, substantive understanding of how (past) transitions unfolded, and some ideas about the endogenous system drivers and feedback that give rise to, or impede, sustainability transitions. The importance of moving from describing historical transitions to explaining how they come about, and potentially guiding future transitions, and from in-depth understanding of a particular transition to comprehending the features that are common across transitions, has been highlighted, and modelling suggested as a promising solution (de Haan, 2021). Transition modellers have already embarked on that journey but there is a lot of work ahead. A key facilitator of progress will be an understanding of the endogenous drivers and feedback that stall or advance transitions of socio-technical systems.

1.4 Research objective

Companies' incentives, and particularly their profit driven nature, has emerged as a common theme. It is often what constrains transitions, it is overlooked in policy design and food system and transition models, but at the same time it is the very reason why policy is needed to guide and accelerate sustainability transitions and therefore needs to be considered in transition studies. Given the urgency of food system sustainability transitions (Willett et al., 2019), the proposed importance of policy to guide such transitions (Köhler et al. 2019), and thus the importance of understanding food systems' endogenous drivers, this thesis' overarching aim is to answer the question:

> *(RQ) "Can the modelling of a food system's endogenous feedback structure using a qualitative system dynamics approach support the system's transition towards sustainability?"*

This is accomplished through studying the salmon aquaculture industry, a food industry where environmental and social sustainability challenges are considerable (Garlock et al., 2024), potential niche innovations exist (Afewerki et al., 2023), but where despite stringent regulations aimed at controlling environmental externalities (Hersoug, 2021), policy makers have struggled to guide the industry towards sustainability (Oglend et al., 2024). Aquaculture is the world's fastest growing food production technology (Tacon, 2020) and the salmon aquaculture industry is a pioneer in terms of farming technology (Afewerki et al., 2023). The potential of aquaculture to contribute to food and nutrition security, and poverty reduction is widely recognized (Dongyu, 2024) and aquaculture production has some benefits in terms of sustainability (i.e., carbon footprint, land use) compared to other animal protein production (e.g., beef). However, despite technological advances, the industry still faces major challenges, mainly local environmental and fish welfare challenges (Osmundsen et al., 2022), but increasingly also challenges related to the industry's social license to operate (Olsen et al., 2023, 2024).

This thesis is comprised of four papers, one proceedings paper (Paper I) and three journal papers (Paper II, Paper III, and Paper IV). In addition to following the traditional steps of model building the road to answering the thesis' overarching question involved resolving some of the challenges related to modelling complex systems. These challenges guided the aims of the first three papers. First, the endogenous feedback structure of food supply systems was identified (Paper I). Next, the challenge of modelling the social aspects of social-ecological and socio-technical systems (i.e., fairness) was addressed (Paper II). Then, the challenges of the sustainability transition of the farmed salmon industry were analysed (Paper III). Finally, to answer the overarching research question, a specific food system, the Norwegian salmon aquaculture industry, was modelled using a qualitative SD approach (Paper IV). The modelling in Paper IV was informed by the findings of Papers I, II, and III, and guided by two research questions:

> *(RQ IV.1) "How does the endogenous feedback structure of the Norwegian salmon aquaculture industry, and specifically profit maximization, impact industry developments in a highly regulated environment",* and
>
> *(RQ IV.2) "How can SD structural thinking and diagramming tools contribute to understanding challenges and impact of policies related to balancing economic sustainability, with environmental and social sustainability".*

The diagram in Figure 1 explains how the overarching research question relates to the objectives of Papers I, II, and III (Obj. I, Obj. II, and Obj. III), and the two research questions in Paper IV (RQ IV.1 and RQ IV.2).

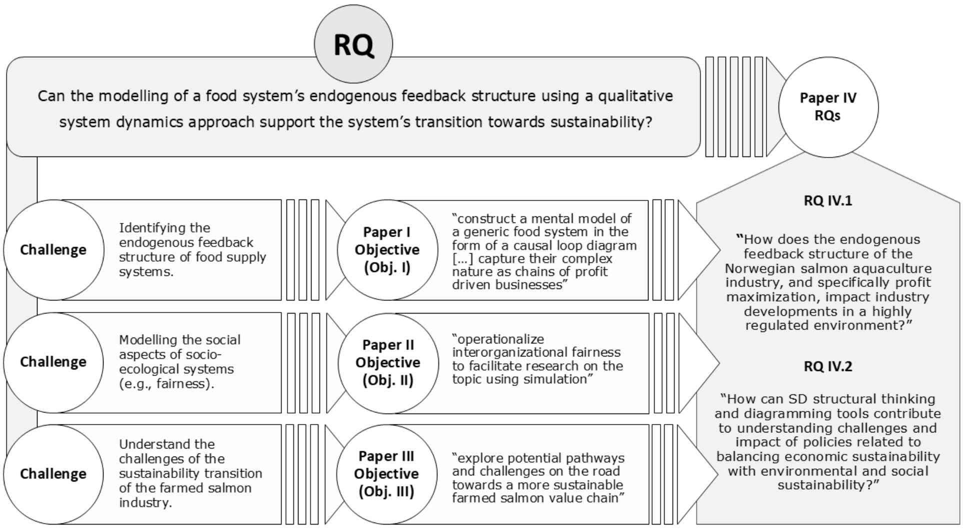

Figure 1 Schematic overview of how the overarching research question (RQ) relates to the objectives of Paper I, Paper II, and Paper III, and the two research questions in Paper IV.

This research was conducted as a part of a larger Horizon 2020 project called VALUMICS. The general aim of the VALUMICS project was to provide tools and approaches to enable decision makers to evaluate the impact of strategic and operational policies aimed at enhancing fairness, integrity, and resilience in future scenarios of sustainable food value chains. Within the project various food value chains were studied and modelled including the French wheat-to-bread value chain, the Italian tomato value chain, and the Norwegian farmed salmon value chain.

The thesis is structured as follows: Section 2 outlines the thesis' overall methodological framework and summarizes the methods and research design of each paper. In Section 3 the results of each paper are presented and summarized before they are discussed in Section 4. Section 5 provides the conclusion to the thesis.

2 Research design and methods

2.1 Research design

The research design is anchored in Mitroff et al. (1974)'s system's view of problem solving. Their framework is based on the idea that "there are certain aspects of science which can only be studied from a whole systems perspective". In their seminal 1974 paper "On Managing Science in the Systems Age: Two Schemas for the Study of Science as a Whole Systems Phenomenon", Mitroff et al. (1974) described the operational research approach as consisting of four phases (see Figure 2): (1) *conceptualization*, resulting in a conceptual model; (2) *modelling*, resulting in a scientific (quantitative) model; (3) *model solving*, resulting in a solution; and finally, (4) *implementation*, resulting in an updated reality or problem situation. They argue that the research process can start and end at any point in this cycle depending on the objectives of the research. Further a research project can include one or more phases and be based on previous research that report on preceding phases.

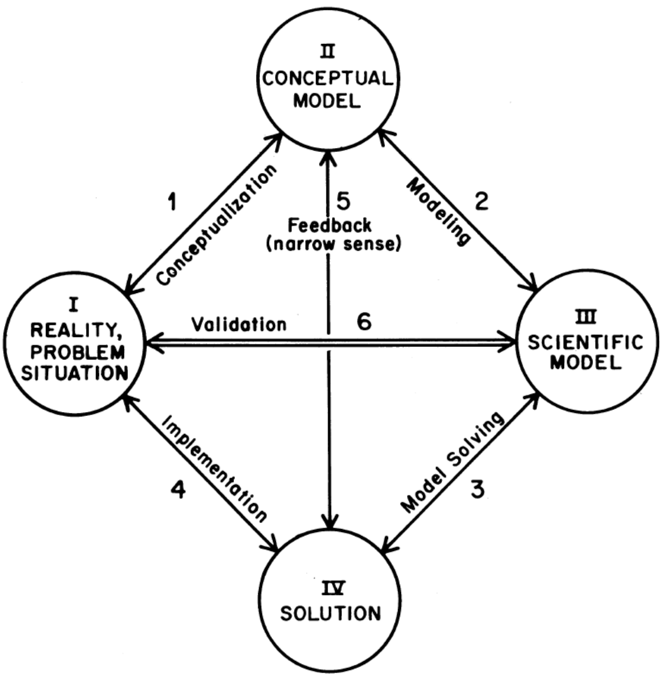

Figure 2 A systems view of problem-solving (Mitroff et al., 1974)

Most operational research projects (e.g., simulation modelling) are focused on the modelling phase (2 in Figure 2) and the validation of the resulting scientific (quantitative) model, sometimes to the extent that the important conceptualization step is brushed aside or at least given limited attention (Brailsford et al., 2019). It can however be argued that conceptualization is the most important step of any modelling exercise as the conceptual model lays the foundation for succeeding steps and serves as a basis for communication with stakeholders (Brailsford et al., 2019; Onggo, 2009; Robinson, 2008). In fact, a conceptual model can on its own provide valuable insights about a system under study and depending on the research objectives a quantitative model might not be needed nor necessarily adding value (De Gooyert et al., 2019; de Gooyert & Größler, 2018). This is often the case with theoretical SD modelling which typically focuses on a small incremental step in a large research agenda to contribute to an understanding of a phenomenon and may therefore not follow the same steps as applied research aiming to solve a problem (de Gooyert & Größler, 2018).

While this research adheres to the Mitroff et al. (1974) framework's holistic systems view of problem solving the focus of the papers that make up the thesis is the conceptualization phase, based on an analysis of the "real world". However, the conceptualization phase has been extended to include both the construction of a conceptual model of a generic food supply system and a conceptual model of a specific food supply system (e.g., the farmed salmon value chain) (see Figure 3).

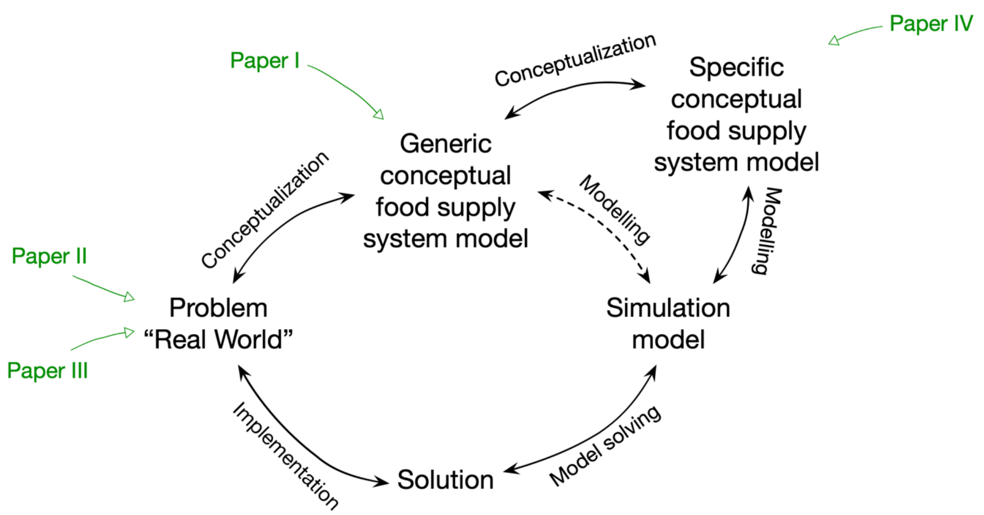

Figure 3 The research design adheres to the Mitroff et al. (1974) framework's systems view of problem solving.

In accordance with the Mitroff et al. (1974) framework, in Paper I the research foundation was laid through the development of a qualitative SD model of the endogenous feedback structure of (food) supply systems. In Paper II the "real world" of interorganizational relationships (e.g., supply systems) was analysed and then in Paper III the "real world" of a specific food supply system, namely the salmon aquaculture industry was analysed in the context of sustainability transitions. Finally, in Paper IV a qualitative SD model of the Norwegian salmon aquaculture industry was developed, based on insights from the first three papers, and then used to analyse current challenges in the industry.

2.2 Methods

While the research design is based on the Mitroff et al. (1974) framework, it is also heavily influenced by the choice of modelling approach in Papers I and IV, namely qualitative SD modelling using SD structural thinking and diagramming tools (i.e., CLDs). Nevertheless, Papers II and III, although informing Paper IV, constitute independent research efforts and thus adopted methodologies in alignment with their respective aims.

The SD methodology offers structural thinking and diagramming tools such as CLDs to aid in the process of mapping up the feedback structure of a system. A CLD consists of variables connected by arrows indicating the causal interactions among the variables which together visually depict the feedback structure of the system in the form of feedback loops. A positive arrow (+) indicates a positive relationship between two variables. When the value of the cause increases, the value of the effect also increases. A negative arrow (-) indicates a negative relationship between two variables. When the value of the cause increases, the value of the effect decreases. In a CLD the variables and arrows form one or more feedback loops, thus depicting the feedback structure of the system. Feedback loops can either be reinforcing (R) or balancing (B) depending on whether they amplify or stabilize change in the system. If an initial variable change is amplified through a loop, it is a reinforcing loop and if the change is counteracted as it propagates through the loop, it is a balancing loop (see Figure 4) (Sterman, 2000).

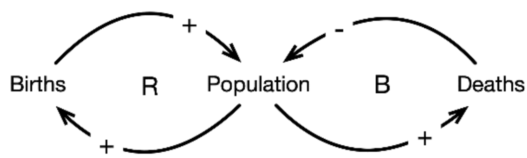

Figure 4 Indication of causal links (e.g., positive (+) and negative (-)) and feedback loops (e.g., reinforcing (R) and balancing (B))

The overarching objective of this thesis does not entail prediction or projection but rather explanation. Understanding (generic) socio-technical system drivers and feedback has been identified as a critical step towards guiding sustainability transitions (Papachristos, 2018) and the work towards this goal is still in its early stages within the transition modelling field (Köhler & Holtz, 2019). While quantitative SD modelling has its advantages, qualitative SD is more appropriate in the beginning of new theory development when little knowledge and data to inform quantitative simulation models is available (de Gooyert, 2019). Well-informed qualitative SD research also forms a basis for subsequent quantitative modelling. Now the methods and research processes for each paper will be described.

2.3 Paper I methods

In paper I, system analysis and SD structural thinking and diagramming tools were used to develop a conceptual model of a generic (food) supply system based on a review of the supply system SD literature and fundamental macro-economic theory. The approach involved two steps: (1) *problem articulation*, based on a literature review, and (2) *system conceptualization*, using SD structural thinking and diagramming tools (see *Figure* **5**).

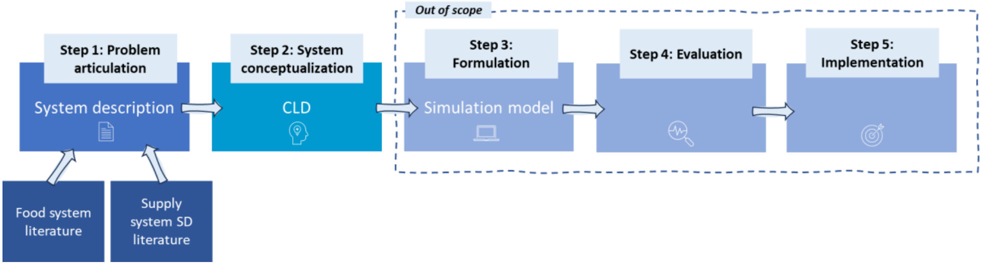

Figure 5 Paper I methodology

Step 1: Problem articulation

The literature review that informed the system description in step one was a combination of a database search and a snowballing approach. First, the ISI Web of Knowledge database was searched for articles assigned topics: "system dynamics" and "supply chain". This resulted in 84 articles. Through an abstract review 10 articles were chosen as a basis for the system description along with a few additional ones identified using a snowballing approach based on the original 10. To inform a broader description of food systems as complex systems, the literature on food systems as social-ecological systems and complex adaptive systems, was consulted. Further, to facilitate the modelling of food supply systems as an integration of supply-, value-, and decision chains, some foundational SD contributions (i.e., Meadows (1971), Forrester (1997), and Sterman (2000)), were considered.

Step 2: System conceptualization

In step two a CLD of a generic (food) supply system with three levels (i.e., primary production, processing, and retail) was constructed based on the system description developed in step one. This CLD was then used as a basis for creating a simplified model of the main drivers of a generic (food) supply system. This simplified model depicts a feedback relationship that is suggested to be repeated for each supplier-buyer relationship in a supply chain and can thus form a basis for research on supply systems, including their sustainability transitions.

2.4 Paper II methods

In paper II the construct of interorganizational fairness (IOF) was translated into (simulation) model operational terms. As the simulation literature offers limited guidance on the critical challenge of operationalising and quantifying immeasurable (social) constructs, well known methods of quantification from the social sciences were used. As fairness is an intangible, unobservable concept that is difficult to quantify the quantification step was preceded by a conceptualization step aimed at identifying factors closely connected to fairness perceptions that might be better suited for quantification. The approach thus involved two consecutive steps: (1) *conceptualization*, and (2) *operationalization* (see *Figure **6***).

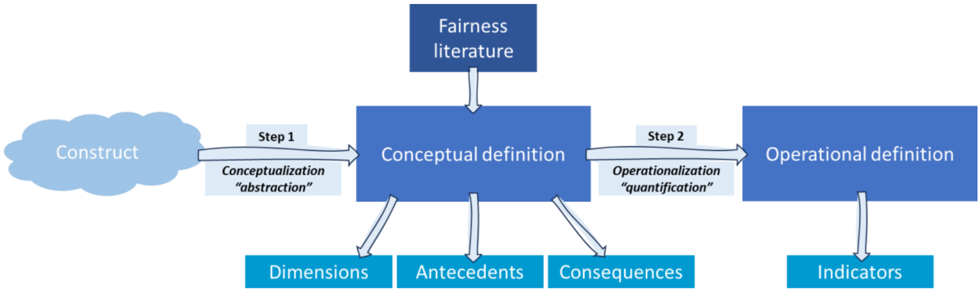

Figure 6 Paper II methodology

Step 1: Conceptualization

In the first step, the immediate factors leading to and resulting from fairness perceptions (e.g., its antecedents and consequences) were identified through a literature review. A systematic literature search was performed using the ISI Web of Knowledge database to identify research on the antecedents and consequences of IOF. The search resulted in 1083 items of which 32 were deemed relevant for the research through an abstract review. The result of the conceptualization phase was a conceptual definition of IOF along two dimensions: distributive IOF and procedural IOF. Furthermore, seven groups of observable factors (e.g., antecedents and consequences) relating to IOF were identified.

Step 2: Operationalization

In the second step, the conceptual definition, resulting from the first step, was used as a basis for the development of a model operational definition of IOF in the form of quantified indicators. Finally, key factor groups relating to fairness perceptions (e.g., power, environmental uncertainty, coordination, outcomes) that were identified in the conceptualization step, were put into the context of organizational decision making and the profit-driven nature of businesses in a competitive market.

2.5 Paper III methods

In paper III industry and expert perspectives of sustainability challenges and possible sustainability transition pathways for the salmon aquaculture industry were explored through focus groups and in-depth interviews, based on an integrated transition- and governance framework. The approach involved four steps: (1) *Develop framework*, (2) *Primary data collection*, (3) *Analysis of primary data*, (4) *Analysis of niche innovations* (see *Figure 7*).

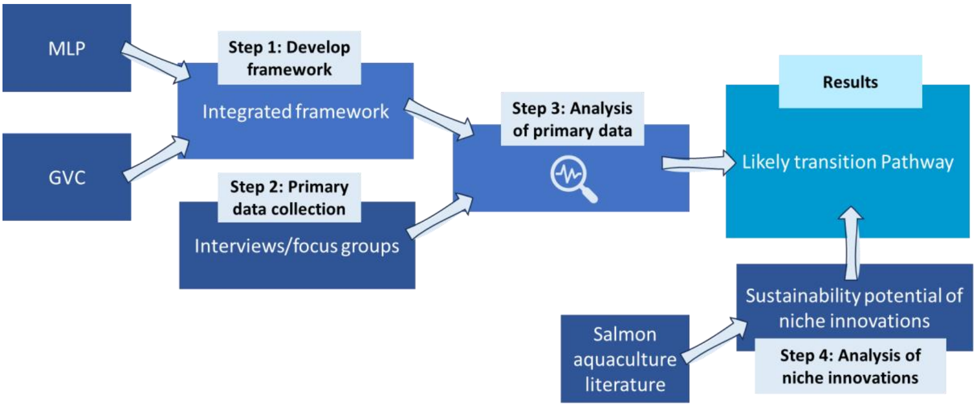

Figure 7 Paper III methodology

Step 1: Develop framework

To complement the MLP transition framework with a governance perspective the Global Value Chain (GVC) governance framework was integrated into the MLP view of socio-technical systems by using it to enrich the regime analysis.

Step 2: Primary data collection

Primary data were collected in five in-depth interviews and two focus groups with three and four participants, respectively. Participants, came from Norway and Iceland, and included industry experts, company representatives, and a policy maker. The question framework was semi-structured to ensure that all topics relevant to the analysis were included and to allow for more spontaneous discussion. The aim of the focus groups was not to reach a consensus but rather to explore different perspectives. The aim of the interviews was to gather in-depth information about the topics of interest from various stakeholders.

Step 3: Analysis of primary data

To analyse the results of the interviews and focus groups the first two authors independently created mind maps of each session, and these were then compared and discussed to ensure common understanding and to enhance internal validity (triangulating analysis). Data were subsequently coded by the first author using the analytical method of constant comparisons. Standard country codes were also used to highlight cross-context analysis. The findings were then further analysed using the integrated framework developed in step one. The qualitative findings based on interviews and focus groups provided information about the three levels of the MLP in the context of the salmon aquaculture industry: (1) the socio-technical landscape, (2) the socio-technical regime, and (3) niche innovations, and were used, in combination with the findings of the sustainability analysis of niche-innovations in step four, as a basis for determining the most likely sustainability transition pathway for the industry.

Step 4: Analysis of niche innovations

To strengthen the analysis and the resulting estimation of the most likely transition pathway towards increased sustainability, the niche-innovations (identified in the primary data collection step) were analysed in terms of their contribution to sustainability challenges based on the salmon aquaculture literature.

2.6 Paper IV methods

In paper IV an abductive SD approach was used to study the endogenous feedback structure of the Norwegian salmon aquaculture industry and how it has shaped its development and contributed to the issues facing it today. The approach involved three steps: (1) *analyse phenomenon*, (2) *formulate hypothesis*, and (3) *test hypothesis* (see *Figure **8***).

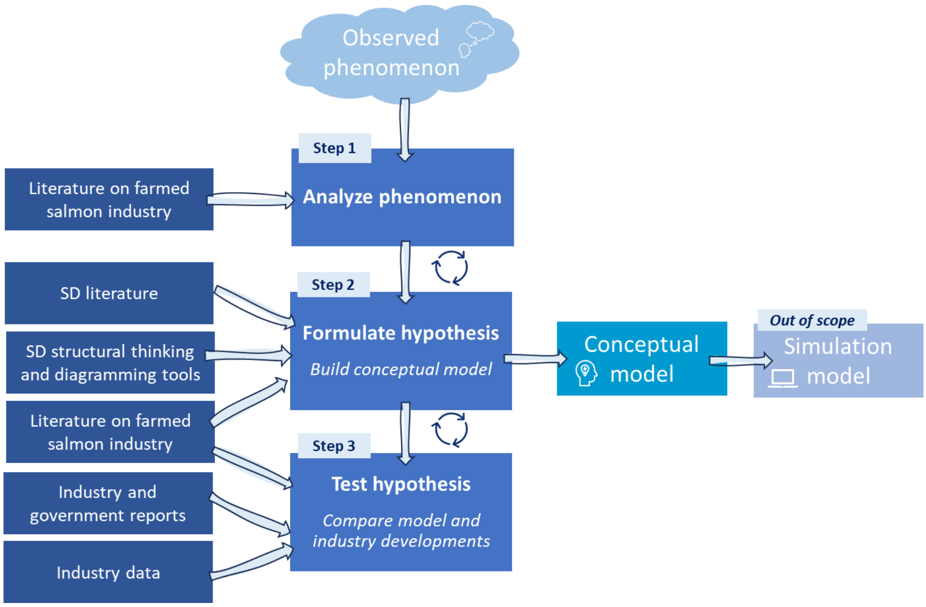

Figure 8 Paper IV methodology

Step 1: Analyse phenomenon

The abductive modelling exercise started with an observation of some puzzling behaviour in the system under study, in the form of unintended policy consequences. The analysis was based on an explorative review of a wide variety of secondary sources including the salmon aquaculture literature, industry reports, company reports, and government reports (e.g., whitepapers, environmental reports). An explorative review here means that it was not systematic but still wide in scope as key sources were identified using Google Scholar and then, based on these key sources, an extensive back- and forward-looking snowballing approach was used to identify other relevant papers. The analysis also drew on findings from the first three papers of this thesis.

Step 2: Formulate hypothesis

Based on prior theoretical knowledge from the SD (model form Paper I) and salmon aquaculture literatures (identified in step one), the industry's internal structure and feedback processes were conceptualized using SD structural thinking and diagramming tools, resulting in a comprehensive CLD of the Norwegian salmon aquaculture industry. This CLD, describing the systems endogenous feedback structure, constituted a dynamic hypothesis of what causes the puzzling behaviour identified in step one.

Step 3: Test hypothesis

Through a process of theory matching (e.g., comparing the CLD to known facts about past industry developments), the hypothesis that the industry's endogenous feedback structure is the cause of the unexpected dynamics in the system (e.g., unintended policy consequences) was tested. The dynamic hypothesis was tested against the data collected in step one and industry data (e.g., production volume, price, cost) extracted from online databases. Finally, the model was used to analyse current challenges facing the industry, again using SD structural thinking and diagramming tools.

2.7 Data

This research draws on both secondary data, from the academic literature, reports and online databases, and primary data. The secondary data underpinning the research originates within the SD literature, fairness literature, salmon aquaculture literature, sustainability transitions literature, as well as various Norwegian aquaculture industry and government reports. Furthermore, the research in Paper III on sustainability transitions in the farmed salmon industry, is based on primary data collected in stakeholder interviews and focus groups. Other interviews, conducted in relation to the VALUMICS project, including interviews with salmon aquaculture experts from industry and academia, inform the research although they are not explicitly reported on. Finally, the salmon price, cost, and production data, used to validate the model in Paper IV, were taken from online databases belonging to the Norwegian Directorate of Fisheries (Norwegian Directorate of Fisheries, 2023), and the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2023).

3 Results

As explained in the introduction the four papers combine to answer the overarching research question (RQ). First, some challenges of modelling food systems in general and the Norwegian salmon aquaculture industry in particular are addressed in Papers I, II, and III. Then, informed by the results of the first three papers the thesis' overall findings are finalized in Paper IV. Now the results and contributions of each individual paper will be presented.

3.1 Paper I: Modelling of Integrated Supply-, Value-, and Decision Chains within Food Systems

A prerequisite for building a model of a specific food supply system (i.e., the salmon aquaculture industry), is understanding the basic endogenous feedback structure of such systems. This guided the objective of the first paper (Obj. I in Figure 1, p. 13) which was to create a conceptual model of the endogenous feedback structure of a generic food supply system. The conceptualization was based on the idea that food systems, as supply systems, can be defined as integrated supply-, value-, and decision chains. This abstraction of supply systems as an integration of the downstream flow of products, the associated upstream flow of money, and the decision chains that link them, contrasts with the one of supply systems as simple flows of orders and products, seen in many supply chain SD models in the literature.

3.1.1 Paper I results

To enhance the traditional SD model of supply chains as simple flows of orders and products the model resulting from this research added to the product flow: (1) the flow of money, (2) the decision chains linking the money and product flow, and (3) the market mechanism that balances the reinforcing profit-seeking nature of the system. Drawing on earlier work on supply system modelling using SD and macroeconomic theory, SD structural thinking and diagramming tools were used to translate information about the feedback processes inherent in supply systems into a CLD of a fully integrated supply-, value-, and decision chain that spans the supply system from the primary processing stage, through processing, and retail to the consumer.

Based on this view of supply systems it was concluded that for each supplier/buyer relationship in the system there exists a generic feedback structure (see Figure 9) featuring a profit-seeking loop (R) and several balancing feedback loops, two of which (B1 and B2) regulate the market through price setting. The reinforcing profit-seeking loop (R) is based on the idea that increased profit expectations drive the downstream flow of products in the chain by increasing willingness and means to engage in value adding activities and supplying products to a market while limiting costs. This generates a reinforcing profit maximization loop that pushes products downstream towards customers and pulls material from suppliers upstream. The chain of agents, each aiming at maximizing profit, therefore, adds up to a reinforcing profit maximizing supply system. This system is however also regulated by price through market dynamics, that is, the relationship between supply and demand. The basic endogenous feedback structure presented in Figure 9, which is repeated for every supplier/buyer relationship in a supply system, is the main finding of this paper and will be used to inform the conceptual model of the Norwegian salmon aquaculture industry in Paper IV.

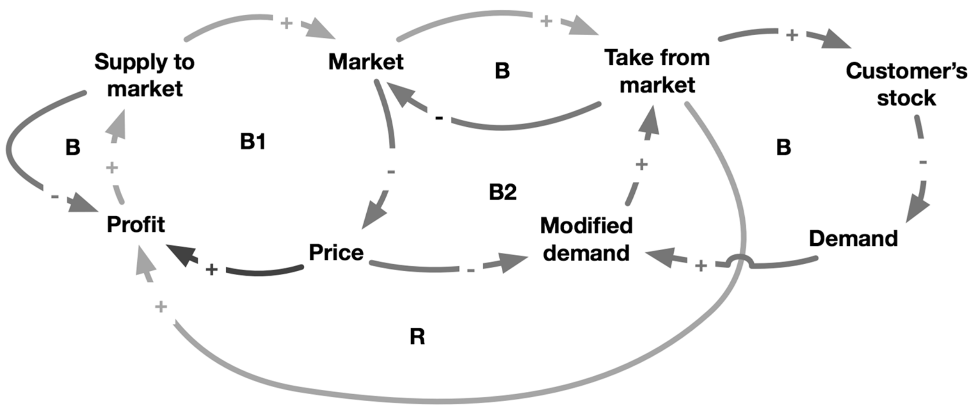

Figure 9 The endogenous feedback structure of a generic food supply system featuring a reinforcing profit-seeking loop (R) that drives the system, and several balancing feedback loops, two of which (B1 and B2) regulate the market through price setting.

3.1.2 Paper I contribution

This paper contributes to research on supply systems by extending the traditional conceptualization of supply chains as a simple downstream flow of products to include the upstream flow of money, the market mechanism balancing the two, and the decision chains that link them, thus incorporating the profit driven nature of the system.

Furthermore, going through the exercise of mapping up the integrated flows in a supply system, highlighted some considerations for the ongoing research project. First, while the importance and impact of profit is highlighted as the main factor affecting decisions in supply systems, its importance also emphasizes the need to consider other factors (e.g., sustainability, governance) in the context of profit seeking. In the long run, the focus on short-term profit can negatively affect the environmental, social, and even economic, sustainability of the supply system, both through loss of resilience but also through overemphasis on own interests to the point that it has damaging effects on the operation of other chain members (e.g., unfair trading practices).

The view put forth in this paper of food supply systems as networks of profit driven businesses has implications for research on transitions towards sustainable food systems as it highlights the importance of considering the endogenous feedback structure of such systems, namely the interaction of a reinforcing profit-seeking loop that drives the system, and the balancing feedback loops that regulate the market through price setting.

Finally, the results have major implications for policy making in general and the urgent need for transforming food systems in particular as they provide information about critical leverage points and can thus inform policy design.

3.2 Paper II: Operationalization of Interorganizational Fairness in Food Systems: From a Social Construct to Quantitative Indicators

One of the key challenges of modelling social-ecological and socio-technical systems like food systems relates to the problem of operationalization, which stems from the intangible nature of many social concepts (e.g., fairness), making them difficult to define in measurable terms. The objective of the second paper (Obj. II in Figure 1, p. 13) was to facilitate research on IOF in food systems using simulation modelling by defining the social construct of IOF in model operational terms in two consecutive steps: (1) *conceptualization* and (2) *operationalization*. IOF, which concerns fairness in exchange relationships (i.e., supplier-buyer relationships), was selected as the focus of the modelling efforts of the VALUMICS project as IOF issues (e.g., unfair trading practices) have the potential to be especially problematic in food supply systems.

3.2.1 Paper II results

Through a process of conceptualization, the observables (i.e., antecedents and consequences) of the unobservable concept of IOF were analysed along two dimensions, distributive IOF (i.e. concerning distribution of benefits and burdens), and procedural IOF (e.g., the procedures of distribution). This resulted in multiple factors related to IOF. To focus the attention on the core factors associated with fairness perceptions, similar or related factors were grouped together resulting in a consolidated view of the antecedents and consequences of fairness in an interorganizational context. The consolidated view consisted of seven groups of factors for both dimensions of IOF: (1) economic outcomes, (2) operational outcomes, (3) information sharing, (4) power, (5) controls, (6) environmental stability, and (7) relationship quality.

To get a more thorough understanding of IOF, particularly the causalities and interrelationships between the different factors they were analysed in the context of organizational decision making resulting in the conceptual diagram in Figure 10. It shows how fairness perceptions relate to the outcomes produced by organizations (i.e., distributive IOF), the challenges of organizational decision-making aimed at fulfilling the purpose of producing outcomes (i.e., procedural IOF), and the strategies organizations use to overcome those challenges. Indeed, fairness perceptions are firmly linked to involvement in decision making in the literature. An organization's decision-making leverage (i.e., the ability to affect the decision-making process and results) is very dependent on its relative *power* position, and the decision-making capacity (i.e., the extent to which they are equipped to make decisions) is affected by the level of *uncertainty about* *the external environment*. Organizations use different *coordination strategies* to affect their decision-making leverage and capacity to make better decisions and meet their objectives. In a chain of businesses, less powerful actors can increase their leverage in decision making by forming horizontal alliances (i.e., cooperatives, producer organizations) and vertical coordination strategies (i.e., contracts, collaboration, information sharing, etc.) can be used to reduce uncertainties and thus influence decision-making capacity.

The conceptual view of IOF in the context of decision making (see Figure 10) shows how procedural fairness perceptions relate to an organization's ability to influence decision making, which also directly influences distributive fairness perceptions as decision-making is the process by which organizations produce outcomes.

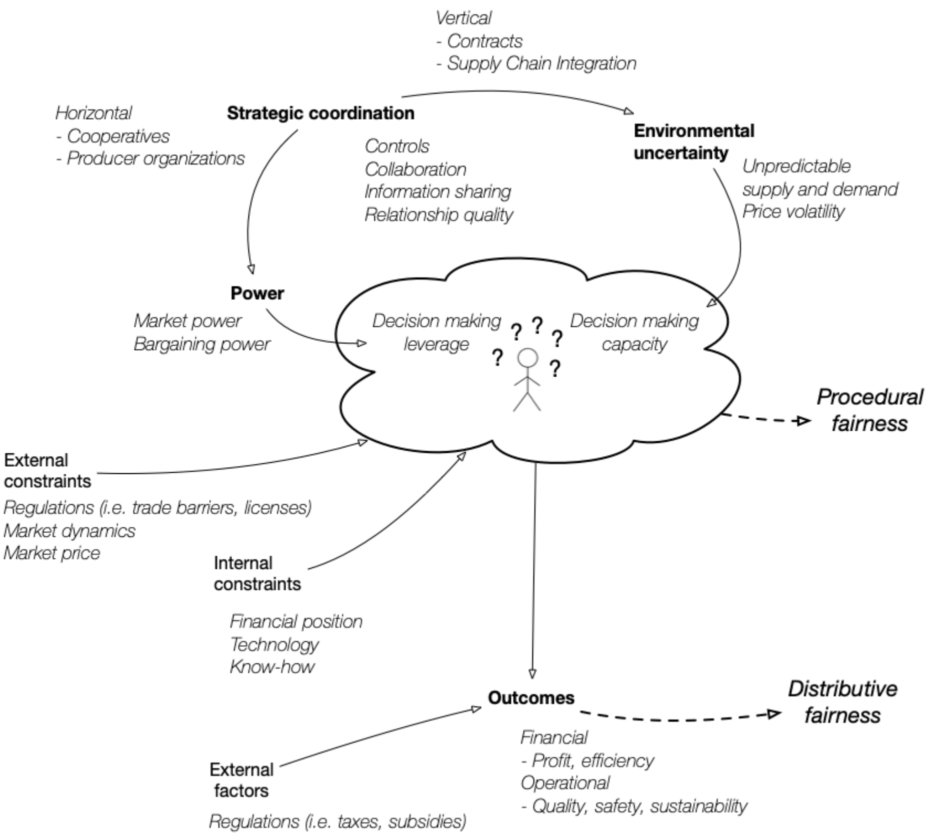

Figure 10 The factors related to IOF viewed in the context of organizational decision making.

From the seven factors influencing perceptions of IOF potential proxy indicators of procedural and distributive fairness were selected. To be applicable a factor needed to be strongly correlated with either distributive or procedural fairness and be quantifiable in such a way that it can be made operational in a simulation model. Two factors, financial outcomes, and power met these conditions and were used as a basis for a quantitative, model operational definition of IOF in the form of proxy variables and quantitative indicators (Figure 11). Financial outcomes were selected as a proxy for distributive fairness and profit margin as a quantitative indicator. Bargaining power and market power were selected as proxies for procedural fairness. Number of available buyers/suppliers and company size were selected as quantitative indicators of bargaining power and Lerner index and Mark-down index as quantitative indicators of market power.

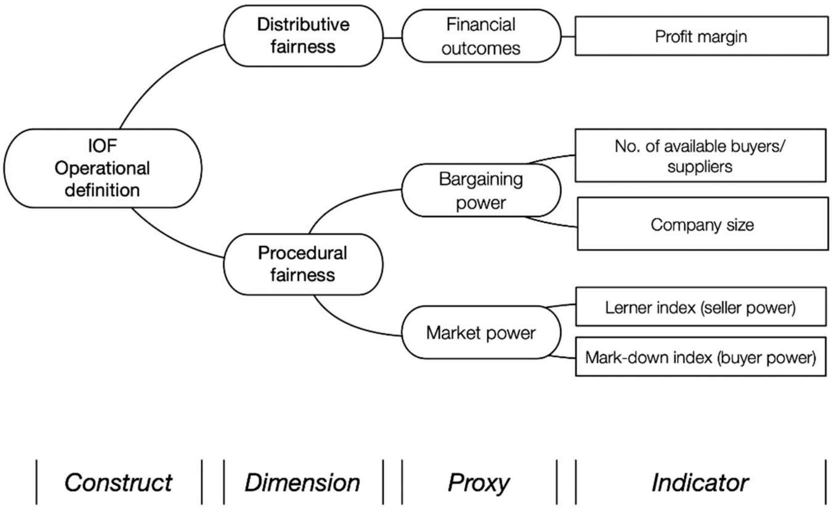

Figure 11 Resulting measurement framework of IOF.

3.2.2 Paper II contribution

The results of this paper have implications for further research. The operational definition of IOF in the form of indicators enables the exploration of problems related to IOF in food (and other) supply systems using quantitative modelling and provides indications of where policy intervention efforts aiming to increase fairness perceptions should be focused. Furthermore, the process of operationalizing a social construct for use in a simulation study can be replicated for other intangible social constructs that are interesting to study using simulation modelling, in particular policy relevant constructs (e.g., social license to operate). Finally, given the observed relationship between fairness perceptions and organizational decision making, the results emphasized the importance of considering the drivers of organizational decision making and the factors that balance them, namely a system's endogenous feedback structure, in policy design.

The operational definition of IOF resulting from this paper was used to study fairness in the French wheat-to-bread value chain (McGarraghy et al., 2022). However, as expert interviews indicated that IOF is not the most pressing fairness issue in the salmon aquaculture industry but rather the distribution of value and (environmental) costs between the resource owner (society) and the resource user (industry), it was decided to shift the focus of this research towards the industry's transition towards sustainability.

3.3 Paper III: Transition Pathways for the Farmed Salmon Value Chain: Industry Perspectives and Sustainability Implications

To determine whether modelling a food system's endogenous feedback structure can support the system's transition towards sustainability it is necessary to understand the challenges related to the system's transition. Thus, the objective of the third paper (Obj. III in Figure 1, p. 13) was to explore potential pathways and challenges on the road towards a more sustainable farmed salmon value chain, based on industry and expert perspectives in Iceland and Norway that were analysed using an integrated MLP-GVC framework.

3.3.1 Paper III results

The results of stakeholder interviews and focus groups were analysed and mapped to the MLP framework. They highlighted the most prominent socio-technical landscape developments and pressures (e.g., supply and demand, global environmental change, resource scarcity), the current state of the value chain in terms of shared regulative, normative, and cognitive rules (i.e. the socio-technical regime), and the niche-innovations currently in development (e.g., land-based, and offshore farming).

Based on the mapping of stakeholder perspectives to the MLP framework a *transformation pathway* was deemed the most likely direction that the industry will take in the next decades due to a moderate level of landscape pressure, not sufficiently developed niche-innovations, and the symbiotic nature of the relationship between the niches and the regime. A transformation pathway is one where regime actors modify the direction of the regime, but basic architecture remains the same (Geels & Schot, 2007). This finding was supported by analyses of the system's governance structure, and the potential contribution of niche-innovations to sustainability.

Key identified contributing factors in terms of the most likely transition pathway were: (1) concentration in the industry (e.g., power asymmetries), (2) mutual dependencies between industry (aiming to maximize profit), and government (depending on businesses to provide jobs, tax payments and economic growth), and (3) the flexible hybrid governance structure consisting of networks of large integrated firms and their subsidiaries that interact with other chain actors using a combination of arrangements depending on what fits at the time. Therefore, it was concluded that a reasonably high and rising landscape pressure, specifically related to global environmental change and changing consumer preferences, would continue to be offset by the resistance to change by powerful actors in the regime and their ability to adapt and align their production network enough to alleviate some of the pressure. Furthermore, that this would be supported by the fact that competitive niche-innovations do not seem to be sufficiently developed to compete with the highly efficient traditional sea-based farming system. Thus, a gradual transformation towards more sustainability within the current regime with, mainly, regime driven innovations and refinements, was identified as the most likely future. These results imply that policy will be an important tool to escalate the necessary transition towards sustainability.

The findings are summarized through the integrated framework in Figure 12 where the governance structure of the farmed salmon value chain as defined by the GVC framework was transposed to represent the socio-technical regime within the MLP.

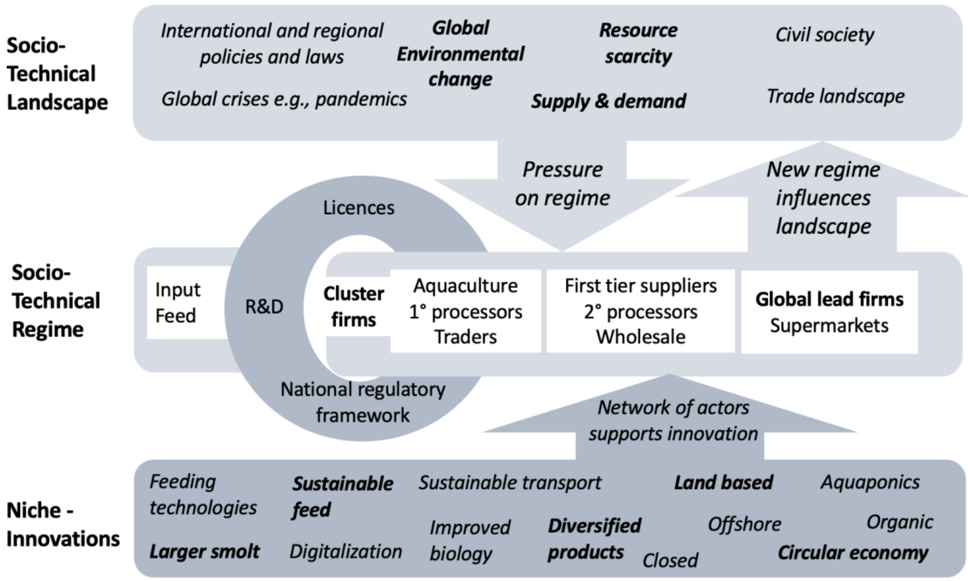

Figure 12 Summary of findings through the integrated framework (authors' own conceptualization based on existing frameworks (Geels & Schot, 2007; Gereffi & Lee, 2016; Olafsdottir et al., 2019).

3.3.2 Paper III contribution

This research identified the most likely transition pathway towards sustainability within the farmed salmon value chain, highlighted the main challenges constraining such a transition, and has several research, policy, and managerial implications.

It contributes to research on socio-technical transitions through the integration of the MLP framework on sociotechnical transitions and the GVC framework on governance in value chains. The addition of a governance analysis to transition studies is useful for emphasizing the role of different actors in contributing to regime resistance as usually the focus is mainly on the driving forces of niche innovations. Furthermore, the assessment of sustainability contributions of niche-innovations strengthens the analysis by indicating their ability to challenge the current regime.

Applying these frameworks to the farmed salmon value chain provided insights into the drivers and barriers to the transition towards sustainability in the salmon aquaculture industry, and on how policymakers, managers, and other actors can promote and support a sustainability transition.

An important finding of this paper with implications for the ongoing research project on the farmed salmon value chain was highlighting the power of regime actors to resist change, which underscores the importance of considering the endogenous feedback structure, including the profit driven nature of chain partners, in policy design. It also highlights the interdependence of regime actors (i.e., government and industry), which has implications for policy makers' ability and willingness to use policy to transition the industry towards more sustainable practices.

3.4 Paper IV: Towards a Systems Perspective in Policy Design: An Analysis of how the Endogenous Feedback Structure of the Norwegian Salmon Aquaculture Industry Impacts Policy Outcomes

In this fourth and final paper of the thesis a specific food system, the Norwegian salmon aquaculture industry, was modelled using a qualitative SD approach, to answer the thesis' overarching research question (RQ in Figure 1, p. 13). The modelling objective, reflected in two research questions (RQ IV.1 and RQ IV.2 in Figure 1, p. 13), was to explore how studying the endogenous feedback structure of the Norwegian salmon aquaculture industry in the context of industry developments, using SD structural thinking and diagramming tools, can contribute to understanding how the feedback structure impacts industry developments and policy outcomes.

3.4.1 Paper IV results

The first objective of this paper, put forth in RQ IV.1, was to study the endogenous feedback structure of the Norwegian salmon aquaculture industry and determine if and how it has shaped its development and contributed to the issues facing it today. The model of the main drivers and feedback in a generic supply system (from Paper I) was adapted to the Norwegian salmon aquaculture industry based on a literature review aimed at identifying the specifics of the industry that influence the system's feedback structure. Several characteristics of the Norwegian salmon aquaculture industry were found to impact its feedback structure (compared to the generic one). Most important in that regard were the longstanding limitations on growth in the industry. Through a review of the salmon aquaculture literature five types of growth constraints in the industry were identified: (1) biophysical, (2) environmental and biological, (3) regulatory, (4) social, and (5) technological constraints on growth.

Based on the generic supply system model from Paper I and the analysis of the specifics of the feedback mechanism in the Norwegian salmon aquaculture industry, a CLD of the system under study was constructed (see Figure 13). The CLD shows the consolidated endogenous feedback structure of the industry and entry points of constraints on growth. Through a process of theory matching the model was then validated against developments in the industry's history. Specifically, industry developments in terms of production volume, cost, and price, were analysed with reference to the system's feedback structure in the context of the active policy instrument (i.e., how the active policy instruments have impacted the profit seeking behaviour of the system in terms of restricted and system-driving loops).

The results of the theory matching process provided an answer to RQ IV.1 as they indicated that industry dynamics are to an extent determined by the system's internal feedback structure. In particular, the system's drivers influence how it responds to external factors like policy interventions and thus has a significant impact on policy outcomes.

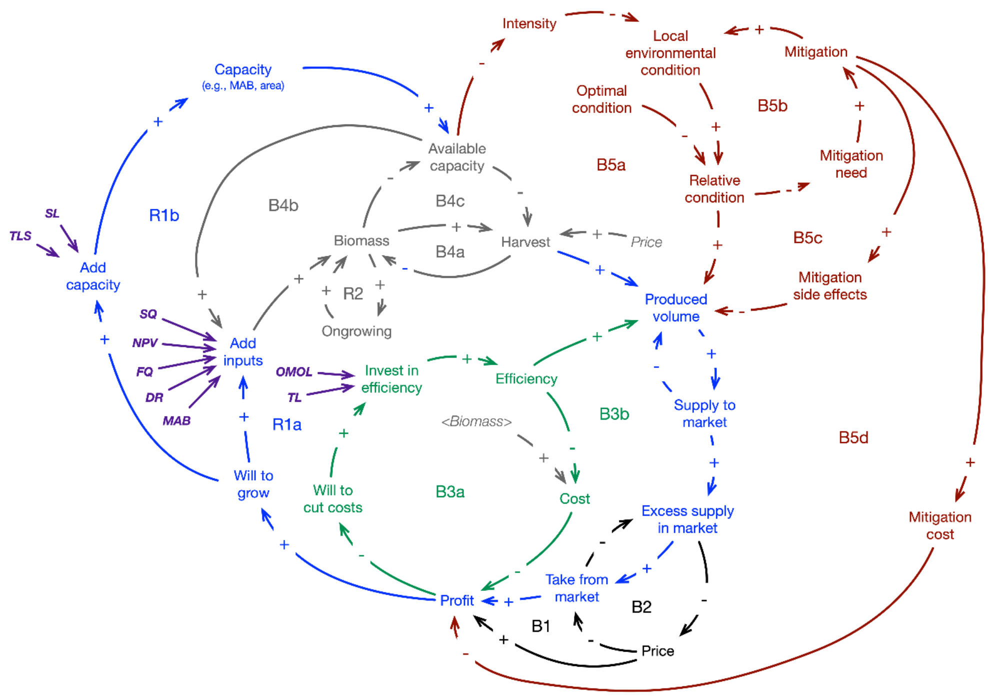

Figure 13 The endogenous feedback structure of the Norwegian salmon aquaculture industry and policy instruments and external factors impacting it. Abbreviations; SL: Social license, TLS: Traffic light system, SQ: Smolt quota, NPV: Net pen volume restriction, FQ: Feed quota, DR: Density restriction, MAB: Maximum allowable biomass, OMOL: "One man, one license", TL: Technological limit.

The second objective of the paper, put forth in RQ IV.2, was to use SD structural thinking and diagramming tools to analyse current challenges in the industry (i.e., mortality, diseases, diminishing social license to operate) in the context of the system's endogenous feedback structure. In doing so, based on the industry's endogenous feedback structure already defined, a second CLD presenting the dynamics of current challenges in the industry related to growth constraints was constructed (see Figure 14). What emerged from the qualitative analysis using the model were three ways in which the current policy regime, the traffic light system (TLS), maintains and even exaggerates the behaviour that it is supposed to constrain by incentivizing a detrimental level of production intensity.

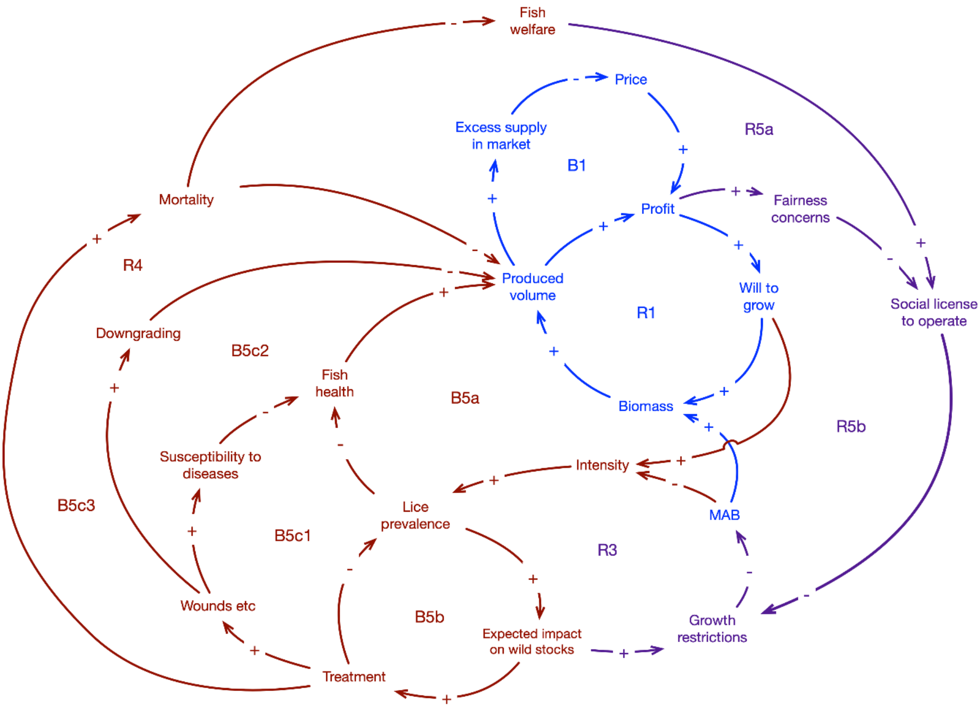

Figure 14 Current challenges in the Norwegian salmon aquaculture industry related to growth constraints.

First, growth restrictions lead to intensification of production as an aggregate reduction in output raises prices and thus increases willingness to grow production, which in the absence of other avenues of growth, leaves only the option of intensification of production, and thus its unfortunate side effects (e.g., mortality, salmon lice). Furthermore, the fact that growth within the TLS regulatory scheme is contingent on lice levels, encourages the use of mitigation methods (e.g., delousing treatments) that themselves have negative side effects (e.g., wounds, mortality) that ultimately lead to further intensification of production through the impact that decreased output has on market prices. Finally, growth constraints reinforce the deterioration of the industry's social license to operate through decreased welfare resulting from increased delousing treatments and more profits, due to scarcity induced high prices.

The analysis indicated that the challenges facing the industry today (e.g., mortality, diseases, diminishing social license to operate) are a case of unintended policy consequences that can be traced directly to the system's endogenous feedback structure, namely the profit-seeking behaviour (R1) and the balancing market mechanism (B1). These findings show how SD structural thinking and diagramming tools can contribute to understanding challenges and impact of policies related to balancing economic sustainability with environmental and social sustainability and thus answers RQ IV.2.

3.4.2 Paper IV contribution

These findings support the view that a systems perspective is useful in policy design and could support a shift from a regulatory system focusing on current issues (e.g., lice levels) to one with a more long-term focus. Furthermore, such a shift could enable the use of policy in shaping the direction of the industry towards sustainability. Therefore, the understanding of the endogenous feedback structure of the Norwegian salmon aquaculture industry and how it impacts the response to different policy instruments, resulting from this study, can inform future research aimed at developing methods to model the industry's transition towards sustainability and thus support the design of policy instruments that could accelerate such a transition.

3.5 Summary of results and contribution

The four research papers jointly contribute to answer the thesis' overarching research question, each contributing evidence of how understanding the endogenous feedback structure of a food supply system can support its transition towards sustainability. Paper I introduced the main drivers and endogenous feedback structure of a generic supply system. Paper II revealed how the distribution of value added has a major impact on fairness perceptions and emphasized the importance of considering the drivers of organizational decision making and the factors that balance them, namely a system's endogenous feedback structure, in policy design. Paper III explained how the profit driven nature and endogenous feedback structure of food supply systems impacts transitions towards sustainability, indicating that policy will be important to steer food supply systems on that journey. Finally, Paper IV, informed by the results of the other three, showed how the endogenous feedback structure of the Norwegian salmon aquaculture industry impacts policy outcomes and contributes to the challenges facing the industry. The combined results of the four papers can be summarized into four key findings:

1) The endogenous feedback structure of food supply systems impacts industry dynamics and policy outcomes,

2) this endogenous feedback structure and specifically the profit driven nature of food systems, impedes transitions towards sustainability, and thus

3) policy will be an important tool in guiding and accelerating transitions, and finally,

4) SD structural thinking and diagramming tools are useful for modelling food systems and thus aiding in policy design and supporting sustainability transitions.

These findings confirm that using a qualitative SD modelling approach to gain an understanding of the endogenous feedback structure of a food system can support the system's transition towards sustainability and thus provides an answer to the overarching research question (RQ).

The findings contribute to research within different fields. They contribute to SD research on supply systems by: (1) extending the traditional conceptualization of supply chains as simple downstream flow of products to that of integrated supply-, value-, and decision chains, and (2) highlighting the importance of considering the endogenous (profit-driven, market balanced) feedback structure of supply systems. Describing the endogenous feedback structure of the Norwegian salmon aquaculture industry contributes to aquaculture policy research by highlighting the role of the profit-driven endogenous feedback structure of the industry in shaping industry dynamics.

Furthermore, the findings contribute to research on the modelling of social systems by introducing a process for operationalizing social constructs for use in quantitative modelling which can be replicated for other social constructs, to fairness research by enabling exploration of problems related to IOF using quantitative modelling, and to fairness policy research by providing indications of where policy intervention efforts aiming to increase fairness perceptions should be focused.

Finally, this research contributes to sustainability transition research. First, through the contribution to research on sustainability transitions in the salmon aquaculture industry by (1) identifying the most likely transition pathway towards sustainability, (2) highlighting the main challenges constraining a transition, and (3) assessing the sustainability contributions of niche-innovations indicating their ability to challenge the current regime. Second, through the contribution to sustainability transition research in general by (1) highlighting the power of regime actors in the Norwegian salmon aquaculture industry to resist change, which underscores the importance of considering the endogenous feedback structure, including the profit driven nature of chain partners, in policy design, and highlights the need for policy to guide transitions, and (2) integrating the MLP framework on sociotechnical transitions and the GVC framework on governance in value chains, thus adding a governance perspective to the widely used MLP framework and a focus on regime resistance which has been lacking in transition studies.

In the next section the findings and their implications will be discussed.

4 Discussion

This research set out to investigate the endogenous feedback structure of food systems in the context of sustainability transitions using SD modelling. While sustainability transitions, have been extensively researched and conceptualized, the focus has mainly been on describing past transitions and less on how to guide future transitions. Furthermore, transition research has been largely concentrated on potential solutions to sustainability challenges in the form of niche innovations, and thus to a lesser extent on factors stalling transitions including resistance to change in the regime. The leap from describing past transitions to guiding future transitions would involve understanding the drivers and feedback mechanisms of socio-technical systems including their profit driven nature, path dependencies, and lock-ins. In that regard the benefits of modelling, for transition research, have been pointed out and resulted in several contributions. However, this sub-field of transition research is still in the early stages of development, dealing with the challenges of modelling the complexities of socio-technical systems and transition processes.

Through the four distinct research papers that make up this thesis it has been confirmed that indeed "[…] the modelling of a food system's endogenous feedback structure using a system dynamics approach [can] support the system's transition towards sustainability". The main drivers and the endogenous feedback structure in a generic supply system were introduced in Paper I. The way in which this endogenous structure relates to organizational decision making and thus impacts fairness perceptions was revealed in Paper II, how it impacts transitions towards sustainability in the aquaculture industry in Paper III, and finally, in Paper IV, how it impacts the dynamics in the Norwegian salmon aquaculture industry and thus policy outcomes.

This research has shown how the endogenous feedback structure of the Norwegian salmon aquaculture industry impacts industry developments and policy outcomes, and through the transition pathways analysis, how it hinders transition towards sustainability. This corresponds well with industry developments as several examples of unintended policy consequences can be linked to the profit driven nature of the industry's endogenous feedback structure. This includes the intensification of production in response to environmental restrictions on growth (Oglend et al., 2024), the biological challenges and overproduction related to unsuccessful restrictions on net-pen volume (Afewerki et al., 2023), and fish welfare issues related to the successful implementation of an indirect limit on production in the form of feed quotas (Hersoug, 2021). The disease driven market failure in the Chilean salmon aquaculture industry in the late 2000's is also an example of how the profit driven nature of a food supply system impacts industry developments. However, in that case, it was the absence of regulation that was the problem (Asche et al., 2009).

While aquaculture regulations in Chile have since improved, the lack of efficiency of aquaculture policy in addressing environmental issues is still a problem in many production regions. In fact, a recent global assessment of farmed salmon escape policies found that due to weak sanctions, an emphasis on inefficient measures such as monitoring and reporting, and provisions allowing regulators to absolve companies from responsibility, current policies in many regions, are unlikely to reduce the number of escapes and their environmental impact (Kolavani & Mather, 2025). These findings are also in line with findings from other food industries like the agri-food industry where powerful conglomerates benefit from power concentration in the industry and support from governments that although “officially” fighting oligopolistic behaviours are so (financially) dependent on the food industry as providers of jobs, nutrition, and tax revenues that they are not willing or able to implement the drastic policy instruments needed to reverse their unsustainable trajectories (Béné, 2022).

Although, environmental issues are high on the agenda when it comes to the salmon aquaculture industry, social factors are increasingly credited with impacting industry dynamics. The final paper of this thesis reported on how this relates to the industry’s endogenous feedback structure as growth constraints reinforce the deterioration of the social license through decreased fish welfare, and more profits, due to scarcity induced high prices. There is work to be done in better understanding the dynamics between environmental impacts, distribution of economic benefits, and the industry’s social license to operate. Aquaculture industries increasingly face challenges related to their social license. Olsen et al. (2024) reported on a cross-country comparison on the subject. While they found that respondents were supportive of the industries’ food production, employment, and business activity contributions, they were less supportive in terms of sustainability, industry regulation, and distribution of the value added. The authors suggest that efforts to increase societal support should be focused on the public’s knowledge of the industry as it influences their process of balancing pros and cons in forming their opinion. As the social license to operate is closely connected to fairness perceptions (Moffat & Zhang, 2014), the results of the second paper of this thesis could provide insights into how to go about increasing societal support, especially the way in which fairness perceptions relate to factors such as power, environmental uncertainty, and outcomes.

While this research indicates the incompetence of policy in guiding transitions it also stresses its importance in that regard. This is in line with previous research (e.g., Soininen et al. (2021) and Köhler et al. (2019)) and is particularly important for research on transitions in the Norwegian salmon aquaculture industry as studies have indicated that although the Norwegian government and industry players officially promote sustainability the regulatory framework does not accelerate a sustainability transition and therefore sustainability ambitions, although frequently and loudly discussed, are unlikely to be met in a business-as-usual scenario (Schøning et al., 2023). Recently Donner et al. (2024) reviewed governance models for food system transitions and found that concentration of power and inefficient policies, treating symptoms rather than structural causes, are among the barriers to sustainability transitions. Furthermore, Béné (2022) showed how various self-reinforcing dynamics in food systems including power concentration, profit driven nature, and policy incoherence are contributing to system lock-ins and therefore a transformation of the food system calls for a transformation of the governance system as well. This is in accordance with the finding of this thesis that policy in general, and one that aims to guide sustainability transitions in particular, must consider a system’s endogenous feedback structure.

This research has implications for transition studies and policy design as it contributes to the leap from merely describing transitions, past or future, to guiding and accelerating them through policy. The use of modelling methods in sustainability transition research is an emerging field which still lacks a generally accepted set of approaches (Köhler & Holtz, 2019). Although several models have been developed, capturing the core features of transition processes, including combining economic, technical, social, institutional, and ecological sub-systems in a co-evolutionary structure remains a challenge (Köhler et al., 2019). Understanding the endogenous feedback structure of the system and how it resists change will be key to further the application of modelling in transition studies. Finding ways of supporting policy design with transition modelling is particularly important in industries, like the salmon aquaculture industry and other food industries, where powerful players have vested interest in maintaining the status quo, but the consequences of doing so are potentially harmful for society. In the salmon aquaculture industry, the stakes are, in some regard, higher as, if the industry manages to solve the local sustainability challenges related to the current production method (e.g., diseases, escapes) and issues related to the sustainability of feed, there is potential for a positive global impact due to the relatively lower carbon footprint of aquaculture production compared to other animal protein production (e.g., carbon footprint, land use).

4.1 Limitations

This research is subject to limitations related to data quality, model comprehension, and depth of insights. Firstly, the results are constrained by the availability, quality, and selection of data. In model building the reliance on available data may limit the depth of insights, as certain variables important to the system may be underrepresented or excluded. The CLDs depicting the endogenous feedback structure of the generic supply system in Paper I and the Norwegian salmon aquaculture industry in Paper IV were based on an in-depth literature review and secondary data analysis. Although, the perspectives emerging from the interviews and focus groups conducted in relation to Paper III on transitions and other industry expert interviews conducted in relation to the VALUMICS project, helped contextualizing the information from the literature, dedicated primary data collection on the causalities related to organizational and government decision making, would provide further insights. Indeed, CLDs are typically a representation of the current understanding of a system's feedback structure and may evolve as understanding improves, especially through continued communication with experts and stakeholders using the model. As such, the insights provided should be viewed with the understanding that ongoing refinement and validation are essential as additional data and insights become available.

Furthermore, the CLDs developed in this research are, like other CLDs, limited in the sense that they are not comprehensive. Simplification is a key part of modelling complex systems, inherently leading to trade-offs between comprehensiveness and interpretability, and there are therefore multiple factors internal and external to the system under study that are disregarded to enable the grasping of complex dynamics by the human brain. For Paper III potential limitations to data quality are related to the very essence of transitions in that experts providing insights including industry representatives, policy makers, and researchers, are a part of the regime and thereby potentially have a conscious or unconscious incentive to resisting change.

Finally, using CLDs without quantitative simulation has the drawback that dynamic behaviour cannot be fully deduced (Lane, 2008). There are different ways of arriving at a conclusion through reasoning and information, but deduction implies that the conclusion cannot be false if the premises are true, regardless of thought, while other forms of inference are dependent on thinking. A key limitation related to the inferring of dynamic behaviour from a CLD is that it is difficult to estimate the magnitude of feedback effects (Lane, 2008) which limits the potential of using the model to test policy scenarios. However, there are benefits to qualitative analysis that outweigh those drawbacks, to some extent, when the goal is to build understanding rather than predicting or projecting. This especially holds for highly complex social-ecological and socio-technical systems like the Norwegian salmon aquaculture industry where concrete data about many variables are scarce, imperfect, or time-consuming to gather and when the aim of the modelling is to improve and consolidate understanding of the relationships between system variables rather than measuring an output given a specific input. Then it may be argued that a qualitative model is more appropriate as a basis for reasoning than a quantitative one.

4.2 Future research

This research opens several opportunities for future research. The CLD of the Norwegian salmon aquaculture industry could be used as a basis for discussions in group model building efforts with stakeholders from industry, academia, government, and society. Such primary data collection could have numerous benefits including providing new insights and model refinement, facilitating discussions towards a shared understanding amongst different stakeholders, and perhaps inspire action and change.

Through continued refinement the model could potentially serve as a blueprint for a quantitative simulation model that could bring further insights about potential transition pathways towards sustainability (e.g., through testing policy scenarios). However, it is likely more suitable for informing other transition models. The current CLD can be defined as a “*Model of the system*” or “*Model of behaviour*”, based on van den Broek et al. (2024)’s typology, but the information it provides on system drivers could inform a “*Model of transition pathways*”, thus supporting the leap from describing past transitions towards guiding future transitions, which entails an understanding of a system’s drivers and feedbacks.

Further information on transition drivers and mechanisms could be generated by analysing the concept of social license in the context of the immediate factors related to fairness described in Paper II (e.g., power, environmental uncertainty, outcomes). This could provide important insights about how the industry and policy makers can accommodate the public’s concerns and thus provide further leverage points that can be used to guide transitions.

Another potential direction of future research would be to increase the generalizability of the findings presented here by analysing other food industries based on the same premises and thus work towards a theory of how the endogenous feedback structure of food systems impacts transitions to sustainability and policy design. Furthermore, the challenges facing the Norwegian salmon aquaculture industry and governance system are far from unique and the findings could benefit other producing countries in their policy design. This includes Iceland, where the industry and governance system are still developing but there are already considerable issues related to the social license to operate (Olsen et al., 2024).

4.3 The wider sustainability research context

An important contribution of this research to the wider sustainability debate might be a more pragmatic view on growth. Focus on (inclusive) green growth in response to climate change and ecological breakdown has been the dominant view within national and international policy (e.g., UN Sustainable Development Goals) and the Norwegian salmon aquaculture regulatory scheme is no exception. Green growth theory maintains that economic growth within the planet's ecological limits will be possible because technological innovation and substitution will allow a decoupling of growth from resource use and carbon emissions (Hickel & Kallis, 2020).

This thesis' findings, however, indicate that a stronger policy push will be needed. The Norwegian green and developmental licenses are an example of aquaculture policy based on green growth theory. Developmental licenses were introduced as a temporary scheme in 2015 where licenses could be granted to projects that involved both considerable investment and significant innovation. The scheme's aim was to promote innovation within the category of environmental conditions (e.g., lice and escapes) by alleviating some of the business risk of taking on large, risky projects that can benefit the wider industry (Hersoug, 2022). As developmental licenses can be granted for up to 15 years it remains to be seen if the scheme is successful in reducing the environmental impact of the industry but from the outset a lack of consideration for the profit driven nature of businesses greatly reduces the likelihood of real lasting impact. The reason for this is that when the developmental license period is up the companies can choose whether they continue using the innovative technology they have developed or revert to the less-sustainable, likely less expensive, technology without having to give up the additional production capacity (for a relatively small price compared to the current market price of production licenses) (Hersoug, 2022). This policy is therefore quite possibly based on a too optimistic view on green growth.

The overall findings of the thesis indicate that while it remains to be seen whether green growth is attainable (Hickel & Kallis, 2020) it would be desirable for policy makers to at least be conscious about the growth driven nature of businesses and industries and design policy accordingly. Rather than focusing on whether growth is good or bad (e.g., inclusive green growth vs degrowth)[2] it could be beneficial to focus on the objectives (e.g., environmental sustainability, social wellbeing, system resilience) and how we are going to reach them by being fully aware of the (growth driven) endogenous feedback structure of food systems.

A whitepaper published by the Norwegian government in April 2025 indicates that Norwegian policy makers are arriving at a similar conclusion. In the report the government proposes drastic changes to the current regulatory scheme. In short, these changes entail the abolishment of production quotas (e.g., MAB) and the system that controls production growth (e.g., TLS), and instead the introduction of a scheme based on a combination of lice quotas and mortality taxes. Thus, producers will need licenses to operate in a specific area but can produce as much fish as they want if their lice limits are within their lice quota. The mortality fees prevent the incentive to keep lice levels down, from driving extensive use of damaging de-lousing treatments.

[2] See van den Bergh et al. (2011), Hickel & Kallis (2020) and Schneider et al. (2010) for more on the green growth vs degrowth debate.

The government expects multiple benefits from these changes. First off, they expect lice levels to go down, thus leading to better fish health and welfare. They further predict this will unlock potential for growth in the industry and better use of production areas through the development of new technology and restoration of the social license to operate (Ministry of Trade and Fisheries (MTIF), 2025). While it remains to be seen whether these changes to the licensing scheme will be implemented and then if they have the intended effect, these developments are certainly interesting considering the results of this thesis. By making it more profitable to operate in an environmentally friendly way and with high animal welfare this change would put the focus on the actual problem (e.g., lice and mortality) and use the companies' profit driven nature to solve it. In other words, this policy change would entail a move from treating symptoms (e.g., lice levels) to managing structural causes (e.g., endogenous feedback structure). Béné, (2022, p. 1) concluded that "what is needed is not just a transformation of the food systems themselves, but a transformation of the governance of those food systems as well". This proposed change could possibly be just that.

5 Conclusion

This thesis set out to answer the question: *Can the modelling of a food system's endogenous feedback structure using a qualitative system dynamics approach support the system's transition towards sustainability?* This entailed solving challenges related to the modelling of complex systems and specifically their sustainability transitions. Paper I introduced the basic endogenous feedback structure of a food supply system, in the form of a CLD, featuring a system driving profit-seeking loop and several balancing feedback loops, two of which regulate the market through price setting. Paper II addressed a major challenge of modelling social systems (i.e., operationalization) by defining the social construct of IOF in model operational terms and showed how fairness perceptions relate to organizational decision making and thus the profit driven nature of supply systems. Paper III described the challenges of sustainability transitions in the salmon aquaculture industry, of which the most prominent one is the resistance to change of powerful actors within the regime. Finally, Paper IV introduced the endogenous feedback structure of the Norwegian salmon aquaculture industry in the form of a CLD and showed how it impacts industry developments and contributes to current challenges.

The findings indicate that the endogenous feedback structure of the Norwegian salmon aquaculture industry impacts industry developments and in particular policy outcomes and thus maintains resistance to change. This implies that policy will be important to guide transitions towards sustainability and that policy design would benefit from considering the endogenous feedback structure of the system. Thus, it is concluded that the modelling of a food system's endogenous structure using SD can indeed support the system's transition towards sustainability.

These findings underscore the relevance of a systems perspective in policy design as well as the usefulness of SD structural thinking and diagramming tools for modelling food systems and thus aiding in policy design and supporting sustainability transitions. Throughout the writing of this thesis an overarching theme emerged: the relevance of a (food) system's endogenous feedback structure, specifically their profit-driven nature. It is what constrains transitions, it is overlooked in policy design and food system and transition models, but at the same time, is the very reason why policy is needed to guide and accelerate sustainability transitions. Therefore, this finding has implications for sustainability transition studies in general and transition modelling, a growing field of research, in particular. Furthermore, it has implications for policy design, especially transition policy as both the development of niche-innovations and the resistance to change in the regime are strongly influenced by the profit-driven nature of industries.

Emphasising the importance of considering the profit-driven nature of businesses in policy design seems like stating the obvious. However, the evidence shows that numerous examples of policy failures and unintended policy consequences can be traced directly to the lack of concern thereof. Therefore, a systems perspective in policy design using SD structural thinking and diagramming tools can be an important part of the urgent mission of transitioning food systems towards sustainability.

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Paper I

Guðbrandsdóttir, I. Y., Olafsdottir, A. H., Sverdrup, H. U., Bogason, S. G., Olafsdottir, G., & Stefansson, G. (2018). Modeling of Integrated Supply-, Value-and Decision Chains within Food Systems. In *Proceedings in Food system Dynamics*.

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Modeling of Integrated Supply-, Value- and Decision Chains within Food Systems

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ABSTRACT

This paper presents a work in progress on the development of a mental model of a food system using system analysis. The aim is to be able to use this model to create a mathematical simulation model that can be used to identify policy intervention opportunities, specifically focusing on the resilience, integrity and sustainability of food supply networks. The traditional view of food systems as supply chains with a downstream physical flow of products is extended to include the associated upstream flow of money and the decision chains that link these flows. Central to this work is the idea that supply systems are driven by profit and regulated by market dynamics and that these factors generate the underlying feedback structure of the system. Studying the structure of such systems as integrated supply-, value- and decision chains has underscored their complexity and the need for further, more food system specific research.

Keywords: System dynamics; food system; supply chain; value chain; decision chain.

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INTRODUCTION

The objective of the work in progress presented herein is to construct a mental model of a generic food system in the form of a causal loop diagram (CLD). The idea behind the current modelling effort is that a generic food system, composed of primary production, processing, retailing and consumption, can be thought of as an integration of supply-, value- and decision chains. Traditionally food systems have been modelled as supply chains but here, in an effort to capture their complex nature as chains of profit driven businesses, that have a major impact on their social and natural environment, the system model will be extended to include economic factors. The downstream flow of goods in a supply chain, by way of business transactions between individual agents, results in an upstream flow of money from consumers to suppliers. Decisions about the extent of operating activity for every agent in a chain of businesses are generally made on the basis of profitability. Thus, the downstream flow of goods and the upstream flow of money are interlinked by decision chains. In order to understand how these flows interact, we analyze the feedback structure of a simple supply system specifically focusing on its profit driven nature and the regulating effect of market dynamics.

This research effort forms a part of VALUMICS, an ongoing Horizon 2020 EU funded project on food supply networks. In line with the project objectives, the aim is to further use the integrated mental model resulting from this research as a foundation for a simulation model that can be used to identify policy intervention opportunities, specifically focusing on the resilience, integrity and sustainability of food supply networks. The current paper first gives a short overview of the background for the research, including an introduction to the vision of food systems as complex networks, and the challenges involved in the modeling of integrated supply-, value- and decision chains. In the main section of the paper we present our initial thoughts on the conceptualization of the system, mainly focusing on the feedback structures that we believe to be the driving forces of behavior in the system. The physical flow of products downstream a supply chain has been modeled using various applications. Similarly, value chains have been mapped using different methods. The integration of these two important flows through a supply system has, however, received less attention. The final result of this research effort, which is still a work in progress, will be a causal loop diagram of an integrated supply-, value- and decision chain that can serve as a foundation for a food system simulation model.

METHODS

The focus of this paper is on the initial system analysis part of an ongoing research effort which leads to the construction of a causal loop diagram (CLD) of a food system. The design of the overall research is in line with earlier work within the field of system dynamics (Sterman, 2000) and consists of five steps. Figure 1 is a visual representation of the research process. The first step involves clearly defining the problematic or rather undesirable behavior of the system that is to be addressed and specify its boundaries. The next step, the system conceptualization, entails analyzing the underlying feedback structure of the system in an effort to formulate a dynamic hypothesis concerning the system's behavior. This causal theory of how behavior is generated in the system is presented as a mental model in the form of a causal loop diagram (CLD). Throughout the modelling process this dynamic hypothesis serves as a working theory of how the problematic behavior in the system arises. The system conceptualization is induced through system analysis. The resulting dynamic hypothesis will subsequently be used to recreate the dynamics of the system using a mathematical simulation model or system dynamics.

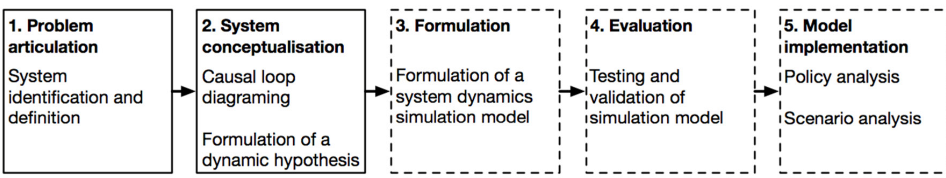

Figure 1 The research process. This paper presents ongoing work on the first two steps in the process

EARLIER WORK

Food systems have traditionally been conceived of as supply chains, or series of activities involved in bringing food products from primary production, through processing and distribution, to the final consumer (Ericksen, 2008). The study of supply chain management has been of interest to researchers

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in various fields for some time (Cooper, Lambert, & Pagh, 1997; Forrester, 1961; Mentzer et al., 2001). Initially the scope of supply chain management covered the product flow from supplier to end user through the value adding operation of the individual firm. The scope was later expanded to include the integrated upstream and downstream processes from the source of supply to the point of consumption (Cooper et al., 1997).

The complexity of many modern supply systems, including food systems, constitutes, not a chain structure but rather a network structure. A food supply network is characterized by a large number of interactions and interdependencies which leads to nonlinear, emergent system behavior that is not easily controlled. Individual agents impact the network with actions resulting from their localized decision-making and in turn they are constrained by the network's structure. In a sense, the system is self-organizing from the viewpoint of the individual agent (Choi, Dooley, & Rungtusanatham, 2001; Surana, Kumara, Greaves, & Raghavan, 2005) and its structure and extended operation are to a large extent invisible to them. The same applies to policy-makers, for whom, a lack of whole-chain overview makes it difficult to predict the effect of policy implementations beforehand (Stave & Kopainsky, 2015). In addition to their structural complexity, food systems are heavily influenced by social and environmental factors. On the supply side, ecological factors constrain possibilities for food production while on the demand side social factors influence the behavior of individual agents in the system (Stave & Kopainsky, 2015). Food production, processing and distribution, in turn, have an extensive impact on the ecosystem, and contribute to global environmental change such as global warming (Ericksen, 2008). Food systems also influence their social and economic environments as providers of nutrition, jobs and economic activity.

The methods of system analysis and system dynamics focus on the dynamic behavior of a system through feedback loops and time delays and are therefore valuable tools when studying complex supply chains or networks. Several system dynamics studies have focused on food supply chains (Conrad, 2004; Georgiadis, Vlachos, & Iakovou, 2005; Kumar & Nigmatullin, 2011; Minegishi & Thiel, 2000; Stave & Kopainsky, 2015). System dynamic models of supply chains, for food and other products, have mostly been restricted to a simple physical flow of products and information in the form of orders, either within a single company or between few companies in a simple supply chain. These models rarely include the flow of money through the system and in those exceptional cases its impact on decision making and the dynamics of the system are usually neglected. In reality, financial factors have a large impact on decision making and thereby the physical flow of products and services. Therefore, in order to use a model of a supply system to anticipate policy implications, it is beneficial to consider not only the physical flow of products in the system but also the associated flow of funds and the effect it has on decision making. What makes this particularly challenging is the fact that the flow of money through the system is subject to market dynamics that take place on a macro level, although its effect comes out and affects decision making on the micro level. In order to introduce financial elements in a supply system model one must therefore work on both the micro and macro level and understand how they interact.

In order to model the dynamic relationships of supply-, value- and decision chains we must introduce market dynamics. The laws of supply and demand are fundamental microeconomic theory and have previously been incorporated into models of supply systems (Conrad, 2004; Meadows, 1971; Sterman, 2000). These models, include both the flow of products through the system and to some extent the affect that price has on decision making, although the process of making decisions is not explicitly presented. The actual flow of money is not present in the models. Including monetary flows gives an opportunity to analyze economic factors such as profit and the equitable distribution of value added in the supply chain. More importantly, profit is a prerequisite for the continued operation of any business and therefore should be considered when modelling the food system which is made up of businesses that have to generate profit to survive. In recent research on metal commodities in the field of natural resources, system dynamics models have been developed that incorporate economic factors, market dynamics and decision chains, into integrated models of supply systems (Sverdrup, 2016; Sverdrup & Ragnarsdottir, 2016; Sverdrup, Ragnarsdottir, & Koca, 2017). The current research builds on the research efforts mentioned above. We draw on earlier work on supply chain modeling using system dynamics, with a specific focus on those that incorporate market dynamics and decision linkage between physical and monetary flows (Conrad, 2004; Meadows, 1971; Sverdrup, 2016; Sverdrup & Ragnarsdottir, 2016; Sverdrup et al., 2017).

PRELIMINARY RESULTS

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In this research, we are developing a causality-based model of a food system which incorporates the physical flow of products through the system, the associated flow of money and the decision chains that link them. The resulting causal loop diagram, which is a work in progress, can be seen in Figure 2. The model is developed in layers. The core layer is the physical product flow. Additional layers are attached to this core layer to introduce market- and price mechanisms that influence decision making. Now the development of each element of the model will be described. We start with the core layer of the model, the physical flow, then we discuss the associated money flow, and finally the decision chains that link the two flows together, and the feedback structures that drive the system.

Physical flow

Physical products flow through the system from the primary producers to final consumers. Individual agents, that is, individual primary producers, processors, retailers or consumers, are only present in the model as parts of aggregated groups. Products flow between agents by way of business transactions. These transactions take place on the micro level but are subject to market dynamics that take place on a larger scale where multiple agents trade in a market that is governed by the laws of supply and demand. To incorporate these transactions on the aggregated industry level we introduce markets between agent groups. The market essentially works like a market table. Agents supply products to the market to make them available for sale and customers take from the market to fulfil their demand. A simplified illustration of the supply chain on an aggregated level with markets between agent groups is presented in Figure 3. The dynamics of these markets and the associated pricing mechanism that affects decision making in the supply chain are discussed in more detail below.

Money flow

The downstream physical flow of products is associated with an upstream flow of money. Money flows between agent groups in the model in the form of costs and revenues. Revenues increase profit while costs decrease profit. Revenues are the amount taken from market times the purchase price. Costs of operation for each agent group is comprised of inventory costs, purchasing costs (the amount taken from market times the selling price) and other operating costs including cost of production, cost of processing and cost of retail. In this simple model, we limit the procurement of each agent group to the products available from the agent group one level upstream in the supply chain. Revenues for an agent group will therefore be equal to the purchasing costs of the group one level down.

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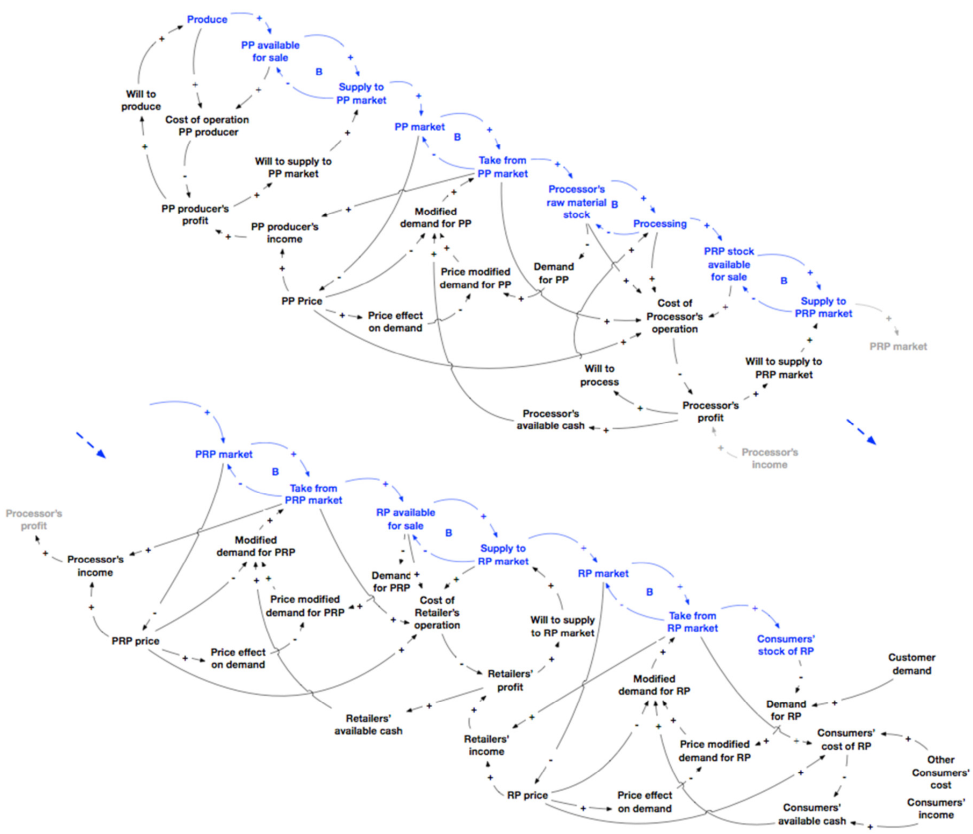

Figure 2 The fully integrated supply-, value- and decision chain. PP= primary product, PRP=processed product, RP=retail product

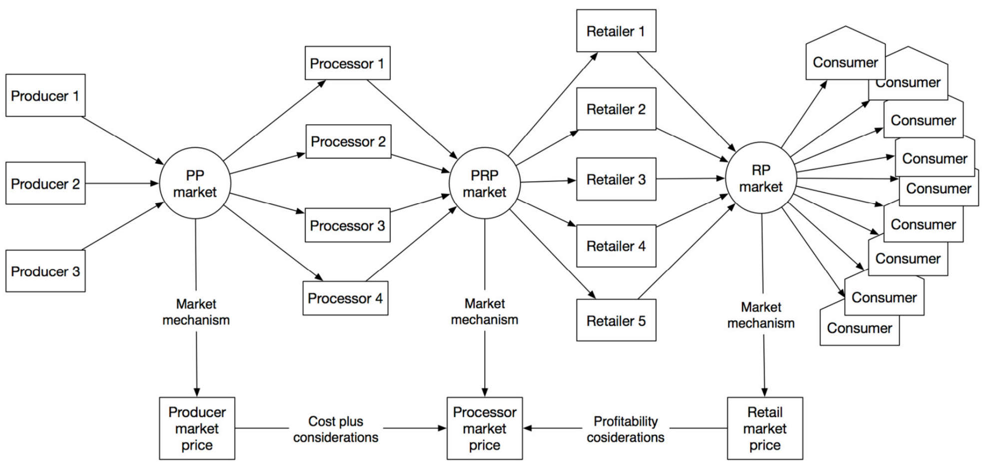

Figure 3 A simplified illustration of the supply chain on an aggregated level with markets between agent groups. The price generated on the macro level is the reference price in micro level business transactions. PP= primary product, PRP=processed product, RP=retail product

Decision chains

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Physical products and money are the major flows in a supply system. These flows are controlled by decisions made by agents in their effort to reach their objectives. In this research, it is presumed that the businesses in the supply chain and thereby the supply chain itself are profit driven. This means that decisions are mainly based on profit expectations. Profitability is clearly not the only purpose of a business, but it certainly is a necessary prerequisite for continued operation.

Figure 4 shows a simplified model of the main drivers of the integrated supply system. The feedback structure presented in this simplified model is repeated for every supplier/customer relationship in the supply system. It features a reinforcing profit-seeking loop (R) and several balancing feedback loops, two of which (B1 and B2) regulate the market through price setting. The reinforcing profit-seeking loop (R) is based on the idea that increased profit expectations drive the downstream flow of products in the chain by increasing willingness and means to engage in value adding activities and supplying products to a market while limiting costs. All else excluded, more products to the market will mean that more can be taken from the market which in turn increases revenues and thereby profit and thus increases willingness to engage in value adding activities even further. This generates a reinforcing profit maximization loop that pushes products downstream towards customers and pulls material from suppliers from upstream. The chain of agents, each aiming at maximizing profit therefore, adds up to a reinforcing supply system. This system is however also regulated by price through market dynamics, that is, the relationship between supply and demand.

Market dynamics result from the feedback relationships of supply, demand and price. The traditional variable name supply can create a confusion as it can both indicate a stock variable of available supply and a flow variable representing the act of supplying. In the current model the amount available for sale in the market, traditionally denoted as supply, is presented as the variable Market. Market is then a stock variable that increases with the flow variable Supply to market and decreases with the flow variable Take from market. On the supply side, higher prices positively affect profits, eventually adding to supply and the amount available for sale in the market. This, in turn, has a negative effect on price, thus creating a negative loop (B1) that regulates the profit driven reinforcing loop of the supply system. On the demand side, there is a second feedback loop (B2) that has a similar balancing effect. Price negatively affects demand, so higher price leads to lower demand. Demand controls the amount that is taken from the market so the lower the demand the larger the amount that is left in the market, which in turn will lead to a price decrease. This structure results in two balancing feedback loops, a demand loop (B2 in Figure 4) and a supply loop (B1 in Figure 4) that together regulate the market through price setting. Both feedback loops are well-documented in the system dynamics literature (Meadows, 1971; Sterman, 2000). This feedback structure is incorporated into the integrated model of supply-, value- and decision chains in Figure 2, linking the flows of product and money through the supply system.

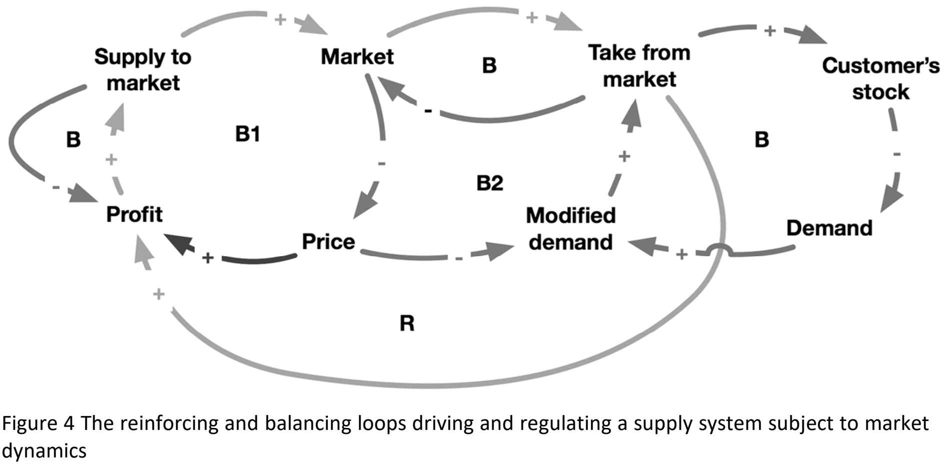

Figure 4 The reinforcing and balancing loops driving and regulating a supply system subject to market dynamics

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DISCUSSION

Now we have suggested how the flows of physical products downstream and money upstream are interlinked in such a way that the physical flow is driven by profit and regulated by market dynamics. The eventual purpose of the model is to use it to evaluate policies aimed at improving the sustainability and resilience of food supply systems, but why is the profit driven feedback structure of such systems important in that regard?

Businesses generally generate profits by maximizing their revenues and minimizing costs and inefficiencies. Restricted focus on short-term profit can have detrimental effects on the supply system in the short and long term through loss of resilience and sustainability. Efficiency gains usually come at the cost of increased vulnerability to disruptions that can affect the operation of individual chain members, thus negatively impacting the chain as a whole. Additionally, in the long run, the focus on short-term profit can negatively affect the environmental, economic and social sustainability of the supply system.

It is not only short-term thinking that can negatively impact the performance of a supply system but also overemphasizing own interests to the point that it has damaging effects on the operation of other chain members. A chain is no stronger than its weakest link. Power asymmetries in the supply chain can undermine the operational profitability of smaller agents in a supply chain such as farmers in the food supply chain. If powerful actors, like retailers, too aggressively use their superior bargaining position to amplify their profits at the cost of eroding revenue margins for less powerful actors, these smaller players will slowly lose their willingness and capacity to add value. The individual agents' pursuit of profit can therefore, in the long-run, damage the performance of the system as a whole by deteriorating the profitability of their suppliers' business operations.

CONCLUSIONS

Food systems are integral parts of societies and their functioning in the long and short term is vital. The aim of this study was to construct a mental model of a generic food supply system that can serve as a foundation for a simulation model, used to identify policy intervention opportunities, specifically focusing on resilience, integrity and sustainability. For policy makers, aiming to contribute to the resilience and sustainability of food systems, it is important to understand the underlying feedback mechanisms that generate system behavior. The multidimensional feedback structure of food supply chains, driven by profit and regulated by market dynamics, results in nonlinear behavior that calls for a modelling approach, like system dynamics, that can capture the dynamics of systems with inherent feedbacks and delays. Studying the structure of such systems as integrated supply-, value- and decision chains has underscored their complexity and the need for further, more food system specific research.

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Paper II

Gudbrandsdottir, I. Y., Olafsdottir, G., Oddsson, G. V., Stefansson, H., & Bogason, S. G. (2021). Operationalization of interorganizational fairness in food systems: From a social construct to quantitative indicators. *Agriculture*, 11(1), 36.

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Article

Operationalization of Interorganizational Fairness in Food Systems: From a Social Construct to Quantitative Indicators

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Abstract: Fairness issues within food systems are of increasing concern for policy makers and other stakeholders. Given the topicality and policy relevance of fairness within food systems, there is value in exploring the subject further. Simulation modelling has been successfully used to develop and test policy interventions. However, the subjectivity and intangibleness of fairness perceptions make them difficult to operationalize in a quantitative model. The objective of this study is to facilitate research on fairness in food systems using simulation modelling by defining the social construct of fairness in model operational terms. The operationalization is conducted in two steps. First, the construct of fairness is conceptually defined in terms of its dimensions, antecedents, and consequences using the literature on interorganizational fairness. Then, by focusing specifically on fairness issues within food systems, the conceptual definition is used as a basis for the identification of proxy indicators of fairness. Seven groups of factors related to fairness perceptions were identified during the conceptualization phase: *financial outcomes*, *operational outcomes*, *power*, *environmental stability*, *information sharing*, *relationship quality*, and *controls*. From these factor groups, five indicators of fairness that are operational in a quantitative model were identified: profit margin as an indicator of distributive fairness and four indicators of procedural fairness related to market power and bargaining power.

Keywords: fairness; UTPs; food systems; simulation modelling; operationalization; quantification; interorganizational relationships

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1. Introduction

Fairness issues within food supply chains are of increasing concern to European Union (EU) and member states' policy makers [1,2] as findings indicate that the negative impact of unfair trading practices (UTPs) on small and medium-sized enterprises in the EU food sector is affecting the competitiveness of the industry as a whole [3]. Although fairness issues can arise in any market or sector of an economy, they have the potential to be especially problematic in food supply chains, as agricultural producers may be placed under undue pressure and have limited bargaining power in negotiations with larger purchasers, such as retailers, given the lack of alternative buyers [1,4,5]. Attesting to the importance of fairness in the context of food systems, the EU recently issued a Directive (2019/633) on UTPs which aims at protecting weaker suppliers (primarily farmers) including their organizations (e.g., cooperatives) against their buyers, as well as suppliers of agri-food products which are further downstream [6]. The Directive is focused on interorganizational fairness (IOF), which is also the focus of this particular research. IOF concerns fairness in exchange relationships (i.e., supplier-buyer relationships). Although not the subject of this paper, fairness within food systems is also of concern at the individual level (i.e., access to nutritious food at a reasonable price), intraorganizational level (i.e., food industry working conditions and pay), and at the societal level (i.e., food security and the environmental impacts of food production). Given the topicality and policy relevance of fairness within food systems, there is reason to further explore the subject. If the aim is to be able to positively affect the level of fairness within food systems, the causalities of fairness perceptions within such systems need to be better understood. This is not a trivial task. Food systems are complex networks, with a mixture of social, technical, and economic elements, and a large number of interactions and inter-dependencies that show nonlinear and at times unpredictable behaviours [7]. Adding to that, the fairness concept is based on individual perceptions and thus highly intangible and difficult to grasp.

Simulation modelling is useful to study complex systems and problems where an analytical solution is not readily available [8]. Although originally intended for the study of physical systems, simulation modelling is increasingly used to model social phenomena, which adds a level of difficulty but also opens up opportunities in the modelling of human behaviours and systems under human control (e.g., socio-technical and socio-economic systems) [9]. Despite technological and methodological advances, simulation modelers still face challenges when attempting to model social systems. One relates to the problem of operationalization, which stems from the intangible nature of many social concepts (i.e., fairness) making them difficult to define in measurable terms. Unlike the physical laws underlying systems in engineering and the natural sciences, the laws governing the dynamics of change in social systems are to a large extent unknown and have not been formalized mathematically. Simulation models are mathematical and therefore require social concepts to be quantified in a meaningful way for them to be operational in a model. In order to study fairness in food systems using a simulation model and test policies that can potentially affect the level of fairness, the model must be equipped to measure fairness as a model output. Unfortunately, the simulation modelling literature offers limited guidance on how to operationalize and quantify social concepts [10,11]. Whereas, making assumptions and simplifications is an integral part of the process of abstracting a simulation model from the real world, it seems worthwhile to carefully and deliberately operationalize the concepts that are fundamental to the modelling work. This issue has been of major concern in the social sciences for a long time, and previous research in the field may be of value for simulation modelers venturing into the social realm.

With raised awareness of the prevalence of fairness issues within food systems and their extensive impact, the subject has moved up on the political agenda, and there is increased willingness to tackle the problem. The European Commission and academic researchers have stressed the need to fill the existing knowledge gap on UTPs within food systems in order to come up with possible solutions [1,7,8]. In the last decade, research on the topic has furthered our understanding of how fairness issues manifest in the different sectors of food systems [1,2], and the first steps towards developing and implementing solutions have been taken with legislative action [6]. Previous research efforts have not taken advantage of the benefits of using simulation modelling to develop policy interventions. The motivation behind this study was to explore the potential of using simulation modelling to develop and test policy implementation options aimed at improving fairness within food systems.

This study was part of a larger Horizon 2020 project called VALUMICS, the general aim of which was to provide tools and approaches to enable decision makers to evaluate the impact of strategic and operational policies aimed at enhancing fairness, integrity, and resilience in future scenarios of sustainable Food Value Chains. This study's specific aim is to operationalize IOF in an effort to facilitate research on the topic using simulation modelling. By drawing on fairness theory and measurement theory, the construct of IOF is translated into model operational terms in two consecutive steps: conceptualization and operationalization. The result is a set of measurements for IOF in the form of quantified indicators (e.g., model outputs). The rest of the paper is organized as follows. Following a summary of the study's theoretical foundations in Section 2, the construct of IOF is defined along two dimensions, and the immediate factors leading to and resulting from fairness perceptions (e.g., its antecedents and consequences) are identified through a literature review in Section 3. This conceptual definition is then used as a basis for the development of a model operational definition of IOF in the form of quantified indicators (simulation model outputs) in Section 4. Finally, in Section 5, the results and their implications are discussed.

2. Theoretical Background

Fairness theory and measurement theory were used to substantiate the operationalization of the fairness construct, specifically the various dimensions of fairness as set out in the literature and the levels of measurement and how they affect the process of operationalizing social constructs.

2.1. Fairness Theory

Fairness, also referred to as justice, is a socially constructed concept based on the perceptions of individuals. Research on fairness has traditionally focused on two types of subjective perceptions called *distributive fairness* and *procedural fairness*. Distributive fairness, first described by Adams [12], is related to the perceived fairness of outcome distributions or allocations while procedural fairness, a concept introduced by Thibaut and Walker [13], is related to the perceived fairness of the procedures used to determine these outcome distributions or allocations. Later the concept of fairness has been extended to include social aspects. Interactional fairness, introduced by Bies and Moag [14], focuses on the quality of the interpersonal treatment people receive when procedures are implemented. Greenberg [15] further divided interactional fairness into, interpersonal fairness, which refers to the degree to which people are treated with politeness, dignity, and respect by those executing procedures, and informational fairness, which focuses on the quality of information provided about the procedures resulting in outcome allocations [16]. Figure 1 describes the development of the fairness concept. The notions of distributive and procedural fairness are well established in the literature while the way in which the social aspects of fairness are defined varies and thus the number of fairness dimensions considered, ranging from a single dimension up to four.

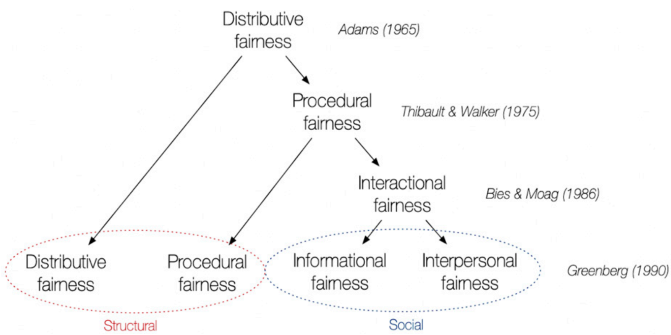

Figure 1. The development of the fairness concept.

The dimensionality of fairness has long been debated. Some authors have argued that while distinguishing between the different dimensions of fairness may be valuable, it may at times be overemphasized and unnecessary [17]. Others argue that the fairness construct is best conceptualized as four distinct dimensions [16,18]. It seems that the level of detail in terms of fairness dimensions should depend on the type of study and its objectives. The different dimensions, although distinguishable, are highly integrated, and in some instances, it might not serve the purpose of a study to focus too much on the dimensionality of fairness. This holds for the current research. Some aspects of fairness are more suitable for quantitative modelling than others (i.e., economic outcomes and structural aspects of procedures). Here, therefore, the research will not be limited to factors related to specific dimensions of fairness but rather the structural aspects of those factors. Certainly, this means that factors relating to the structural dimensions of fairness (e.g., distributive fairness and procedural fairness) will be prominent. However, factors relating to the social dimensions will not be automatically excluded.

2.2. Measurement Theory

Mathematical modelling is increasingly used to model social phenomena. While it is easier to model systems based on well-established physical laws that can be easily expressed in mathematical terms, it is interesting to try and expand into the social world as human decisions are the main drivers of physical systems. The problem of operationalization, e.g., the difficulty in defining intangible concepts, often social constructs, in measurable terms, is well known and thoroughly addressed in the social sciences. Constructs are phenomena that cannot be observed, neither directly nor indirectly. We may be able to observe their antecedents or consequences, but we cannot observe the constructs themselves [19]. Fairness is a social construct; hence, it is neither directly nor indirectly observable but can be operationalized based on observables (i.e., antecedents and consequences). The characteristics of data on social constructs usually make it difficult to operationalize them and develop meaningful measurements. Generally, data can be measured at four levels; nominal, ordinal, interval and rate [20]. The nominal level of measurement is only used for classification (i.e., religion). The ordinal level adds some ordered relationship between observations (i.e., a scale from least to most desirable), and at the interval level, the distance between the ordered observations has meaning (i.e., IQ). Rate, the highest level of measurement, encompasses the lower three levels, and hence, it has an order, a set value between units and additionally, a true zero, which enables the use of fractions (i.e., income) [20].

The precision and usability of data increases as we move from nominal towards ratio level of measurement. Different statistical and mathematical techniques (including simulation modelling) require measurement at the interval and preferably the rate level. Limited analysis can be done on a nominal measurement which simply classifies each observation. The ability to rank-order observations opens up some opportunities for analysis and indeed, ordinal data (i.e., measuring fairness on a scale from unfair to fair based on survey responses) are important to the discussion of social constructs. However, they are subjective (judgemental) in nature and cannot communicate true operational meaning [21]. Most social and behavioural data can be measured at one of the four levels of measurement, but as they become more subjective, like constructs, they are more likely to belong to the lower levels of measurement. As part of the operationalization process, measurements of constructs can be "moved up a level" through a process of quantification, which involves giving a numerical value to a measurement and thus allowing for statistical procedures and mathematical calculations [22]. Quantification methods include the creation of rating scales and the use of proxy variables (e.g., indirect indicators) with which the intangible concept under study is highly correlated. A good proxy variable e.g., one that is strongly related to the unobservable variable of interest and a reasonable substitute for it [11] can enable the study of intangible concepts (i.e., fairness) using quantified methods such as simulation modelling.

3. Materials and Methods

The purpose of this paper is to enable the exploration of problems related to IOF using a simulation model. To achieve this objective, an operational definition of IOF, in the form of quantitative indicators, was developed. Before defining the construct in operational terms, there was a need to conceptually define it. The multidimensional nature of fairness called for a consideration of the different dimensions and how they relate to each other. Additionally, because IOF is an unobservable construct, as a part of the conceptualization phase, the immediate factors leading to and resulting from fairness perceptions (e.g., antecedents and consequences) were identified and later used as a basis for the development of proxy measures in the operationalization phase. The research process therefore consisted of two steps: (1) conceptualization, and (2) operationalization and resulted in an operational definition of the construct in the form of quantified indicators along two dimensions (see Figure 2). Each step is described in more detail below.

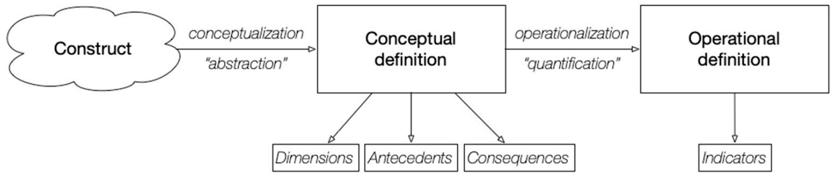

Figure 2. The two-step research process of defining model operational indicators of interorganizational fairness (IOF).

3.1. Conceptualization

The conceptualization process involved defining the construct of IOF including its dimensions and identifying associated observables (e.g., antecedents and consequences) in the IOF literature. A systematic literature search was performed using the ISI Web of Knowledge database to identify peer reviewed papers presenting research on the antecedents and consequences of IOF. The search was set up to identify articles with either the word fairness or justice in the title and at least one of the following words and phrases as topics: inter(-)firm, inter(-)organiz(s)ational, supply chain, value chain, channel, buyer-supplier and business. These search terms were identified through an explorative preliminary literature review using the Google Scholar database. The search resulted in 1083 items of which 32 were deemed relevant for the current research through an abstract review. Relevant papers were those that considered the interorganizational level of fairness, identified antecedents and/or consequences of fairness, and were accessible.

The result of the conceptualization phase was a conceptual definition of IOF along two dimensions: distributive IOF and procedural IOF. Furthermore, seven groups of observable factors (e.g., antecedents and consequences) relating to IOF were identified.

3.2. Operationalization

The operationalization phase had the seven factor groups resulting from the conceptualization phase as a starting point. The operationalization process involved defining proxy variables for IOF that can be used in a simulation model (e.g., indicators) and then quantifying them. Potential measurements were identified by reviewing the literature on food systems, specifically focusing on the factors comprising the conceptual definition. The result of the operationalization phase was an operational definition of IOF in the form of five quantified indicators that can be used to operationalize the concept of IOF in a simulation model. The operational definition consists of (1) the variable being measured (here, distributive or procedural IOF), (2) the measure to be used (here, proxies of distributive and procedural IOF), and (3) a description of how the results of the measure will be interpreted.

4. Results

4.1. Conceptualizing IOF

IOF is an unobservable, multidimensional construct. Unobservable constructs can be conceptualized in terms of associated observables (i.e., antecedents and consequences). The multidimensionality and lack of observability of the IOF construct call for an analysis of its dimensions, antecedents and consequences.

4.1.1. Dimensions of IOF

Fairness, in general, has been defined along up to four dimensions. Here, in line with the objectives of the research, the focus is on the structural dimensions of fairness (e.g., distributive and procedural), and the other dimensions (e.g., interpersonal and informational) are categorized as social aspects of procedural fairness. The definition of procedural fairness in an interorganizational context which follows therefore encompasses the interpersonal and informational aspects of fairness.

Distributive fairness deals with the fairness of outcomes, or in an interorganizational context, how benefits and burdens are distributed among business partners [23]. More specifically, it relates to the fairness of the ratio of a business' inputs to its outcomes and how they compare to the ratio of others [12]. Inputs, in this context, can generally be defined as either cost (e.g., workload, financial input) or risk (e.g., due to uncertainty in supply and demand, price fluctuations, environmental factors) [12], and the most important outcome is the price that the company gets for its products [24]. Examples of distributive fairness issues in interorganizational settings are unfair pricing (e.g., retailers using their purchasing power to drive down suppliers' prices to uneconomic levels), unfair cost burden (e.g., suppliers having to bear unforeseeable costs and costs that were unjustly forced upon them), and unfair risk burden (e.g., suppliers having to bear risk that does not result in a larger share of profits) [5,25]. Here, drawing on the work of Kumar, Scheer and Jan-Benedict [23] and Duffy, Fearne and Hornibrook [5], distributive IOF will be defined as "the fairness of outcome distributions and allocations, that is, the fairness of how benefits and burdens are distributed between business partners".

In an interorganizational context, procedural fairness deals with the ways (e.g., procedures) in which outcomes are distributed between partners. Thibaut and Walker [13] extended the fairness concept to include procedural fairness and identified process control, the extent to which people have a chance to express their opinions about decisions, and decision control, the actual level of influence people have in decisions, as its antecedents. Leventhal, et al. [26] extended the notion of procedural fairness into nonlegal contexts such as interorganizational relationships by defining the six criteria of fair procedures in decision making. Such procedures should be consistent, free from bias, based on accurate information, equipped with a mechanism for correcting mistakes in decision making, ethical and moral, and take into account the opinions of various groups affected by the decision. Examples of potential procedural fairness issues in interfirm relationships are unequal power among partners to define prices (i.e., as a result of the existing governance structure and/or different firm strategies), unequal access to relevant information, and the inequitable treatment of different partners in a supply chain on behalf of a powerful party [24,25]. Here, procedural IOF will be defined as: "the fairness of the procedures (e.g., means) used to determine outcome distributions and allocations, that is, the extent to which individual organizations are in a position to express their feelings on those procedures and influence them".

In order to underpin the process of operationalization the antecedents and consequences of IOF were identified next.

4.1.2. The Antecedents and Consequences of IOF

Several authors have researched the antecedents and/or consequences of IOF (see Figure 3). Perceived IOF has been found to have a positive impact on relationship quality in a chain of businesses [23], mainly through increased trust [27–32] and commitment [28,29,33–36]. Furthermore, studies have concluded that perceived fairness leads to less opportunism [37,38] and conflict [39–41] between business partners who are then also more likely to share information with their partners [33,38], invest in their relationships [33,38], and view them as long-term [42,43]. Additionally, perceived fairness has been found to precede satisfactory operational outcomes [31] and result in businesses offering better quality products and services [27,37,44], spending more on research and development (R&D) and product innovation [37,44], and an overall better financial performance [40,45–48].

The observed positive consequences of perceived fairness have motivated research into the antecedents of fairness. The price a company or a business receives for their product is an important outcome and study findings have suggested that price satisfaction and resulting overall financial performance has a strong impact on perceptions of distributive fairness and is therefore considered one of the most important antecedents of a supplier's fairness perceptions [28,37]. Important antecedents of fairness in general and procedural fairness in particular are related to the sharing of information between business partners [28], the quality of that information [27], and the stability of the business environment [28]. Furthermore, the exercise of power [46] and formal and social control [48] affect both distributive and procedural fairness perceptions.

A closer look at the antecedents and consequences of IOF reveals at least three things worth mentioning. First, there are overlaps between the two groups which indicates (not surprisingly) that fairness, to some extent, is a reciprocal concept (e.g., both a cause and an effect). Second, the factors affecting the different dimensions of fairness are often the same or at least related. This is to be expected as the different dimensions of fairness are interrelated and although separate dimensions, they affect each other. Fair procedures are probably more likely to lead to fair outcomes and perceived distributive fairness in a business relationship presumably leads to more courteous communication. Finally, there is some variability in the terminology used by different authors, and it seems that in some instances, different words are being used to describe the same or at least similar concepts.

The aim here is to identify observables associated with IOF that can be used to develop proxy indicators. To focus the attention on the core factors associated with fairness, similar or related factors are grouped together resulting in a consolidated view of the antecedents and consequences of fairness in an interorganizational context. The consolidated view consists of seven groups of factors for both dimensions of IOF: (1) economic outcomes, (2) operational outcomes, (3) information sharing, (4) power, (5) controls, (6) environmental stability, and (7) relationship quality. A list of the items comprising each factor group can be viewed in Table 1. These factor groups, extracted from the IOF literature, will serve as a foundation for the operationalization phase.

4.2. Operationalizing IOF

The factors resulting from the conceptualization relate to interorganizational relationships and fairness in different ways. Power asymmetries and lack of environmental stability pose challenges, particularly for the more disadvantaged organizations operating in a competitive market. Controls, collaboration, information sharing, and relationship quality relate to strategies used to meet these and other challenges facing organizations, both internally and when dealing with stakeholders. Outcomes are the results of their operational efforts and ultimately the main reason for doing business and thus the measure of success. In order to operationalize the social construct of IOF, these immediate observable factors leading to and resulting from perceptions thereof will now be examined in the context of supply chains in general and food supply chains in particular in an effort to identify potential proxies of IOF.

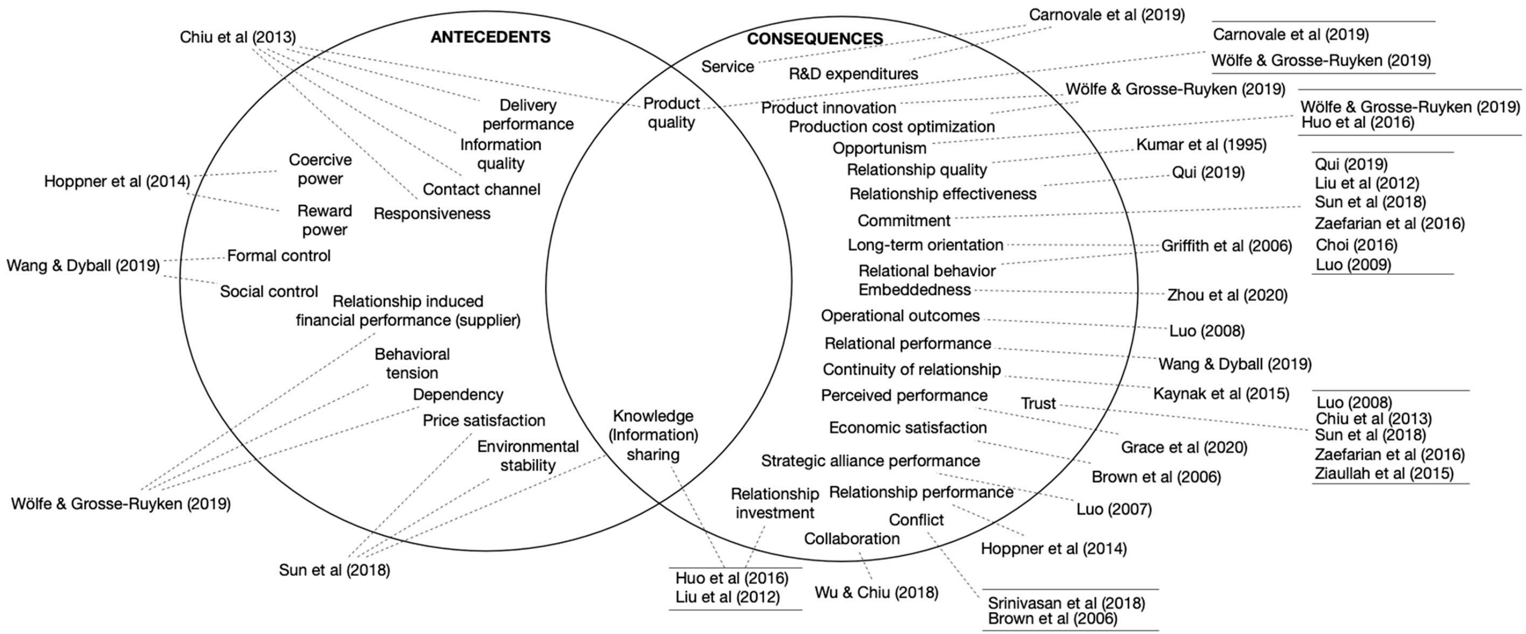

Figure 3. The antecedents and consequences of IOF based on a review of the interorganizational fairness literature.

Table 1. The factors (e.g., antecedents and consequences) comprising the factor groups.

Factor Group	Factor	Reference	Definition
Financial outcomes	Financial outcomes	Luo (2008) [31]	"alliance performance in financial return (i.e., profitability)"
	Price satisfaction	Sun et al. (2018) [28]	na
	Relationship induced financial performance	Wölfel and Grosse-Ruyken (2019) [37]	na
	Strategic alliance performance	Luo (2007) [47]	"cooperation payoffs"
	Perceived performance	Grace et al. (2020) [45]	"financial goals of running the business"
	Production cost optimization	Wölfel and Grosse-Ruyken (2019) [37]	na
	Economic satisfaction	Brown et al. (2006) [40]	na
	Relationship performance	Hoppner et al. (2014) [46]	"the multidimensional outcomes, including financial, strategic and satisfaction elements, resulting from the activities performed by firms on behalf of the relationship"
Operational outcomes	Operational outcomes	Luo (2008) [31]	"operational consequence (i.e., competitive strength in labor productivity, quality control, technology development, customer service, and managerial efficiency)"
	Delivery performance	Chiu et al. (2013) [27]	"the time taken to receive the item purchased from a seller"
	Contact channel	Chiu et al. (2013) [27]	"the availability of assistance"
	Responsiveness	Chiu et al. (2013) [27]	"the willingness to help customers and provide prompt service"
	R&D expenditures	Carnovale et al. (2019)	na
	Service	Carnovale et al. (2019)	na
	Product quality	Wölfel and Grosse-Ruyken (2019) [37]	na
	Product innovation	Wölfel and Grosse-Ruyken (2019) [37]	na
Information sharing	Information sharing	Sun et al. (2018) [28]	"effectively using acquired information and rationally sharing information with partners"
	Knowledge sharing	Liu et al. (2012) [33]	"two firms simultaneously and equally exchange relevant knowledge and information thorough dynamic processes, including both explicit information (e.g., electronic data interchange) and tacit technology know-how"

Table 1. *Cont.*

Factor Group	Factor	Reference	Definition
	Information quality	Chiu et al. (2013) [27]	"the quality of information provided by sellers, including relevance, understandability, reliability, adequacy, scope, and perceived usefulness"
	Communication	Huo et al. (2016)	"the exchange of information associated with business transactions and related issues with a supply chain partner"
Power	Coercive power	Hoppner et al. (2014) [46]	"based on their partner's perception that the party has the ability to mediate punishments"
	Reward power	Hoppner et al. (2014) [46]	"based on their partner's perception that the party has the ability to mediate rewards"
Controls	Formal controls	Wang and Dyball (2019) [48]	"an architecture that 'institutionalizes' how partners cooperate, interact and learn from each other","contracts, planning and budgeting formal authority relationship standardized procedures and rules, supervision performance evaluation, structural grouping and departmentalization and management reports"
	Social controls	Wang and Dyball (2019) [48]	"focus on informal cultures and systems, communication, socialization and self-regulation","include meetings and organized personal contact, networking and other socialization processes, teams and taskforces, transfer of managers/lateral movements, rituals, traditions and ceremonies rotation of personnel, ad hoc committees, face-to-face communication and participatory decision-making"
Environmental stability	Environmental stability	Sun et al. (2018) [28]	"the ability of an enterprise to forecast the future markets, policies and other factors accurately, according to the current external environment"
Relationship quality	Relationship quality	Kumar et al. (1995) [23]	"encompassing conflict, trust, commitment, and two constructs that represent the converse of disengagement—willingness to invest in the relationship and expectation of continuity"
	Commitment	Sun et al. (2018) [28]	"an ongoing relationship with another and is important enough to warrant a great deal of effort to maintain it"
		Liu et al. (2012) [33]	"both parties actively maintain and strengthen the exchange relationship"
		Qui (2018) [36]	"a high level of affective attachment to the relationship and a strong expectation of relationship continuity"

Table 1. *Cont.*

Factor Group	Factor	Reference	Definition
		Zaefarian et al. (2016) [29]	"the willingness of the exchange partners to make short-term sacrifices to develop and maintain long-lasting, stable, and profitable relationships"
		Choi et al. (2016) [35]	na
		Luo (2009) [34]	na
	Trust	Sun et al. (2018) [28]	na
		Chiu et al. (2013) [27]	na
		Zaefarian et al. (2016) [29]	"the willingness of the firm to rely on its partner in whom it has confidence"
		Luo (2008) [31]	"the willingness to take a risk in the partnership that is expected to create a higher payoff than pursuing it alone"
		Ziaullah et al. (2015) [30]	"a willingness to rely on the exchange partner"
	Long-term orientation	Griffith et al. (2006) [42]	"when an exchange partner believes that the on-going relationship with another is so important as to warrant maximum effort in maintaining the relationship"
	Continuity of relationship	Kaynak et al. (2015) [43]	na
	Relationship investment	Liu et al. (2012) [33]	"both parties make idiosyncratic investments in the relationship","creates a lock-in situation in which two parties are interdependent and are motivated to maintain the relationship"
	Relational behaviours	Griffith et al. (2006) [42]	"desired behaviours on the part of one or more partners in the exchange such as flexibility, sharing of information and solidarity"
	Relationship effectiveness	Qui (2018) [36]	"focuses on the extent to which relationship partners find the relational interactions satisfying, productive and worthwhile"
	Embeddedness	Zhou et al. (2020) [49]	"represents a kind of reciprocal relationship between partners; it is a type of investment that brings about mutual benefits by way of cooperation, trust, and learning from one another"

Table 1. *Cont.*

Factor Group	Factor	Reference	Definition
	Behavioural tension	Wölfel and Grosse-Ruyken (2019) [37]	"characterized by the co-existence of two, contradicting forces with dichotomous goals between partners, which induces conflicts and risks to break up the social exchange"
	Conflict	Brown et al. (2006) [40]	na
	Task conflict	Srinivasan et al. (2018) [41]	"the awareness that there are differing viewpoints and opinions on task execution among transacting partners"
	Opportunism	Wölfel and Grosse-Ruyken (2019) [37]	na
		Huo et al. (2016) [38]	"self-interest seeking with guile"
	Dependency	Wölfel and Grosse-Ruyken (2019) [37]	na
	Specific investment	Huo et al. (2016) [38]	"tangible and intangible investments in a particular buyer-supplier relationship that are difficult to redeploy to other relationships"
	Supply chain collaboration	Wu and Chiu (2018) [50]	"a mechanism to managing interdependencies for operations, product/process designs, marketing effort and sale planning/forecasting, as well as establishing strategic decision among SC members"

4.2.1. Challenges: Power Asymmetries and Environmental Uncertainty

The concept of fairness in the context of transactional relationships is closely connected to power. The more powerful party in a business relationship is in a position to misuse its power and thus treat their business partner unfairly [51]. Power asymmetries in interfirm relationships can therefore potentially lead to unfair trading practices [1,2] and indeed, Hoppner, Griffith and Yeo [46] confirmed power as an antecedent of both procedural and distributive fairness.

Traditional research on power asymmetries in food systems has focused on market power or "the ability of a firm (or group of firms) to raise and maintain a price above (if selling) or below (if buying) the level that would prevail under perfect competition, ultimately leading to lower output levels, higher profits and (usually) welfare losses" (Bonanno, et al. [52], p. 8). Both oligopolistic (e.g., few sellers), but more frequently, oligopsonistic (e.g., few buyers) market power is observed in food supply chains (i.e., retail power). However, Bonanno, Russo and Menapace [52] suggest that the traditional market power models are not applicable to modern food systems, characterized by high levels of concentration, vertical coordination, cooperative behaviours and focus on quality. Bargaining power, or "the power to obtain a concession from another party by threatening to impose a cost, or withdraw a benefit, if the party does not grant the concession" (Kirkwood [53], p. 637), is considered to better describe the power complexities of such systems [51,52].

Bargaining power in interorganizational relationships is a consequence of both the relative strategic significance of the partners (i.e., size of supplier or buyer) and the availability of alternatives (i.e., number of available suppliers/buyers and ease of switching supplier/buyer) [54,55]. Bargaining power asymmetries are evident in food supply chains and in agri-food in particular. These imbalances have been highlighted by the European Commission and are seen as the driving force behind UTPs within European food systems that have an extensive impact on the outcomes of a large number of businesses through ripple effects [2].

The relationship between environmental stability and procedural fairness was described by Kumar, Scheer and Jan-Benedict [23]. Later Sun, Liu and Yang [28] confirmed environmental stability defined as "the ability of an enterprise to forecast the future markets, policies and other factors accurately, according to the current external environment" (Sun, Liu and Yang [28], p. 4), as an antecedent of both procedural and distributive fairness. The main sources of uncertainty (e.g., lack of stability) in the external environment of supply chains, including food systems, are unpredictable quantity and timing of supply and demand [56,57]. The actions of the various stakeholders of an organization (i.e., its suppliers, customers, and competitors), affect the actual demand for its products and whether it has the appropriate amount of supplies to meet that demand. The socio-political environment can also affect both supply and demand through constrictions on trade, production licensing, etc. The unpredictability of prices, which are closely related to the dynamics of supply and demand, can seriously increase the uncertainty faced by organizations in their decision making. The ability to predict prices depends amongst other things on types of transactions between chain partners (i.e., long- or short-term contracts, spot market transactions, auctions, etc.) and the price volatility in the market. Agricultural prices vary because both production (e.g., supply) and consumption (e.g., demand) are variable (i.e., draught or diseases affecting production and changes in income and diet trends affecting consumption) [58].

4.2.2. Coordination Strategies: Controls, Relationship Quality, Collaboration, and Information Sharing

Many characteristics of food products, including their perishability and the mandatory requirement of food safety and quality, call for coordination within food supply chains in addition to governmental rules and regulations. Furthermore, coordination helps to minimize transaction costs [59] and facilitate decision making by reducing uncertainties, mainly in terms of supply, demand, and price. These relationships are of various types, either vertical or horizontal, and include strategic alliances, long-term contracts, licensing, subcontracting, joint ventures, franchising, and cooperatives [60]. Although, distinct factors, controls, relationship quality, collaboration, and information sharing, to some extent all relate to the way in which supply chain partners interact and cooperate. Collaboration implies the interdependence of the interacting parties [50], and information sharing is a prominent coordination strategy. Controls concern the (formal and informal) management of partner interactions [48], and relationship quality concerns the relational behaviours, such as trust and commitment, that facilitate the collaborative partnerships [23].

The dynamics of food systems and the ways in which individual organizations interact and cooperate are to a large extent shaped by the modes of governance. Governance structures are complex and fluid. They include international as well as national regulations, and public (i.e., government regulations), private (i.e., cooperatives), and social (i.e., non-governmental organizations) forms of governance, acting vertically (e.g., along the chain) or horizontally (e.g., within a single level of the chain) [61]. Individual organizations or networks of organizations use private forms of governance to countervail issues and challenges they face in their operations. These include both vertical and horizontal coordination strategies aimed at counteracting or diminishing the effects of power asymmetries and environmental uncertainty.

Vertical coordination strategies concern the alignment and control of sources of risk and uncertainties, namely, price, quantity, quality and terms of exchange [62]. They range from open markets to complete vertical integration. Between those extremes lie various types of hybrid coordination strategies, from formal contracts to more informal arrangements such as information sharing and joint planning [63]. At the spot market end the coordination is typically short-term, information sharing is limited, and the partners are not dependent on one another. As we move towards full vertical integration, the interests of the involved parties become more intertwined, the relationships are more likely to be long-term, and information sharing is more open and frequent [62]. In an empirical study of the governance structures in European food value chains, Schiefer, et al. [63] positioned transactions on a continuum ranging from spot markets, through different forms of contractual forms, to vertical integration. Their findings indicated that governance structures along food value chains are diverse, but contractual relationships of different types are notably dominant.

Horizontal coordination strategies (i.e., cooperatives and producer organizations) are useful as countermeasures against known market failures such as power asymmetries between different levels of food chains due to increasing concentration at certain levels and efficiency problems faced by small actors (mainly farmers) causing them to have problems with reaching economies of scale. Particularly, small farmers lack bargaining power and access to markets and can with collective action generate countervailing power and reduce likelihood of buyer opportunism and UTPs [64].

Private standards increasingly drive innovation and change in food systems as although not legally-binding they have become prerequisits to suppliers' access to markets [65]. Certain standards are specifically focused on the social aspects of food systems, including fairness (i.e., the "Fairtrade"-seal) [66]. In recent years the food industry and academia have increasingly turned their focus towards emerging information technological developments such as blockchain, internet-of-things, machine learning, and artificial intelligence, to solve problems related to food safety, quality, and traceability [67,68]. Of particular relevance to fairness in food systems is the application of blockchain technology as it can improve the transparency and efficiency of processes and transactions [69]. Increased transparency has been highlighted as instrumental in the effort to improve fairness in food systems [1].

4.2.3. Outcomes: Operational and Financial

Food safety, quality, and sustainability are important operational outcomes in food supply chains as consumer demand for food is increasingly focused on those factors rather than price only. This has led to the development of private standards and third-party certification of food safety, quality and sustainability that increasingly shape the global food systems in addition to public regulations and control [65]. Adherence to these standards has been linked to operational and thus financial performance, and in many cases, it is a prerequisite for continued operation of food production and processing companies. Various factors relating to operational outcomes have been confirmed as both antecedents and consequences of IOF (i.e., [27,31,37,44]).

Fairness of financial outcomes within food systems has mainly been considered in relation to the value distribution among chain partners. Indeed, according to Adams [12], people are more concerned with the fairness of the distribution of outcomes than the absolute level of those outcomes. The value distribution in food supply chains has been of concern to policy makers for some time. Research has indicated that farmers create more value than they capture, in some cases to the extent that their businesses are barely profitable [70,71]. This has led to suspicions of UTPs of more powerful chain partners [1].

Various indicators have been used to determine the value distribution among chain partners. Price has been identified as an important outcome for any supply chain partner, and several studies have confirmed that price satisfaction is positively correlated with perceived fairness [23,28,37]. When asked about issues relating to fairness and power, 50 stakeholders representing five European food chains mainly mentioned issues related to price setting and the means by which pricing decisions are made [72]. Price has been used to measure the value distribution in food supply chains (i.e., Seják and Zaviral [73]); however, a good price is relative, and an outcome should preferably be rated against the relevant inputs used to obtain it and the outcomes of other chain partners and their contributions. One such indicator is the share of the retail food dollar (or euro), which measures the share of the consumer's dollar received by each stage of the agri-food chain [74]. Food dollar analysis has been used extensively by researchers and policymakers to estimate value distribution (i.e., Canning, Weersink and Kelly [71]). While the division of the food dollar gives indications as to the distribution of the value captured by different chain partners, it does not take into account their contributions to the value addition along the chain, e.g., their inputs. In their research, Cucagna and Goldsmith [75] found that farmers, indeed, capture less value than other chain partners but that they also create relatively less value. In any case, it is important that a measure of outcomes takes into account the inputs used to obtain them.

Profit is the difference between the amount spent and the amount earned and thus takes into consideration both the outcome (e.g., the revenues resulting from the product's sales price and volume) and the inputs (e.g., the various expenses made in order to make and sell the product). While not the only objective of a business, turning profit is vital for long-term survival in a competitive market. Hence, profit is a good measure of financial outcomes, and consequently an appropriate measure of perceived fairness of outcomes in business relationships (e.g., distributive fairness). Companies of different sizes can earn radically different but equally fair amounts of profit. To be able to compare profits of different supply chain partners and establish the outcome distribution, one can use profit margin (e.g., the ratio of profit to revenues). This was the approach used by for example Bertazzoli, Ghelfi, Rivaroli and Samoggia [70].

Table 2 summarizes the manifestation of the immediate factors leading to and resulting from fairness perceptions in food supply chains. While the literature confirms the relationship between these factors and fairness perceptions, the causalities are not obvious nor whether and then how the factors are interrelated. In order to get a more thorough understanding of IOF, it is helpful to view the different factors in context.

Table 2. Manifestations of the immediate factors leading to and resulting from IOF in food systems.

	Factor Groups	Food Supply Chain Manifestation
Challenges	Power	- Bargaining power - Market power
	Environmental uncertainty	- Supply uncertainty (i.e., crop failure, disease, regulations) - Demand uncertainty (i.e., diet trends, substitute products) - Price volatility
Strategic coordination	Controls, Collaboration, Relationship quality, Information sharing	- Vertical (i.e., contract types, alliances, information sharing, trust, commitment, transparency, interbranch organizations). - Horizontal (i.e., cooperatives, producer organizations)
Outcomes	Financial outcomes	- Profitability - Efficiency
	Operational outcomes	- Safety - Quality - Sustainability

Figure 4 presents a conceptual view of the factors related to IOF. It shows how fairness perceptions relate to organizations' challenges in their decision-making to fulfil their purpose of producing outcomes and the strategies they use to overcome those challenges. The key to understanding fairness in the context of interorganizational relationships might possibly lie in the fact that the primary purpose of doing business is to produce outcomes. Indeed, outcomes and the means by which they are achieved are what shapes fairness perceptions [72]. In a sense, perceptions of fairness relate to equal opportunities of businesses to meet their objectives. In simple terms businesses operate and thus meet their objectives by making series of decisions. These decisions are constrained by internal (i.e., financial position, know-how, technology, etc.) and external (i.e., rules and regulations, market dynamics, etc.) factors. Fairness perceptions are firmly linked to decision making in the literature and involvement in decision making in particular [13,76]. Involvement essentially means to take part or have a say. In order to have a say, one must be allowed at the table and be equipped to take part. When considering the say that organizations have in decision making affecting their outcomes, two factors can therefore be considered, their decision-making leverage (e.g., the ability to affect the decision-making process and results), and their decision-making capacity (e.g., the extent to which they are equipped to make decisions). An organization's decision-making leverage is very dependent on its relative power position, and the decision-making capacity is affected by the level of uncertainty about the external environment. Organizations use different coordination strategies to affect their decision-making leverage and capacity in an effort to make better decisions and meet their objectives. In a chain of businesses, less powerful actors can increase their leverage in decision making by forming horizontal alliances (i.e., cooperatives, producer organizations). Vertical coordination strategies (i.e., contracts, collaboration, information sharing, etc.) can be used to reduce uncertainties and thus influence decision-making capacity. Procedural fairness perceptions are strongly related to the ability to influence decision making. The ability to make decisions also directly influences distributive fairness perceptions as decision-making is the process by which organizations produce outcomes. Better decision-making leads to better outcomes and thus more distributive fairness.

This research has identified several factors that influence perceptions of IOF and could therefore potentially be used to develop proxy indicators of the construct for use in a simulation model. However, these factors differ in terms of ease of quantification. In the next section, in line with the study objectives, indicators of IOF along two dimensions will be selected among the factors that have been analysed.

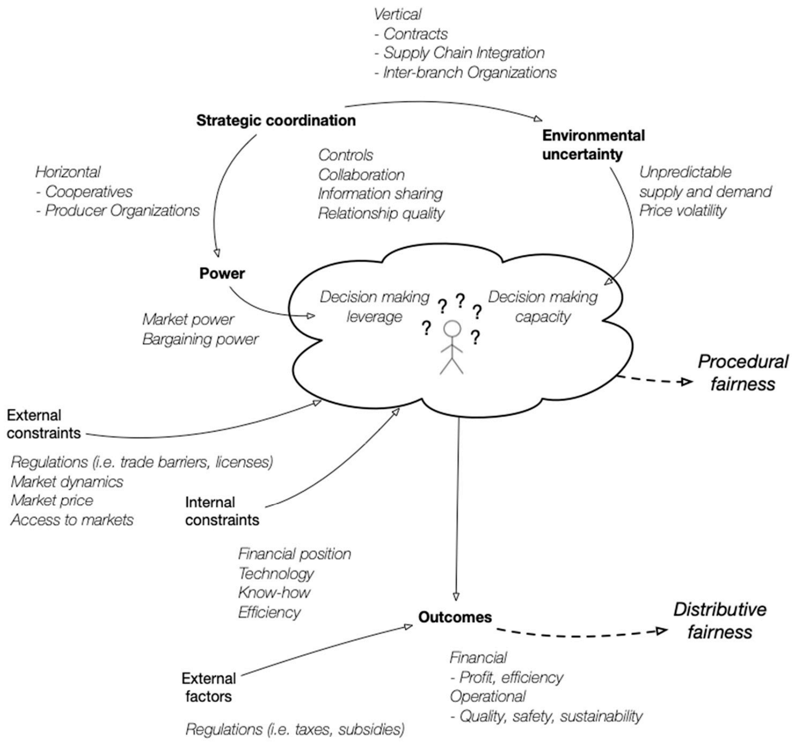

Figure 4. The factors related to IOF viewed in the context of organizational decision making. Perceptions of distributive fairness depend on outcomes and perceptions of procedural fairness depend on the influence individual actors have on their outcomes. Prominent factors impacting such perceptions are power dynamics, environmental uncertainty, and coordination strategies.

4.3. Suggested Simulation Model Indicators of IOF

To be applicable for use as a proxy measure of IOF in food systems, a factor needs to be strongly correlated with either distributive or procedural fairness and be quantifiable in such a way that it can be made operational in a simulation model. Two factors, financial outcomes and power, meet these conditions. The link between financial outcomes and perceptions of distributive IOF have been repeatedly confirmed in research on interorganizational relationships, and their monetary nature makes them easily quantified. In particular, profit margins, as a measure of financial outcomes, are especially suitable as proxy measures of distributive IOF. This is due to the way in which they concern not just outcomes but outcomes relative to inputs and thus can be compared to the outcomes of other chain partners of different types and sizes.

Power in interorganizational relationships, both in the form of market power and bargaining power, has been strongly linked to procedural fairness. Most recently, the pass-through report by the European commission specifically highlighted the importance of power in relation to UTPs in European agri-food chains [2]. Well known measures of market power (e.g., mark-up and mark-down models) exist in the economics literature, and bargaining power in buyer-supplier relationships has been quantitatively measured in terms of the relative strategic significance of actors and their available alternatives (i.e., [55]). Bargaining power, measured as company size (i.e., total assets or total revenues) and number of available suppliers/buyers, and market power, measured by the Lerner index (for seller power) and a mark-down index (for buyer power), are suggested as proxy measurements of procedural IOF.

The Lerner index of monopoly power is a widely adopted metric which provides an estimate of seller market power in an industry, measuring the price-cost margin through the difference between the output price of a firm and its marginal cost (e.g., the cost of producing one additional unit) divided by the output price. The greater the difference between the price and marginal cost (e.g., the price mark-up) the greater the monopoly power [77]. The Lerner index is used for the output market (e.g., seller market power) but analogically, a price mark-down index can be defined for the input market (e.g., buyer market power) [78]. Both indices can be used as measures of the departure from perfect competition, and as such, they can be considered as proxy measures of procedural fairness. The indices range from a high value of 1 to a low value of 0, with a higher number implying greater market power, hence, less procedural fairness.

The measurement framework for IOF resulting from this research is presented in Figure 5. This is a quantitative model operational definition of distributive and procedural IOF in the form of proxy variables and quantitative indicators.

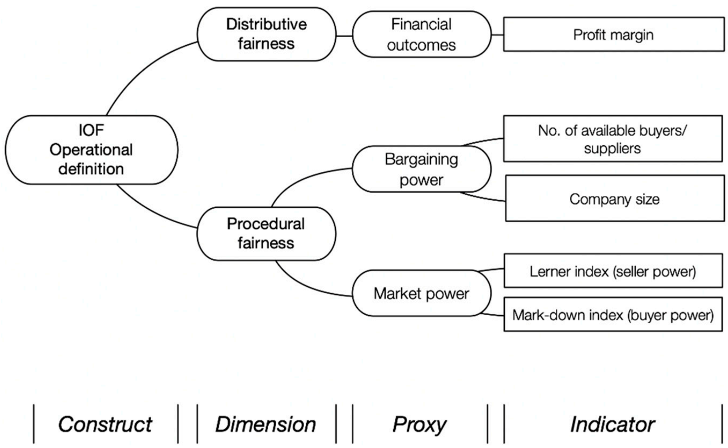

Figure 5. Resulting measurement framework of IOF.

To be able to use these indicators to estimate IOF in a simulation model, there is a need to establish how the indicator outcomes will be interpreted. Research suggests that fairness perceptions are based on comparisons. Hence, the perceived fairness of an outcome is not only related to the level of that outcome but rather the way in which the outcome compares to the outcomes of others. Therefore, in order to estimate overall fairness, the distribution of the suggested indicators can be analysed in terms of its central tendency and spread (e.g., variability). If it is presumed that the highest level of distributive IOF would occur when all actors in a chain of businesses have the same profit margin the symmetry and spread of the profit margin distribution can be used as a measure of the overall distributive IOF. More symmetry can be interpreted as more fairness. Full symmetry occurs when the mean (average), mode (most frequent), and median (middle) values of a distribution fall on the same point (i.e., normal distribution). Skewness is a measure of the deviation from symmetry e.g., the larger the difference between a distribution's median or mode (depending on data) and its mean, the more skewed and hence asymmetrical it is [79]. In a chain of businesses where the most frequent level of profit margins (mode) and the median profit margin are lower than the average profit margin (mean), it would mean that few actors have considerably higher profit margins than the bulk of the actors. The closer the average profit margin is to the most frequent level of profit margins, the fairer the distribution of profits can be presumed to be (see Figure 6). In a similar manner, variability can indicate unfairness. Spread is used to measure the variability within a sample or a population. The more spread out the distribution of profit margins in a chain of businesses, the more likely it is that the actors in the low range perceive their position as unfair.

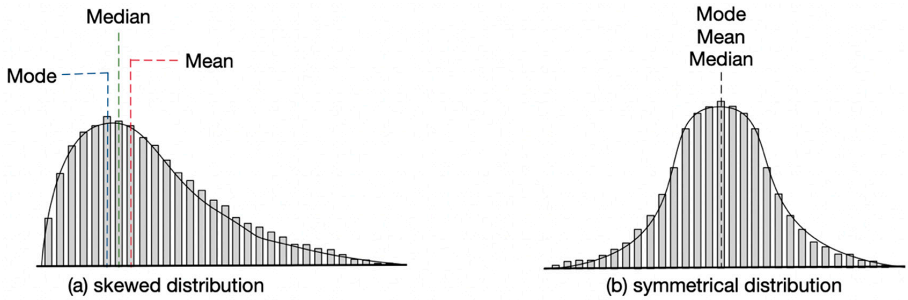

Figure 6. Examples of (**a**) skewed and (**b**) symmetrical frequency distributions of profit margins; (**b**) would be considered fairer than (**a**) as more actors have a profit margin that is close to the average profit margin.

Correspondingly, the overall procedural IOF can be estimated using the distribution of the number of available suppliers/buyers and total sales/assets (for bargaining power) and the distribution of the Lerner and mark-down indices (for market power). In Table 3, the indicators and the interpretation of their results are described in more detail. Every one of these indicators may be used independently to measure a single aspect of fairness, or alternatively, more than one measure can be combined to estimate fairness along both the distributive and procedural dimension.

Table 3. Resulting indicators of IOF including computational method and result interpretation.

	Proxy	Measure	Computation	Result Interpretation
Distributive fairness	Financial outcomes	Profit margins	Revenues less expenses divided by revenues.	More skewness and spread of the distribution of profit margins (e.g., more difference between the distribution mean and median/mode and more variability) means less overall distributive IOF.
Procedural fairness	Bargaining power	No. of available suppliers/buyers	The number of suppliers (buyers) the individual buyer (supplier) can do business with.	More skewness and spread of the distribution of available suppliers/buyers (e.g., more difference between the distribution mean and median/mode and more variability) means less overall procedural IOF.
Procedural fairness	Bargaining power	Company size	The total sales/assets of an individual actor.	More skewness and spread of the distribution of total sales/assets (e.g., more difference between the distribution mean and median/mode and more variability) means less overall procedural IOF.
Procedural fairness	Seller market power	Lerner index	The difference between the output price of a firm and its marginal cost divided by the output price.	More skewness and spread of the distribution of price mark-up (e.g., more difference between the distribution mean and median/mode and more variability) means less overall procedural IOF.
Procedural fairness	Buyer market power	Mark-down index	The difference between the input price of a firm and its marginal cost divided by the input price.	More skewness and spread of the distribution of price mark-down (e.g., more difference between the distribution mean and median/mode and more variability) means less overall procedural IOF.

5. Discussion and Conclusions

The aim of this study was to operationalize IOF in an effort to facilitate research on the topic using quantitative modelling. Due to the topicality and policy relevance of fairness it is valuable to explore the subject further using quantitative methods (i.e., simulation modelling), especially in the context of food systems where fairness issues are prominent. By analysing the immediate factors leading to and from IOF, certain aspects of interorganizational relationships have been identified as being more important than others when it comes to perceptions of fairness. Financial outcomes are closely related to the fairness of the distribution of rewards among chain partners and the fairness of the procedures leading to the distribution of these rewards is dependent on the perceived influence of individual actors over their resulting outcomes. Prominent factors impacting such perceptions are power dynamics, environmental uncertainty (i.e., in terms of supply, demand, and price), access to information, and coordination strategies. Based on these factors that have been linked to fairness perceptions, five quantitative proxy indicators that can be used to estimate the level of both distributive and procedural fairness in interorganizational relationships have been identified. Statistical analysis (e.g., measuring skewness and spread of a frequency distribution) is used to translate the indicator outcomes into levels of fairness.

Research suggests that fairness perceptions are based on comparisons. Hence, the perceived fairness of an outcome is not only related to the level of that outcome but the way in which the outcome compares to the outcome of others. Indeed, fairness issues in food value chains seem to relate to the asymmetric distribution of power and profit [6]. In agri-food chains in particular, few actors, mainly retailers and some processors, have exceedingly more power and higher profit margins than a mass of farmers that are often barely profitable and thus perceive their position as unfair. The asymmetry of these distribitions reflects the consolidated market structures that are well known in modern food systems. Excessive concentration brings with it power imbalances within a chain of businesses, potentially leading to UTPs and other fairness issues [1]. In fact, fairness issues were brought to the political agenda mainly by the pressure from farmers to enforce "fair" prices and to protect them against abuse of power by large food companies [2].

Complicating the task of dealing with fairness issues is their inherently subjective nature. The perceived level of fairness is dependent on both the context and the perspective. While market power and unequal bargaining between farmers and more concentrated market segments can undeniably negatively affect farmers, research has indicated that the relationship between concentration and power is complex. Moreover, the concentration can have positive welfare effects such as efficiency gains, transaction cost reductions, countervailing power, and investment in research and development, eventually benefitting consumers through lower prices [80]. Moreover, while the interests of farmers and consumers might not be aligned, reserch on the negative consequences of market concentration and resulting power asymmetries for farmers are not inconclusive either. Swinnen and Vandeplas [80] point out that the benefits for small farmers in developing countries of inclusion in modern supply chains to some extent outweigh the negative consequences of concentrated market power. Research has also indicated that imperfect competition is not the only reason for the widening margin between consumer and farm gate prices of food. Alternative contributing factors have been suggested, such as an increased degree of processing resulting from more focus on product differentiation, the implementation of standards and regulations relating to safety, quality and sustainability, differences in productivity growth across sectors, agricultural policy reforms, and increased international trade [81].

While, the extent of the negative effects of excessive concentration in food markets and the resulting power asymmetries is debatable, the fact still remains that, at least to some extent, the less powerful agents in European food chains perceive their position as unfair [2]. According to research on fairness in interorganizational relationships, the indicators resulting from this study are linked to these perceptions, as antecedents, consequences, or both. Although, the perfect level of fairness for all actors in a food system will never be reached, there is value in using these factors to guide us towards a food system that is fairer for more agents. Further limitations of his research relate to the constraints of quantitative modelling in terms of the types of data that can be operationalized within a model in a meaningful way and restrict opportunities for measuring IOF. The conceptual analysis of the construct resulted in a number of factors whose causal relation to fairness have been confirmed by research. However, it was concluded that only two of those factors, financial outcomes and power, could be made model operational. This creates limitations as it means that each dimension of IOF is only measured based on one of many known aspects. Nevertheless, in an effort to further knowledge on the subject of IOF, it is valuable to study it using quantitative modelling even within those limitations. The advantage is that the fairness indicators are very general and can therefore be used to study different types of food systems and in fact any system of interfirm relations.

Although food systems share many important characteristics, they differ in some aspects affecting the prelavence and extent of fairness issues including power asymmetries and profit distribution. Therefore, the distribution of the selected indicators of fairness within distinct food systems will vary. A notable example concerns the position of farmers in agri-food chains compared to the primary producers in aquaculture. The disadvantaged bargaining position of farmers, partly resulting from extensive concentration at the processing and retail end, is well dcoumented [1]. The position of the primary producers in aquaculture value chains, who benefit from favourable market conditions (e.g., demand far exceeding supply) and typically claim a proportionally large share of the value distribution is vastly different [72]. Even different sectors within agri-food vary in terms of power asymmetries and profit distribution. Such differences can to some extent be attributed to differences in the extent of horizontal coordination within individual chains. Cooperative and producer organization membership is one of the main mechanisms used by farmers to improve their bargaining position [55], and research has indicated that members are less likely to be subject to UTPs [2]. Furthermore, a strong cooperative presence in the market has been found to result in higher prices for all farmers, including those who do not belong to a horizontal alliance [64].

The operational definition of IOF resulting from this study in the form of indicators enables the exploration of problems related to fairness in food value chains and the development of possible solutions. In relation to policy, these results provide indications of where policy intervention efforts aiming to increase fairness perceptions should be concentrated and give opportunities to test these intervention options using quantitative methods such as simulation modelling. Furthermore, the process of operationalizing a social construct for use in a simulation study can be replicated for other social constructs that are interesting to study using simulation, in particular policy relevant constructs.

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Paper III

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Article

Transition Pathways for the Farmed Salmon Value Chain: Industry Perspectives and Sustainability Implications

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Abstract: Salmon is the most consumed farmed seafood in the EU and there is no indication that demand will abate. Yet salmon aquaculture's environmental impacts are significant, and its future is likely to be shaped by demands of increased but at the same time more sustainable production. This study developed an integrated theoretical framework based on the multi-level perspective (MLP) and a global value chain (GVC) governance framework and applied it to the global farmed salmon value chain. The objective was to provide insights on the most likely transition pathway towards sustainability based on industry and expert perspectives. The perceptions on challenges and drivers of change, were gathered through focus groups and in-depth interviews, and fitted to the integrated framework to facilitate the transition pathway analysis. Viewing the qualitative findings in the context of the MLP framework provided information about the current workings of the system, the drivers of change in the socio-technical landscape and niche-innovations and their potential to challenge or enhance the current system and thus indicated possible system transitions. To emphasize the role of industry actors in shaping the future of the salmon value chain, the analysis was strengthened using the GVC model which added information about power relations, signaling the ability of system actors to motivate or resist change. The findings indicate that, due to resistance in the regime and the fact that niche-innovations are not yet sufficiently developed, the farmed salmon value chain will continue to be predominated by traditional sea-based aquaculture but that there will be a gradual shift towards more diversity in terms of production methods in response to landscape pressures. The discussion addresses sustainability challenges and policy implications for the farmed salmon value chain and highlights the need for a food system perspective.

Keywords: transition theory; multi-level perspective; governance; global value chain framework; salmon aquaculture; sustainable food systems

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1. Introduction

Sea-based salmon aquaculture is arguably one of the most advanced and most efficient animal-based food supply chains [1]. As an oily fish, salmon is a rich source of healthy fats and micronutrients necessary in the promotion of healthy diets [2]. However, there are several negative environmental impacts associated with sea-based salmon aquaculture such as sea lice [3], escapements, disease [4], eutrophication and algal blooms [5]. Salmon aquaculture also contributes to, and is impacted by, global environmental change and especially climate change through the provision of feed ingredients, production methods, distribution, and waste. Feed in particular is an important issue for the industry as it links fisheries, aquaculture, and terrestrial ecosystems [6]. Feed production is by far the largest contributor to the industry's environmental impact [7,8]. Transport is also responsible for a significant share of the carbon emissions of seafood supply chains, in particular transport of feed ingredients and air transport of products to distant markets [9,10].

The sustainability challenges of sea-based aquaculture are deeply rooted in the industry itself, the technology, the ways of working, interorganizational relationships and interdependencies, but also the wider societal structure, rules and regulations, institutions, and cultures. Therefore, their solution calls for extensive action, and a complete change from the current system to a transformed system might even be necessary. An understanding of the dynamics of such transitions, how they come about and evolve, drivers of change and structural inertia, may assist policy makers in their quest to bring about wide-ranging system transformations [11]. In general, sustainability transitions have been most-commonly defined as large scale transformations "deemed necessary to solve grand societal challenges" [12] (p. 600). Various transition theory frameworks have been developed and applied, but the multi-level perspective (MLP) is one of the more prominent ones [13] and has been applied to various integral socio-technical systems such as energy [14], mobility [15], and food [16].

The MLP is a particularly useful framework for aquaculture—a production system—since it emphasizes the embeddedness of technological innovations in social systems [17]. Innovative technologies have played an important role in aquaculture's expansion [18] and are often considered as integral to addressing sustainability concerns [19,20]. Despite the suitability of the MLP framework for aquaculture, very few studies have explored sustainability transitions in aquaculture through the framework. A recent systematic review of the use of the MLP in agri-food systems [13] identified only one study [17] with a focus on aquaculture. Bush and Marschke (2014) explored the contribution of the MLP framework to analyzing social dimensions of change for aquaculture in terms of resilience [17]. More recently, Mok and Gaziulusoy (2018) integrated theoretical insights from the MLP into strategic design considerations using Finnish aquaculture as a case study [21]. Hansen (2019) applied the MLP framework to examine the development of feed as part of a sustainability transition in Norwegian salmon aquaculture and concluded that economic factors have dominated in this transition which has not reached its full sustainability potential [22].

While the MLP framework includes policy as one dimension of the socio-technical regime, the role of power and politics in shaping transitions of socio-technical systems, mainly in the form of resistance to change has been under-theorized [23]. Furthermore, while the focus of transition studies has been on niche innovations, less attention has been paid to the forces maintaining the status quo within socio-technical systems [23]. The governance structure of a value chain provides information about interfirm relations and power dynamics within the chain [24]. A governance structure characterized by few dominant players and power asymmetries can indicate that incumbent actors are able to use their power to resist landscape pressures and steer future development away from fundamental system change [23]. A well-known framework for analyzing value chain governance is the global value chain (GVC) model [24], which has been used to study interfirm relations in various industries including food value chains [25–27]. In order to focus more on actors' motivation or resistance to change in socio-technical systems, this study incorporated elements of governance analysis based on the GVC model, into the MLP framework.

In this study, industry and expert perspectives in Iceland and Norway were analyzed using an integrated framework based on the MLP and GVC frameworks and the results used to explore potential pathways and challenges on the road towards a more sustainable farmed salmon value chain. The Norwegian aquaculture industry is the global leader in salmon farming and the most cost-efficient producers [28]. Other salmon producing countries are e.g., Chile, UK, Canada, Faroe Islands, and Iceland. The EU is the largest importer of salmon globally and absorbs around 60% of the total salmon export from Norway, mainly as fresh whole fish [29]. Many of the world's largest salmon producers are Norwegian enterprises and Iceland's salmon aquaculture industry is largely owned by Norwegian companies [30]. Fitting the farmed salmon value chain to the MLP framework provides information about the current workings of the system, the drivers of change in the socio-technical landscape and niche-innovations and their potential to challenge or enhance the current system and thus indicates possible system transitions. To emphasize the role of industry actors in shaping the future of the salmon value chain, the analysis is strengthened using the GVC model which adds information about power relations and hence indicates the ability of system actors to motivate or resist change. In addition, the sustainability contribution of niche innovations was estimated and thus their ability to challenge the status quo in the system. Based on the stakeholder perspectives, the governance analysis, and the sustainability contribution assessment, probable transition pathways towards sustainability for the farmed salmon value chain are suggested.

The study was part of a Horizon 2020 project called VALUMICS. The overarching aim of the VALUMICS project was to provide tools and approaches that inform decision-makers' evaluation of the impact of various policies with the ultimate aim of enhancing fairness, integrity and resilience in sustainable food value chains (FVCs). This article is structured as follows: Section 2 introduces the integrated framework by providing more detail on the MLP and the GVC approaches. Section 3 outlines the research method and analysis conducted for this study. The findings are then presented (Section 4), analyzed (Section 5) and finally discussed (Section 6). Section 7 provides the conclusion.

2. Theoretical Background

This section provides a more detailed overview of the MLP framework [23], including the different types of transition pathways as described by Geels and Schot (2007) [31], and the GVC governance framework [24,32] in the context of the salmon value chain and explains how an integrated perspective can increase understanding of sustainability transitions for salmon aquaculture.

2.1. The Multi-Level Perspective on Sustainability Transitions

The MLP posits that transitions take place through the interactions that occur in and between three main analytical levels: (a) landscape, (b) regime and (c) niche-innovations [31,33]. Transitions according to the MLP refer to changes in dominant regimes often resulting from landscape pressures and the emergence of niches which can be technological, social, or institutional [33]. Below each level of the MLP framework and the associated types of transition pathways are explained in more detail.

2.1.1. Socio-Technical Landscape

The socio-technical landscape refers to the external macro-level context of socio-technical systems [31]. It consists of a series of heterogeneous elements (e.g., commodity prices, cultural values, broad political coalitions, environmental problems) and is the backdrop of agent interactions in the system, thus influencing the regime and niche innovations. While socio-technical landscapes do change over time the rate of change is slow and they are much more stable than regimes [34]. Landscape developments can either have a reinforcing relationship with the regime (e.g., urbanization and economic development leading to higher demand for salmon), or a disruptive one (e.g., increased focus on sustainability and animal welfare). When they occur, changes in the landscape that do not align with the current regime can put pressure on it, either resulting in "windows of opportunity" for niche-innovations to break through and radically influence or replace the dominant regime or lead to incremental changes to it [31]. Landscape pressures might be for example "demographic changes, macro-economic trends, political developments, wars and crises, deep cultural and societal values, and climate change" [13] (p. 2). The ongoing pandemic [35] constitutes an example of a crisis which can also act as a window of opportunity.

In the case of aquaculture, the socio-technical landscape is comprised of the food system as a whole. It is important to situate salmon aquaculture within the broader food system landscape as it affects and is affected by food system-level macrotrends [36]. The Food and Agriculture Organization (FAO) defines a food system as:

> "*The entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption and disposal of food*

products that originate from agriculture, forestry or fisheries, and parts of the broader economic, societal and natural environments in which they are embedded" [37] (p. 1)

In recent years, various landscape pressures in the socio-technical landscape of the farmed salmon value chain seem to have created the conditions for the emergence of a variety of innovations. One of the primary pressures is the tightening of regulations to address environmental challenges in connection to sea-based salmon aquaculture which has effectively limited expansion for major producers such as Norway [38] and Chile [39].

2.1.2. Socio-Technical Regime

The socio-technical regime is comprised of a set of interrelated, shared rules that coordinate the activities of actors in a socio-technical system [34]. These rules can be regulative (e.g., formal rules, laws, etc.), normative (e.g., values, norms), or cognitive (e.g., priorities, bodies of knowledge) and thus, contain both social and technical elements [11]. Socio-technical regimes serve important societal functions involving not only technologies but also user practices, markets, cultural meanings, public policies and regulations, business models, and infrastructure [40]. Due to the shared rules within an existing regime it tends to be stable. Nevertheless, it is maintained and improved in an incremental fashion by incumbent actors in response to landscape developments. Incumbent actors can be firms, users, scientists, policymakers, special interest groups, and civil society actors who interact with each other building networks and creating mutual dependencies [41].

Regime stability has been attributed to factors such as lock-ins and path dependence [33,42] which lead to mostly incremental innovations rather than radical innovations [11]. Lock-ins can take various forms, i.e., (a) economic, due to vested interests, sunk investments in infrastructure and accumulated competences and scale advantages which often ensure low costs; (b) social, due to embedded beliefs, an alignment between social groups, and established user practices such as values and consumer preferences or beliefs which can be difficult to change; and (c) politics and power whereby incumbents will tend to resist change they perceive to go against their vested interests, and new entrants often have to contend with an uneven playing field and established policy networks which make it harder for innovations to break through [11]. While lock-ins and path dependence, seem to be out of direct control of individual incumbent actors, Geels (2014), has suggested that regime stability can be, at least in part, the outcome of active resistance by incumbent actors that have mutual dependencies and benefit from the status quo [23].

2.1.3. Niche-Innovations

Socio-technical innovations can emerge at all stages of the value chain and range from improvements in production technologies to changes in business models and value creation. While regimes generate incremental innovations, radical innovations are developed by small networks of actors, in niches, protected from 'normal' market selection in the regime. There they have room to develop, both the technology and the networks necessary to get it to the user. Initially, niche-innovations are unstable, show low technical performance and are often expensive. Therefore, they benefit from the protection of the niche until they are ready to compete with the dominant regime [11,34]. Few niche-innovations reach that level of performance or get the opportunity to break-through, but niches serve an important function as providers of space for learning processes [34] and sometimes niche-innovations are picked up by the regime and used to improve the dominant technology [31].

2.1.4. Transition Pathways

Geels and Schot (2007) developed a typology of transition pathways based on the timing and nature of multi-level interactions [31]. The status of niche innovation developments at the time of landscape pressure or internal struggles within the regime is important and has an impact on what kind of transition takes place. To be sufficiently developed to break through niche-innovations has to meet four conditions: (a) learning processes have stabilized in a dominant design, (b) the support network includes powerful actors, (c) price and performance have improved and there is indication of further improvements, and (d) the niche innovation is in use in market niches with a total market share of at least 5% [31].

The nature of the relationship between the different levels also affects the type of transition. Landscape developments can either have a reinforcing relationship with the regime and thus support the status quo or a disruptive relationship which puts pressure on the current state. Similarly, niche innovations either have a competitive or symbiotic relationship with the regime and thus aim to replace it or enhance it [31]. Based on the timing and nature of multi-level interactions Geels and Schot (2007) defined four types of transition pathways in addition to the stable, reproductive regime: transformation, de-alignment and re-alignment, technological substitution, and reconfiguration (see Table 1) [31]. In addition, they proposed that a given transition may shift between pathways.

Table 1. Transition pathway typology (adapted from: [31]).

Transition Pathways	Landscape Pressure	Status of Niche-Innovation(s)	Nature of Regime-Niche Relationship	Description of Type of Transition Pathway
Transformation	Moderate	Not sufficiently developed	Symbiotic	Regime actors modify direction of regime, but basic architecture remains the same
Technological substitution	High	Sufficiently developed	Competitive	Niche-innovation(s) break through and replace(s) regime
Reconfiguration	Moderate	Sufficiently developed	Symbiotic	Niche-innovations are adopted to solve local problems and subsequently trigger further adjustments eventually resulting in a new regime with substantial changes to regime's basic architecture
De-alignment and re-alignment	High	Not sufficiently developed	Competitive	Multiple niche innovations emerge and co-exist until one becomes dominant

2.2. The Global Value Chain (GVC) Governance Framework

The GVC governance framework posits that increasing globalization of production and trade have led to significant structural changes in the governance of industries. The framework was developed to capture these structural governance shifts in sectors producing for global markets [24,32]. Specifically, Gereffi et al. (2005) defined five distinct value chain governance types, with different levels of coordination and power dynamics between chain actors (i.e., market based, modular, relational, captive and hierarchy) [24]. The GVC framework has proved useful in studying interfirm power relations and the role of lead actors, however, it has been criticized for not capturing the societal, political and policy contexts and interventions that occur in, and impact upon, intraregional European food value chains [27]. Further analysis in the VALUMICS project on the governance of food value chains through stakeholder interviews demonstrated that the characteristics of the salmon value chain governance, namely co-governance activities of three main categories of different actors: private firms, public actors and civil society fitted more with the extended GVC framework [32] and was more suitable for the global salmon value chain (Figure 1) [43].

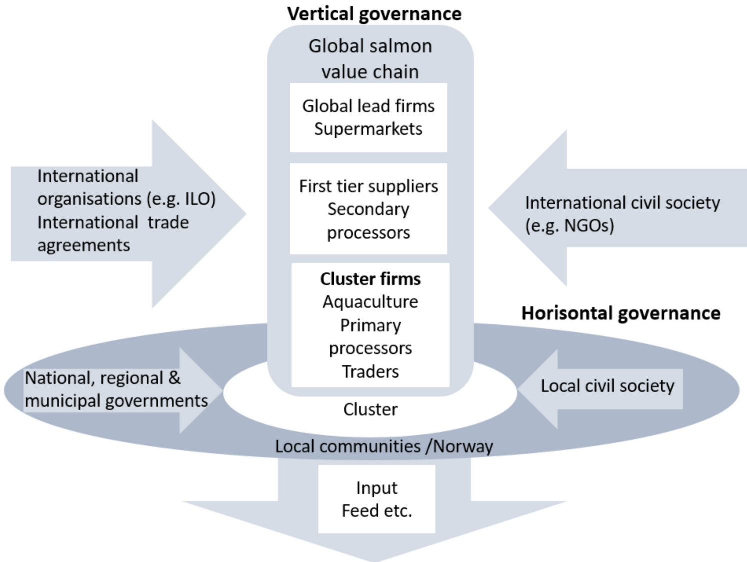

Figure 1. An extended GVC governance form suggested by Gereffi and Lee (2016) adapted to the governance structure of the Norwegian salmon aquaculture value chain, where GVC and cluster governance frameworks are combined (Source: [43]). (Note. ILO: International Labour Organization; NGOs: non-governmental organizations).

The structure of the salmon value chain starts with input suppliers of feed for the aquaculture production and extends through processing, wholesale, and retail/foodservice to the end consumer. On the supply side, the main actors are the aquaculture producers, dominated by large companies, some of which have integrated downwards in the chain by establishing processing facilities and trading companies in the EU to avoid tariffs and to ensure access to market. On the demand side, trading companies and wholesalers buy from integrated production companies or independent processors and sell to retail and foodservice who sell the end product to the consumer [43].

Power relations within the farmed salmon value chain and the impact of concentration and strategic coordination are important issues to consider in transitions. The interfirm relationships in the salmon value chain show signs of various governance forms depending on company size, level of vertical integration and product markets. The retail sector in France and the secondary processing sector in Poland dominate the salmon trade business, reflected in strong integration of these markets with the salmon export market in Norway [44]. The governance structure is best described as "hybrid" as networks of large integrated firms and their subsidiaries interact with other chain actors using a combination of arrangements. These range from a "market" structure with a low level of power asymmetries to "hierarchy" with high level of power asymmetries. The transactions between producers and primary processors selling commodity products (e.g., head-on-gutted) on the spot market to mostly wholesalers or secondary processors show characteristics of "market" governance. Product specifications are easily translated as they are based on industry standards, the complexity of transactions is low and the capabilities in the supply base are high. Therefore, the cost of switching business partners is low and the degree of explicit coordination and power asymmetry is low. However, even though there are no barriers to entry in trade activities, prevailing price volatility may discourage new entrants as it constrains the margins of secondary producers and traders [45].

Due to market conditions (demand far exceeding supply) producers are in a very favorable position which is further empowered by vertical integration which at times leads to a "hierarchy" form of governance. Although the chain is "producer driven" in that way, supermarkets are the lead firms with the most bargaining power. Independent secondary processors who carry out filleting, smoking and other value-added processing and are not a part of large integrated producing companies end up being 'stuck in the middle' in the value chain. They are positioned between two powerful actor groups, producers and retailers and need to negotiate both ways, sometimes by fixing price and volume in a long-term contract and then having to buy raw material on the spot market [46].

2.3. An Integrated MLP and GVC Governance Framework

The Norwegian aquaculture industry is the global leader in production and export of farmed salmon. It is characterized by consolidation at the farm level, with few large producers with international presence, extensive vertical integration, focus on technological innovations and close cooperation between industry, research, and government bodies [43,46]. The powerful position of aquaculture producers and the mutual dependencies of business actors, aiming to maximize their profit, and the Government, depending on businesses to provide jobs, tax payments and economic growth, highlights the importance of considering the role of power and resistance to change in transition studies [23]. This can be accomplished by adding an examination of the governance of the value chain to the transition pathway analysis. Specifically, governance structure provides information about power dynamics in the chain, who the lead actors are and the level of power asymmetries and thus the extent to which individual actors or a group of actors can resist change. Finally, adopting a governance framework to the study of transitions is important for two reasons: (a) it situates transitions in the real world and focuses research attention on the agents of change and their embeddedness in socio-economic systems, and (b) it incorporates political aspects as sustainability transitions often involve conflicting worldviews and objectives among different actors [47].

3. Materials and Methods

3.1. Focus Groups and Interviews

Data were collected in five in-depth interviews and two focus groups with three and four participants, respectively. The interviews included two Norwegian industry experts, three Norwegian aquaculture production company representatives and one high-level EU policy maker. The two focus groups in Iceland were comprised of three aquaculture production company representatives in the first group and one expert, and three aquaculture company representatives in the second group (Table 2).

Table 2. Descriptions of participants in the study's interviews and focus groups.

Pseudonym	Organization	Role	Interview	Focus Group	National Context
P1	Funding agency	R&D director	#1		NO
P2	Research institution	Expert	#1		NO
P3	Company	CFO	#2		NO
P4	Public institution	Policy maker	#3		EU
P5	Company	Community Relations	#4		NO
P6	Company	CEO	#5		NO
P7/A1	Company	CFO		#1	IS
P8/A2	Company	CEO		#1	IS
P9/A3	Company	CEO		#1	IS
P10/B1	Public institution	Expert		#2	IS
P11/B2	Company	Project and quality manager		#2	IS
P12/B3	Company	CEO		#2	IS
P13/B4	Company	CEO		#2	IS

Participants are only referred to by their pseudonyms to preserve their anonymity. Prior to the group discussions and interviews all participants received a short concept note with background information detailing the motivation of the research project. They also received a consent form which informed them of their rights and the ethical guidelines the study adhered to [48]. Participant selection was based on purposive sampling whereby industry representatives and experts were sought out based on their level of expertise. Participants were also asked to recommend other experts (snowball method) to ensure that key informants were included in the research.

3.2. Procedures and Analysis

The focus groups and semi-structured interviews were conducted online via the conferencing platform Zoom due to the COVID-19 pandemic and travelling restrictions. The design followed Daniels et al.'s (2019) recommendations for conducting online focus groups considering the particularities of the medium [49]. There were two researchers present at all the sessions. One researcher acted as the moderator steering the discussion towards relevant topics and ensuring all participants were afforded opportunities to voice their opinions. The other researcher acted as facilitator, taking notes, ensuring time limits were kept [50] and addressing any technical problems in case they came up [49]. The semi-structured interviews were also conducted using the same procedures to ensure consistency in the two approaches. A pilot session took place in April 2021 to test the materials and technical equipment. The focus groups and interviews were subsequently conducted in May–June 2021.

The question framework was semi-structured to ensure that all topics relevant to the analysis were included and to allow for more spontaneous discussion [51]. The aim of the focus groups was not to reach a consensus but rather to explore different perspectives [51]. The aim of the interviews was to gather in-depth information about the topics of interest from various stakeholders. Combining focus groups and interviews has been found to enhance data richness [52] and internal validity [53].

The sessions and interviews were all recorded in video form using Zoom's recording function and then transcribed. All sessions and interviews were conducted in English. The first two authors independently created mind maps of each session and interview, and these were then compared and discussed to ensure common understanding and to enhance internal validity (triangulating analysis) [53]. Data were subsequently coded by the first author using the analytical method of constant comparisons [54]. Standard country codes were also used to highlight cross-context analysis. The findings were then further analyzed using the integrated theoretical framework described in Section 2.

3.3. Limitations

Synchronous online focus groups and interviews do not differ substantially from conventional face-to face interactions in terms of the quality and richness of the data collected [55]. When certain elements are carefully considered and implemented at the design phase such as including a short introductory session to create a comfortable environment, making contingency plans for dropouts, and ensuring the facilitator can also provide technical support, all serve to mitigate the potential drawbacks of an online focus group [49,56]. Under normal circumstances online focus groups can present unique challenges most notably the challenge of participants not being entirely familiar with the use of online web conferencing services and bandwidth issues [56].

Although, we did make a contingency plan as recommended by [49], lack of familiarity with web conferencing services was not a challenge we encountered. An entire year of professional life adjusting to contagion measures due to the global pandemic has accelerated knowledge and familiarity with such services. In addition, neither technical nor bandwidth issues arose during the focus groups and interviews. Finally, although our participants were largely Norwegian and Icelandic industry actors, the issues discussed are common to most wealthy nations with aquaculture operations [57]. Norwegian companies are also the largest producers in the world, many with operations worldwide including in Iceland. The perceptions and views of powerful actors are important to gauge in the context of sustainability transitions.

4. Findings

This section presents main findings from the interviews and focus groups underpinning our analysis in Section 5.

4.1. Socio-Technical Landscape

Supply and demand and global environmental change were the main factors driving change in the farmed salmon value chain according to participants. The most discussed driver of change in the socio-technical landscape, consumer preferences, was related to increased demand for salmon. Participants stated that consumers increasingly call for more sustainable food production and are more concerned with issues such as animal welfare. Changing diets ranging from increased focus on health in general to more transformative change such as veganism were also mentioned as drivers of change that are currently affecting the industry.

> "*I'm positive for the industry, I think we'll be in a good place [by 2050], a sustainable place, because consumers—new generations—[...] are very aware of sustainability, environmental impact and so on*" (P8/A2).

Global environmental challenges, including climate change, were also mentioned as drivers of change in the current landscape, although on a longer timescale than the other drivers. Environmental challenges influence aquaculture production both directly (e.g., rising sea temperature) and indirectly through mitigative action. Various regulatory changes were discussed in the context of climate mitigation related to countries' NDCs (Nationally Determined Commitments) to the Paris agreement with some participants anticipating higher carbon taxes targeting for example transportation and other regulatory change in the near future.

> "*Of course, we see also the climate risk including future regulatory change. [This] is also a topic we discuss in every investment project. How are the regulations going to change, how do we have to invest today to adapt to future regulatory changes?*" (P5)

Regional policies and strategies were also discussed as drivers of change at the national level, for example: the EU directive on non-financial disclosures, the EU Green Deal, the Sustainable Development Goals, and circular economy considerations (e.g., regulations on the use of by-products as feed). In the EU's Farm-to-Fork strategy, which is part of the Green Deal, the guidelines for sustainable aquaculture were also recently revised with an emphasis on increasing aquaculture production in the member states. The EU imports a large proportion of seafood and farming could increase the region's food security alongside other considerations such as health and nutrition, jobs, and livelihood objectives.

> "*Today, sustainability is still very important also in the context of the EU Green Deal and the Farm to Fork strategy: they recognize that farmed seafood is a good source of proteins and that it has a lower footprint and an important role to play in sustainable food systems.*" (P4)

Much of the discussion involved the increasing role of civil society (e.g., international, and local non-governmental organizations—NGOs) in sustainability awareness-raising and decision-making in the value chain. NGOs were discussed in terms of local communities' opposition to the industry, the effect on local-level decisions, and the difficulty of navigating the multiple and often differing objectives of different civil society organizations. However, the role of NGOs was also mentioned in the context of partnerships in certification schemes especially in relation to sustainable feed sources. Some participants also highlighted the importance of the private sector's presence in countries such as Brazil in terms of applying pressure to national authorities for halting deforestation in close collaboration with local and international NGOs such as WWF.

> "*We have to source soy from somewhere and we choose to source from Brazil because we are pushing them to become more sustainable by doing that, because we are in collaboration with NGOs to produce more sustainable feed. And if you leave the country completely then it's up to the local organizations there, and they don't have a lot of power*" (P6).

Finally, the trade landscape was discussed in terms of macro-level trends that can affect the value chain, e.g., with regards to trade agreements and political tensions affecting trade.

> "*We have seen that political tensions between Russia, EU, NATO aren't becoming less common and there have been a few rounds where we have been excluded from China and also Russia—we are still excluded from Russia. And it doesn't seem like this trend is easing off.*" (P5)

The topics which emerged relating to the drivers in the socio-technical landscape are listed in Table 3.

Table 3. Elements of the socio-technical landscape mentioned by the participants.

Elements of the Socio-Technical Landscape	National Context
Supply and demand (e.g., global crises, buyers' demand, consumer preferences)	EU, IS, NO
Global environmental change (e.g., climate change, resource scarcity)	EU, IS, NO
International and regional policies and laws (e.g., Paris agreement, SDGs)	EU, IS, NO
Civil society (e.g., environmental NGOs)	IS, NO
Trade landscape (e.g., trade agreements, market access, political tensions)	NO

Note. SDGs: Sustainable Development Goals; NGOs: non-governmental organizations.

4.2. Socio-Technical Regime

Market conditions were described by participants as very favorable with demand consistently exceeding supply resulting in generally favorable prices. The most discussed challenges were regulatory challenges, environmental challenges related to traditional production methods, and the negative public perception of the industry.

In Norway the regulatory challenges mostly mentioned related to the licensing system which hinders growth of traditional sea-based farming. Indeed, several participants mentioned that the policy environment, and specifically growth restrictions, are driving the industry to change their production methodologies because of economic concerns. In order to sustain growth, industry players need to find new ways of producing salmon. Policy initiatives such as the Norwegian developmental licenses further support these efforts by steering industry players towards other production methods.

> "*Obviously the most urgent driver is Norwegian policy and how the authorities are steering the development of our industry. One concrete example is of course developmental licenses. [. . .] That's a clear driver for change. In order for us to be able to produce more salmon to grow as a company we needed to come up with [new] technologies*" (P5).

When describing the current conditions in Iceland, where the regulatory system and the industry are still in development, most of the interviewees agreed that the system is overly complex, inefficient, time consuming and lacking predictability, resulting in detained growth.

> "*Licensing [in Iceland] is very time consuming, there is a lot of paperwork involved, often you have to do the same thing just a slightly different version for governmental institutions. So, it's not very effective and they don't have the people to work on everything they have to deliver*" (P11/B2).

Many respondents mentioned the various environmental challenges of traditional sea-based farming, including mortality, diseases, problems related to lice, lice treatment and escapes. Repeatedly discussed in relation to environmental challenges were the carbon footprint of feed and transport which are responsible for a large share of the total carbon footprint of the industry.

> "*Salmon farming is like 80% transportation: we are moving smolt, we are moving people, we are moving feed . . . it's all on movement*" (P9/A3).

Icelandic participants specifically mentioned the challenges of operating traditional farming systems in their harsh environment, increasing the magnitude of problems related, to e.g., mortality and escapes. When discussing challenges of the industry today all participants in the study agreed that the negative public perception of salmon farming is a serious issue that needs to be addressed.

> "*Sometimes the critics of the industry are unfair, some are fair, and some do not base their criticism on facts. Discussion is healthy but it should be built on facts*" (P12/B3).

All the topics which emerged relating to the current socio-technical regime are listed in Table 4.

Table 4. Topics relating to the socio-technical regime mentioned by the participants.

Aspects of Socio-Technical Regime	National Context
Strong market and profitability	EU, IS, NO
National regulatory challenges	IS, NO
Growth restrictions (licenses)	NO
System deficiencies (e.g., complexity and lack of predictability, lack of infrastructure, support, and direction)	IS
Environmental challenges related to traditional sea-based production systems (e.g., diseases, lice, mortality, escapes, carbon footprint, harsh environments).	EU, IS, NO
Strong government-supported R&D in Norway (e.g., development licenses) which others benefit from.	IS, NO
Rural development	IS, NO
Negative public image	EU, IS, NO

Note. R&D: research and development.

4.3. Niches

In terms of technological developments, participants both mentioned advances related to the traditional methods of producing and distributing salmon (e.g., digitalization and improved biology) and more disruptive developments that could potentially have a more transformative effect on the current socio-technical regime (e.g., land-based, and offshore salmon farming). Participants mentioned several developments aimed at improving traditional salmon production and distribution methods. Very prominent were solutions aimed at reducing the carbon footprint of feed and transport, particularly the development of new raw materials for feed, bringing feed production closer to production, and the combination of improved freezing/thawing technologies and more sustainable modes of transport.

> "*Feed is by far the largest GHG contributor to our product [. . .] 80% of the climate emissions related to salmon aquaculture is feed and transport of feed. We need to make sure that the production and transport of these ingredients are [improved] going forward*" (P5).

Technological improvements of open net pen farming were frequently mentioned, including the digital transformation of fish monitoring, and feeding technologies. Many interviewees also mentioned innovations aimed at battling the biggest biological challenges in open net pen farming, namely diseases, lice, and mortality. These include the development of better vaccines and genetic innovation. Furthermore, the progression towards larger smolts aimed at better utilizing licenses and diminishing the likelihood of diseases was also a recurrent theme in the interviews.

> *"For sea cage aquaculture: it will develop but I foresee that the size of smolts will be larger so the time in the sea will be shorter and that solves problems with escapes and sea lice. So, this will be one of the system transformations and [will] make it more sustainable"* (P10/B1).

In addition, also mentioned as potential updates to the current regime were different advancements related to marketing and product development such as more focus on value added products, branding, and convenience food resulting in more product diversification.

> *"So going from whole fillets of smoked salmon to 200 gr packs to 100 gr packs to 50 g I think is a development [. . .] Salmon is running 12 years behind chicken and cod is running 5 years behind salmon in terms of product development. Innovation on the product side is a key driver"* (P3).

As a potential improvement of the current farming system, elements of circular economy such as whole fish utilization and the production of biogas from sludge were mentioned by several participants.

> *"If we are serious about increasing [circularity] then we need to make these discussions happen and we need to start asking the consumer these questions: what are [you] willing to compromise in order to have more sustainable food choices?"* (P6).

Land based salmon farming using recirculating aquaculture systems (RAS) was the most frequently mentioned topic by participants. Other frequently mentioned new technologies were offshore farming, closed or semi-closed farming systems, aquaponics, and organic aquaculture.

> *"In 2050 we will have land-based salmon farming as a big segment living side by side with the traditional farms in the fjords . . . I think there is plenty of room for many technologies and they will live side by side"* (P3).

All the topics which emerged relating to niche developments are listed in Table 5.

Table 5. Niche innovations mentioned by the participants.

Type of Niche Innovation	National Context
Socio-technical improvements to traditional farming distribution systems (symbiotic)	
Larger smolt	IS, NO
Improved biology (e.g., vaccine, genetic innovation)	EU, IS, NO
Circular economy (e.g., full utilization, sludge management, biogas)	IS, NO
Digitalization (e.g., monitoring, feeding technologies)	EU, NO
Sustainable feed (e.g., alternative ingredients, local feed production)	EU, IS, NO
Sustainable transport (e.g., transport and freezing/thawing innovation)	IS, NO
Diversified products (e.g., more value added, branding, convenience food).	EU, IS, NO
New farming systems (competitive)	
Land-based farming	EU, IS, NO
Offshore farming	EU, IS, NO
Closed/semi-closed sea-based farming	NO
Aquaponics	EU, IS, NO
Organic aquaculture	EU

5. Summary Findings and Analysis

This section presents our summary findings through the integrated framework (Section 5.1), an evaluation of the sustainability potential of niche-innovations emerging from the findings (Section 5.2) and, the delineation of likely transition pathways for the industry (Section 5.3).

5.1. The Farmed Salmon Value Chain in the Context of the Integrated MLP and GVC Governance Framework

Figure 2 summarizes our findings through the integrated framework developed in this study.

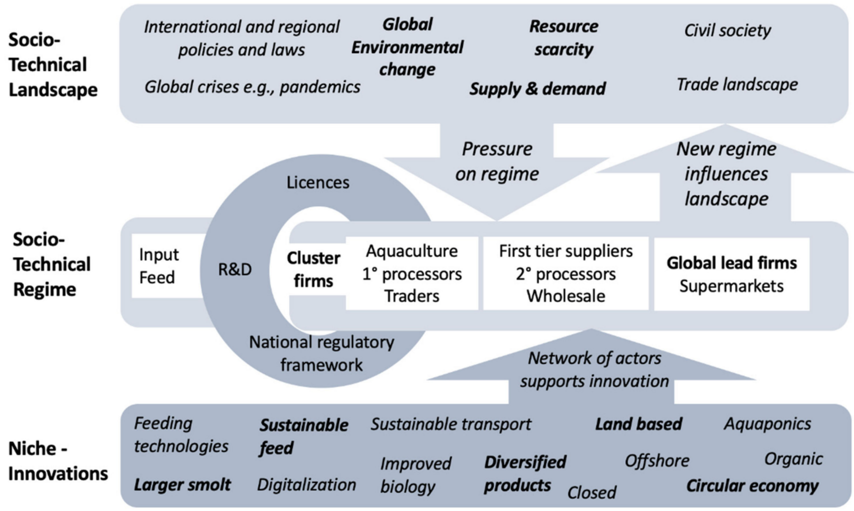

Figure 2. Summary findings through the integrated framework (authors' own conceptualization based on existing frameworks [31,32,43]).

The stakeholder interviews provide information about the farmed salmon value chain in terms of the three levels of the MLP framework. They highlight the most prominent landscape developments and pressures, the current state of the value chain in terms of shared regulative, normative, and cognitive rules, and the niche-innovations currently in development. To strengthen the analysis and the resulting estimation of the most likely transition pathway towards increased sustainability, a governance perspective was added using the GVC governance framework and was transposed to represent the sociotechnical regime (see Figure 2). Based on the governance analysis of the farmed salmon value chain presented in Olafsdottir et al., 2019, the interactions between the different levels and specifically the reactions of the current regime to landscape pressures and looming niche-innovation breakthroughs, are placed in a value chain governance perspective [43].

As discussed in Section 2.2. what characterizes governance in the farmed salmon value chain are horizontal collaboration and vertical integration, including relations through networks, third-party assessment, and certification schemes on top of the traditional model of state-only regulations (licenses and environmental impact assessments) representing a hybrid governance form in aquaculture [58]. This form of governance further entails that the global salmon value chain is influenced by international organizations and trade agreements, international civil society, and industry initiatives, which on the other hand are motivated by societal pressures from non-governmental organizations e.g., through sustainability standard settings and auditing (e.g., Aquaculture Stewardship Council).

In terms of innovation and industrial development, the success of salmon farming in Norway is based on close cooperation between industry actors, governmental bodies and research institutes which contribute to a strong cluster [46]. The governance structure of the farmed salmon value chain points to power asymmetries. There are powerful value chain actors and networks of actors with vested economic interests in sustaining the current regime. Furthermore, the hybrid form of governance indicates flexibility and ability to adjust. Specifically, large integrated producers are in a powerful position in the chain, and they are heavily invested in the traditional form of sea-based salmon farming. Their hybrid governance structure also makes it easier for them to adjust to landscape pressures through incremental adjustments (symbiotic niches) to the prevalent technology of sea-based cages.

Incumbent actors are driven by profits and therefore their resistance could ease if the relative profitability of traditional farming compared to the niche farming systems changes due to for example increased mitigation costs. In the next section we critically assess proposed solutions (niche innovations) based on their potential contributions to a more sustainable farmed salmon value chain. This is important because it underpins participants' perceptions on the potential of niche breakthroughs and resulting pathways.

5.2. Sustainability Contributions of Niche-Innovations in Salmon Aquaculture

There was common agreement among participants that salmon aquaculture is set to expand in the future both due to increasing demand for salmon but also because national and regional-level governments project and plan for its increase (e.g., [59,60]). This perspective is also echoed in high-level policy reports [61,62] and recent academic literature [2,63]. As such, the discussions centered around *how* to achieve growth in a sustainable manner with the range of niche innovations emerging from these discussions. Hansen (2019) highlighted, that an analysis of transition pathways without an assessment of overall contribution to sustainability outcomes provides an incomplete picture of the underlying challenges that need to be addressed [22]. Therefore, a critical evaluation of niche innovations in terms of their sustainability contributions was necessary, providing a more comprehensive assessment of the sustainability transition of the farmed salmon value chain and emphasizing the limitations of the mentioned niche-innovations in terms of contributions to sustainability challenges. For a niche-innovation to be able to compete with the current regime it needs to solve more of the regime's problems than it adds to it.

Numerous sustainability challenges related to traditional sea-based salmon farming have been identified both in the literature [64–66] and in this study. These mainly relate to environmental sustainability, but also economic viability and animal welfare. Table 6 summarizes the contributions of the niche innovations mentioned in the interviews with regard to various known sustainability challenges in the farmed salmon value chain, based on selected literature. The niche-innovations are shown to have either a positive effect (+) on a given challenge compared to traditional sea-based farming, a negative effect (−), or no known effect (0). The analysis is not exhaustive, in part due to a general lack of comprehensive assessments in the literature for many of the niches. Nonetheless, it provides an overview of the major sustainability challenges according to the literature and an initial explorative evaluation of the extent to which they are addressed by the selected niche-innovations.

As can be seen from Table 6, many of the niches solve delimited challenges, have little or no effect on others and might add to some. Their design and objectives are naturally in alignment with the focus of regulatory bodies and other forces that shape the current regime. In terms of the salmon value chain the focus has been on local environmental challenges related to aquaculture production and less on global sustainability challenges such as carbon emissions and therefore many of the niches are geared towards solving those challenges. Other niches center on global sustainability challenges, but none are capable of addressing both. In addition, almost none of the niche-innovation developments have reached a level of economic feasibility.

Table 6. Contributions of niche innovations towards selected sustainability challenges in the farmed salmon value chain.

Niche—Regime Relationship	Niche Innovations	Sustainability Challenges												Select Academic Literature
		Environmental									Econ.	Social		
		Sea Lice	Escapements	Disease	Eutrophication	Waste (Sludge)	Carbon Footprint	Land Use	Energy Use	Water Use	Econ. Feasibility	Animal Welfare	Public Perceptions	
Symbiotic	Larger smolt	+	+	+	+	-	-	-	-	-	+	0	0	[67]
	Improved biology	+	+	+	0	0	0	0	0	0	0	+	0	[67,68]
	Circular economy	0	0	0	0	+	+	0	+	0	0	0	+	[69]
	Digitalization	+	+	+	+	0	0	0	0	0	-	+	0	[70,71]
	Sustainable feed	0	0	0	0	0	+	0	0	0	-	0	+	[70]
	Sustainable transport	0	0	0	0	0	+	0	0	0	0	0	+	[9]
	Diversified products	0	0	0	0	0	+	0	0	0	0	0	0	[72]
Competitive	Landbased farming	+	+	+	+	-	-	-	-	-	-	-	+	[67,70,73]
	Offshore farming	+	0	+	+	0	-	0	-	0	-	+	+	[19,20,67,70]
	Closed/semi-closed	+	+	+	+	0	0	0	-	0	-	0	+	[67,73]
	Aquaponics	0	0	0	+	+	+	-	+	+	-	0	+	[20,64]
	Organic Aquaculture	-	0	-	0	0	0	0	0	0	-	+	+	[74–76]

Note. (+): positive effect; (-): negative effect; (0): no effect or N/A.

A fully contained farming system reduces biodiversity impacts to zero (no escapes) but siting needs to take very careful consideration of land use issues, clean energy provision, and fish welfare concerns, and at the same time be able to compete with traditional sea-based systems on economic terms [70,77]. Similarly, closed/semi-closed and offshore farming systems are intended to lessen biodiversity impacts [67] but even with perfect siting conditions met, these farming systems do not address sustainable feed provision, the farmed salmon value chain's main source of carbon emissions [22]. Full life cycle analyses of farming systems are necessary in order to include otherwise neglected sources of carbon such as embedded emissions from construction.

Symbiotic niches focused on environmental challenges related to aquaculture production include digitalization and biological improvements (i.e., triploid fish). The digital transformation of aquaculture using tools such as computer vision and environmental monitoring leads to more sustainability through, e.g., early detection of problems regarding animal health and welfare [71], improved feeding techniques reducing water pollution and optimized feed use [78]. An example of biological improvements aimed at reducing environmental impacts are triploid fish which are sterile and therefore potentially reduce the negative impact of escapes [68].

There are symbiotic niche innovations which many incumbent companies could implement right now to tackle a sizable part of their carbon emissions including reducing emissions from transportation throughout the supply chain [10]. Reducing transport emissions relates to optimizing logistics and product development. In this regard, freezing technologies and maritime transport instead of air transport constitute opportunities for emissions reductions especially if customers and consumers can be convinced that quality is not compromised. Less reliance on the aviation sector may also constitute a proactive strategy for companies since the aviation sector is facing increased pressure to decarbonize [79] and exhibited limited resilience to sudden shocks such as the pandemic [80].

In addition, value-added activities constitute a viable avenue for improved resource utilization and reduced carbon emissions for the farmed salmon value chain but may be constrained by various factors. Approximately 80–90% of Norway's production volume is exported as marginally processed, fresh products to EU countries and by airfreight to the Asian markets [81,82]. Increasing processing in Norway and exporting more value-added products would have benefits for both the Norwegian industry and society and globally by reducing the carbon footprint of the industry as around 50% of what is currently transported is by-products [72]. There are several challenges standing in the way of increased processing in Norway including high labor costs compared to the EU, lower margin of processors than producers [83], and higher tariffs on value-added products [84].

Some of the declared benefits of a circular economy are waste and carbon emission reduction. However, circular economy considerations are not fully developed despite the rhetoric pervading the discourse [84]. It is unclear what the concept of a circular economy really entails, and different stakeholders do not always have the same understandings as previous research has also shown [85]. As participants also pointed out, various circular solutions to sustainable feed have not been adequately explored and public debate has been minimal. Consumer reticence, public opposition and regulatory frameworks may be significant barriers in circular economy solutions such as the use of animal by-products in feed for aquaculture. Livestock by-products in feed have also been found to significantly raise the environmental impacts of farmed salmon [7,86]. Aside from that, it is important to consider whether creating mutual dependencies with the livestock sector constitutes a viable long-term solution for aquaculture and pollution prevention in general. Careful consideration needs to be paid also to fish health and nutritional quality when changes in feed composition are pursed [87].

In the next section, probable transition pathways of the salmon value chain are proposed based on the stakeholders' views on the landscape pressures on the current regime, the governance analysis of the regime and the proposed niche innovations and their contribution to addressing sustainability challenges.

5.3. Probable Transition Pathways of the Farmed Salmon Value Chain towards More Sustainability

Following Geels and Schot (2007)'s typology [31] described in Section 2.1.4 and Table 1, our findings, based on the mapping of stakeholder perspectives to the MLP framework, governance analysis and the sustainability contributions of niche-innovations, suggest that a transformation pathway is the most likely direction that the industry will take in the next decades. Although, landscape pressure, specifically related to global environmental change and changing consumer preferences, seems to be reasonably high and on the rise, it continues to be offset by the resistance to change by powerful actors in the regime and their ability to adapt and align their production network enough to alleviate some of the pressure. Furthermore, competitive niche-innovations such as land based, and offshore farming systems do not seem to be sufficiently developed to compete with the highly efficient traditional sea-based farming systems. Therefore, a gradual transformation towards more sustainability within the current regime with, mainly, regime driven innovations and refinements is the most likely future.

There is, however, a small potential for a technological substitution pathway depending mostly on how aggressive policy interventions in response to environmental challenges will be and the developmental progress of alternative production systems, especially in terms of economic viability. If the landscape pressure becomes too heavy for the regime actors to withstand and align to, possibly resulting in disruptive policy interventions such as a total ban on sea-based aquaculture, the course towards sustainability could be different. Indeed, such a transition might be underway in Canada, where the Government has set in motion a plan to completely transition from open-net pen farming in coastal British Columbia (BC) by 2025. The aim is to protect and rebuild the wild fish stocks in the area and at the same time position BC as a global leader in innovative and sustainable aquaculture [88]. If the development of niche-innovations such as land-based farming is sufficient when such a disruptive policy intervention takes place, a technological substitution would probably take place. Otherwise, a de-alignment and re-alignment transition would take place eventually resulting in a new regime.

It should be noted that this study was largely based on incumbents who have a clear stake in the industry's current direction. Nonetheless, the perceptions of industry experts and that of a CEO of a company heavily invested in land-based activities did not significantly diverge from the perceptions of the incumbents, indicating that this pathway description is not entirely biased. It is also difficult to ascertain whether these perspectives represent resistance to change and cognitive bias or legitimate assessment of the potential of different innovations to transform their industry [89].

6. Discussion

As this study has shown, numerous often interrelated factors can influence the direction of an industry. This ranges from drivers at the landscape level to various regime developments, and not least the maturity and potential breakthroughs of niche-innovations. Crucially, when viewed in the context of the integrated MLP and GVC framework, the governance structure of the farmed salmon value chain indicates that incumbent actors in the chain are in a strong position to resist change to a new regime, using power to withstand landscape pressures and flexibility to adapt when needed. Most participants agreed that sea-based aquaculture would predominate in the future although diversity in terms of farming systems would increase. This transition pathway of gradual change is mainly the result of the interplay of the different factors summarized in Figure 2 and the preliminary analysis of niches' state of development in Table 6. In what follows, we briefly discuss some of the governance implications of these findings and how a food system approach can be useful in this context.

Political decisions can heavily influence salmon aquaculture by regulating the location of farm sites and slaughter plants and their social impacts on communities. Limited availability of new licenses for salmon farming in Norway motivates Norwegian companies to operate and expand salmon production in other salmon producing countries (e.g., Chile, Scotland, US, Canada, and Iceland) to ensure continued growth and stable supplies of Atlantic salmon to markets. However, many salmon producing wealthy nations (including Iceland and Norway) are facing similar socio-ecological challenges which have placed limits to salmon aquaculture expansion [57].

The fact that aquaculture is a biological process carried out in an open environment and that there are still uncertainties regarding its environmental impact, poses challenges for both industry actors and governmental agencies. These challenges have been described as a wicked problem [90]. Fish farmers continually deal with environmental uncertainties in their operations and they, as well as policy makers, face steady pressure from society and media to quickly adapt to rapid improvements in knowledge regarding environmental externalities and the associated technological advancements. These challenges make the salmon value chain both hard to manage and govern and call for a flexible and adaptive approach to governance [90,91]. Therefore, hybrid forms of governance characterized by the active involvement of non-state and state actors [92] will likely continue to play an important role in the industry's ongoing pursuit of social legitimacy and for solving grand sustainability challenges where collaboration and coordination of different actors is necessary.

Collaboration and coordination point to the need of providing formal procedures for genuine engagement of stakeholders in deliberation, decision-making, and management of conflicts in connection to aquaculture sites and impacts are of crucial importance to the industry's social license to operate [58]. Iceland, as an example, could benefit from the implementation of comprehensive marine spatial planning processes [57] which would ensure that legitimate concerns of local communities and civil society groups are addressed through formal avenues. It is also important to have a robust governance system which seeks to prevent conflict of interest in the regulatory and administrative system strengthening accountability and thus public trust and acceptance [93].

The need for accountability and transparency has been partly addressed through the creation of multistakeholder certification schemes which are a form of self-regulation by the private sector serving a value and trust enhancing purpose in the market [94,95]. Multistakeholder certification schemes, such as the Aquaculture Stewardship Council, have emerged as a way of meeting normative demands of various stakeholders regarding the sustainability performance of companies. The hierarchical form of governance in salmon aquaculture [43] makes it easier for firms to adopt certifications as vertical integration facilitates the implementation of standards [96]. This, however, also means that smallholders and companies in the global south with fewer capabilities to implement standards may be excluded from markets [93] leading ultimately also to slow uptake of the standards globally. A relatively narrow focus on sustainability especially in terms of long—term biophysical impacts [97] is also a major limitation.

National regulations constitute an influential driver of change as can be seen by the impact of the licensing system in Norway on the industry [98]. As Hersoug (2015) has shown by emphasizing lice as the single most important performance indicator, the Norwegian licensing system effectively restricted environmental sustainability considerations to the narrow focus of biological sustainability [98]. Although protection of local ecosystems and wild species is important, the question arises whether stakeholders' sustainability considerations should be broadened to include the entire value chain and its impact from a food system perspective with a view towards balancing local and global concerns [99]. Broadening actors' perspectives and reframing challenges in a food system perspective which considers the whole value chain and its role in the wider system is important for transitioning the industry towards more sustainability [100]. As the European Environment Agency stated in a recent report: "sustainability in food requires a policy framework that embraces a food system approach, and that allows a shared understanding of the food system to be built" [6] (p. 5). Achieving this shared understanding among the different stakeholders of the farmed aquaculture value chain may be a viable way forward in ameliorating conflicts as well as an important consideration for a sustainability transition.

From a food system perspective, salmon constitutes a healthy source of animal protein with relatively lower environmental impact compared to other animal protein sources [8]. However, for salmon aquaculture to grow sustainably, livestock pressures on the environment would have to be achieved concurrently. As previous research has shown [22] and participants confirmed, one of the major sustainability challenges for the farmed salmon value chain is the provision of sustainable feed. No niche so far can resolve the reliance of farmed salmon on plant and, to a lesser extent, marine-based proteins and alternative feed sources come with their own drawbacks and possible unintended consequences [101]. In fact, our analysis showed that no single niche innovation adequately addresses the various sustainability challenges of the farmed salmon value chain. In addition, most of the policy-making focus has been on the production-side, thus allowing opportunities to address large sustainability challenges along the entire value chain to remain unexploited.

Recent scientific assessments underscore the importance of reducing meat consumption from a health and sustainability perspective [63,102] and both regional and national policies have begun to incorporate this goal in their dietary recommendations and policy frameworks [103,104]. Although seafood has been afforded less consideration in the transition to more sustainable food systems, it has an important role to play due to its nutritional profile and its relatively lower environmental impact compared to livestock [2]. Seafood's nutritional significance is due to the provision of protein, healthy fats, and essential nutrients [105]. Aquaculture, in particular, has been singled out as a sector that will need to expand production to meet future food demand in part due to the stagnating state of capture fisheries [106]. The production efficiency, nutritional contribution and comparatively lower environmental impact of farmed salmon are reasons to consider it in debates about the role of seafood in sustainable food systems.

The lack of integration of fish in food policies in general [105] and the relative dearth of studies assessing the role of seafood—both wild and farmed—in sustainable food systems constitute important future research directions [99]. Negative public perceptions of the industry at both the local (community) and international level emerged as one of the major challenges for conventional sea-based aquaculture underpinning previous research [107]. Emphasizing the industry's role in providing healthy and nutritious products with a relatively lower environmental footprint compared to other animal protein production may represent a useful strategy for improving the industry's public image.

7. Conclusions

This study elicited the perspectives of industry representatives and experts to explore and evaluate future directions towards a more sustainable farmed salmon value chain.

It contributed to research on socio-technical transitions through the integration of the MLP framework on sociotechnical transitions and the GVC framework on governance in value chains. The addition of governance analysis to transition studies is useful for emphasizing the role of different actors in contributing to regime resistance [23] and thus the development of transition pathways. The assessment of sustainability contributions of niche-innovations further strengthened the analysis by indicating their ability to challenge the current regime. Applying these frameworks to the farmed salmon value chain provided insights into the drivers and barriers to the transition towards sustainability and how policymakers, managers and other actors can promote and support a sustainability transition.

There was broad consensus amongst the interviewed stakeholders on the most likely pathway i.e., not a complete regime shift but rather a continuance of the dominant regime with a gradual shift towards more diversity in production methods. This finding is supported by the governance analysis, which highlights the power of regime actors to resist change, and the analysis of the sustainability contributions, which indicates that they do not address some of the major sustainability challenges in the chain (e.g., sustainability of feed and transport). The result of the sustainability contribution analysis also reflects the industry's focus on local environmental challenges rather than global sustainability challenges such as the carbon footprint of the extended value chain. In order to find a path towards more sustainability in the farmed salmon value chain a broader food system perspective is needed.

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Paper IV

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Towards a systems perspective in policy design: An analysis of how the endogenous feedback structure of the Norwegian salmon aquaculture industry impacts policy outcomes

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ABSTRACT

The Norwegian salmon aquaculture industry has seen remarkable growth since its beginnings merely 60 years ago. Key to this growth have been technological innovations resulting in major productivity improvements and a licensing scheme that has enabled much faster growth than in other salmon-producing countries. This growth and efficiency improvements, combined with high prices, have resulted in a highly profitable industry. However, the same industry still faces considerable environmental and social sustainability challenges. In part, they relate to external factors like the uncertainty of the production environment, and the regulatory framework. However, it seems that part of the reason for these challenges is endogenous to the system, relating to its internal structure and feedback processes and how this structure impacts its response to external factors. In this work, an abductive system dynamics approach is used to study the endogenous structure of the Norwegian salmon aquaculture industry and how it has shaped its development and contributed to the issues facing it today. The findings indicate that the industry's dynamics are, to an extent, determined by the system's internal feedback structure and that the way in which the system responds to external factors, such as policy interventions, has contributed to the industry's current challenges by maintaining and even exaggerating the behaviour that they are supposed to constrain.

1. Introduction

The Norwegian salmon aquaculture industry is in many respects a success story. Since its humble beginnings in the late 1960s early 1970s the industry has seen phenomenal growth both at the extensive (e.g., new production sites, more licenses) and intensive margin (e.g., production per license) (Afewerki et al., 2023; Asche et al., 2022) with production volume of Atlantic salmon (hereafter salmon) rising from mere 50 t per year in 1970 to over 1.5 million t in 2022 (FAO, 2023). Key to this growth were major productivity improvements (Kumar and Engle, 2016), especially in the 1990s and early 2000s, resulting in more production per license and lower production costs (Asche, 2008). The drawback of this intensification of production is increased risk of environmental externalities (Bohnes et al., 2019; Jansen et al., 2012). In fact, despite major technological advances that have enabled the industry's economic success, and a licensing regime focused on mitigating environmental externalities, it still faces considerable environmental and social sustainability challenges (Hersoug et al., 2021; Osmundsen et al., 2022). At the same time as salmon farming companies turned record profits in 2023, 62.7 million salmon died in Norwegian net pens, which corresponds to a mortality rate of 16.7 % (Sommerset et al., 2024). Both the unprecedented profits and rising environmental and fish welfare issues increasingly raise concerns and cause challenges related to the industry's social license to operate and thus further growth (Osmundsen and Olsen, 2017).

Trade-offs between environmental, social, and economic sustainability are well known in intensive agriculture like crop and livestock production (e.g., loss of soil fertility, loss of biodiversity, air, and water pollution), and the salmon aquaculture industry is no exception (Garlock et al., 2024). According to the Food and Agriculture Organization of the United Nations (FAO) a sustainable food system is one that *"is profitable throughout (economic sustainability); has broad-based benefits for society*

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(social sustainability); and has a positive or neutral impact on the natural environment (environmental sustainability)" (Neven, 2014). It is generally accepted that sustainability is dependent on balancing these three pillars (Giddings et al., 2002). Although, successful in many respects, it is apparent when one studies the history of the Norwegian aquaculture industry, that industry players have struggled to strike that balance despite a regulatory system that aims to: *"[…] promote the aquaculture industry's profitability and competitiveness within the framework of sustainable development and contribute to value creation along the coast"* (Akvakulturloven, 2006). While governance, is an important tool for addressing sustainability trade-offs (Asche, 2008; Garlock et al., 2024), and is often considered the fourth pillar of sustainability (e.g., Bojic et al. (2022), certain policies (e.g., growth restrictions) can have unintended consequences, lead to undesirable behaviours, and even amplify the impacts that are to be mitigated (Oglend et al., 2024).

Salmon production traditionally takes place in open net pens in the natural environment and therefore there are many potential negative externalities related to the production process, including water pollution, antibiotic use, genetic mixing with wild salmon populations from escaped fish, and spread of diseases and parasites (Asche et al., 2022; Osmundsen et al., 2017). In addition to these local environmental externalities, the aquaculture industry has a significant impact on a global scale, mainly through GHG emissions, related to feed production and transport, of both feed and products, to distant markets (Winther et al., 2020), but also through loss of biodiversity due to the reliance on forage fish and soya for feed (R. L. Naylor et al., 2000; Osmundsen and Olsen, 2017). To the extent that externalities impact profits they are internalized by salmon farmers in their decision making (Asche et al., 2022). When there is limited negative feedback from an environmental issue on expected profitability or when the potential impact on external parties or society is greater than that on the farmer himself, there is need for some sort of policy instrument to minimize the impact (Asche, 2008; Tveterås et al., 2020). This may include traditional regulatory "command and control" instruments (e.g., licenses, feed quotas), economic incentives (e.g., subsidies, taxes) (Cojocaru et al., 2024), and informational instruments (e.g., sea-lice count disclosure) (Vormedal, 2024). Today the biggest externality concern in Norwegian salmon farming is the impact on wild salmon through crossbreeding with escaped farmed salmon and the spread of infectious diseases (Aasetre and Vik, 2013; Bailey and Eggereide, 2020). These concerns have contributed to rigid constraints on the issuance of new production licenses for over a decade (Hersoug et al., 2019; Oglend and Soini, 2020) and from 2017 growth in production has been contingent on lice levels only (Tveterås et al., 2020). At the same time, global demand has been rising fast as salmon, a healthy source of animal protein with relatively low environmental impact compared to other animal protein sources, is well aligned with, both macro drivers of consumption like rising middle class, and consumer trends like health and sustainability. This has caused an imbalance between supply and demand resulting in exceptionally high prices and thus profitability (Misund and Tveteras, 2020). High profitability in the industry provides strong incentives for further growth (Osmundsen et al., 2022).

While regulations have been successful in controlling production volume their performance when it comes to their objective, that is mitigating environmental externalities to society and the ecosystem, has not been as convincing. The 2022 Norwegian Fish Health Report stated that despite regulations focused on limiting lice prevalence the overall disease burden is increasing resulting in more mortality and rising biological costs (e.g., costs related to diseases and treatments) (Sommerset et al., 2023). Research on the topic is indicating that the reason lies in the way in which growth constraints create regulatory rents in the industry that incentivize intensification of production (Oglend et al., 2024; Oglend and Soini, 2020). In addition, growth restrictions are having unintended consequences related to social sustainability including a diminishing public acceptance of the industry due to ongoing environmental externalities at the same time as profits are soaring, concentration of power in the industry, and lack of fairness in terms of distribution of the value created (Misund et al., 2023; Oglend et al., 2024; Oglend and Soini, 2020; Olsen et al., 2023, 2024).

The Norwegian salmon aquaculture industry, like other food industries, is a dynamic and complex social-ecological system (Ericksen, 2008). Social systems including human societies, economies and cultures are embedded in ecosystems. They shape them through active interventions (e.g., farming, fishing, logging) and at the same time benefit from them through ecosystem services (e.g., fuel, food, recreation) (Ostrom, 2009). Social-ecological systems emerge from this interaction and the key to their sustainable development lies in understanding the complex and evolving dynamics between ecosystems and human societies, especially as they increase in scale, scope, and intensity (Fischer et al., 2015), as has been the case with salmon aquaculture. Due to the complexity of the Norwegian salmon aquaculture industry, it is not straightforward to grasp the causal relationships that shape the industry and thus predict its behaviour, including response to policy interventions. This complexity has even resulted in the management of aquaculture, by farmers as well as regulators, being described as a "wicked problem" (Osmundsen et al., 2017). However, as there are plans to further increase aquaculture production in Norway (Olafsen et al., 2012) and other countries like Iceland (Björnsson et al., 2023) it is important to increase understanding of these complex dynamics. This requires a systems approach.

System dynamics (SD), a modelling approach frequently used for policy analysis and design, is well suited to the study of complex systems such as the salmon aquaculture industry. It assumes that it is the system's structure that drives its behaviour through endogenous feedbacks and non-linearities. Specifically, SD structural thinking tools are used to investigate the nature of reinforcing and balancing feedbacks within a complex system to estimate its dynamics over time (Sterman, 2000). Several aspects of the Norwegian salmon aquaculture industry make it interesting to study through the "causality lens" of SD. It is in essence a network of businesses that operate by making a series of decisions to fulfil their purpose of producing various outcomes, of which profit is an important one since turning profit is vital for long-term survival in a competitive market. These decisions are constrained by internal (i.e., financial position, know-how, technology, etc.) and external (i.e., regulations, market dynamics) factors (Gudbrandsdottir et al., 2021a). The industry is heavily regulated, and while the governance has supported its growth to being the largest globally it has at the same time contributed to some of the negative aspects that increasingly limit the industry's growth (e.g., fish welfare issues, social license erosion). In effect these growth constraints are sprung from the ongoing challenge of balancing the three pillars of sustainability. Future sustainable growth in the salmon industry is dependent on finding that balance (Misund and Tveteras, 2020).

How come the highly successful Norwegian salmon aquaculture industry, with its advanced technologies and extensive regulatory framework, still struggles with environmental and welfare challenges? In part it is due to external factors like the uncertainty of the production environment, and the regulatory framework. But it seems that part of the reason is endogenous to the system, relating to its internal structure and feedback processes and how this structure impacts its response to external factors. To an extent, mortality issues and stricter environmental regulation support the unprecedented high prices in the industry and thus profitability, the main driver of the system seeking to maximize profits. During a round table discussion at the North Atlantic Seafood Forum in Bergen in March 2024 one of the participants stated: *"this is the only industry where the worse you do, the more money you make […] the more losses you have, the higher prices go"* (Salmon Business, 2024). It is this paradox that has inspired this research.

In this work an abductive SD approach is used to study the endogenous structure of the Norwegian salmon aquaculture industry and how it has shaped its development and contributed to the issues facing it today. An abductive approach, as opposed to a deductive or inductive one, starts with an observation of a system showing puzzling behaviour. Through a process of theory matching a hypothesis is put forth about what could be the cause of the observed behaviour, here the system's internal feedback structure. This hypothesis is then tested and improved through an iterative process of comparing it to known facts. An in-depth literature review and secondary data analysis are combined with SD structural thinking and diagramming tools to study the system's structure, specifically how it impacts its dynamic behaviour over time and influences how it responds to disturbances and policy changes. Based on prior theoretical knowledge from the SD and salmon aquaculture literature the industry's internal structure and feedback processes are conceptualized. The model is then validated by comparing it to developments in the industry's history and finally used to analyse the current challenges facing the industry. Specifically, the focus is on answering the following research questions:

RQ1: How does the endogenous feedback structure of the Norwegian salmon aquaculture industry, and specifically profit maximization, impact industry developments in a highly regulated environment?

RQ2: How can SD structural thinking and diagramming tools contribute to understanding challenges and impact of policies related to balancing economic sustainability with environmental and social sustainability?

The article is structured as follows: Section 2 describes the methodology. Section 3 provides a theoretical background to the conceptual model that is presented in Section 4. In Section 5 the model is validated by viewing it in the context of historical industry developments (to answer RQ1) before it is used in Section 6 to analyse the industry's current policy environment and challenges (to answer RQ2). Finally, conclusions are drawn in Section 7.

2. Methods

In this paper SD structural thinking tools and abductive inference are used to form a hypothesis of how the endogenous structure of the Norwegian salmon aquaculture industry has contributed to some of the issues the industry is facing today. This section describes the research process but first a more detailed description is provided of SD structural thinking tools and abductive reasoning and how a combination of the two can build understanding of developments in the Norwegian salmon aquaculture industry.

2.1. System dynamics structural thinking tools

SD is a model-based approach that is well-suited for studying the nonlinear behaviour of complex systems. The SD methodology assumes that it is the endogenous feedback structure of a system that determines its dynamic behaviour over time and how it responds to disturbances. SD modelling involves analysing the internal structure of a system and viewing it as a collection of feedback loops that interact to generate dynamic patterns of behaviour (Sterman, 2000). To aid in the process, the SD methodology provides structural thinking and diagramming tools such as causal loop diagrams (CLD). A CLD, which visually depicts the feedback structure of a system, consists of variables connected by arrows indicating the causal interactions among the variables. A positive arrow (+) indicates a positive relationship between two variables. When the value of the cause increases, the value of the effect also increases. A negative arrow (−) indicates a negative relationship between two variables. When the value of the cause increases, the value of the effect decreases. In a CLD the variables and arrows form one or more feedback loops, thus depicting the feedback structure of the system. Feedback loops can either be reinforcing (R) or balancing (B) depending on whether they amplify or stabilize change in the system. If an initial variable change is amplified through a loop, it is a reinforcing loop and if the change is counteracted as it propagates through the loop, it is a balancing loop (see Fig. 1) (Sterman, 2000).

The goal of CLD modelling is to structure such a diagram that can by

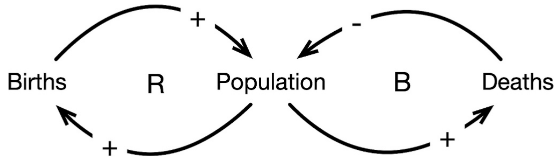

Fig. 1. Indication of causal links (e.g., positive (+) and negative (−)) and feedback loops (e.g., reinforcing (R) and balancing (B)).

itself through feedback loops explain the dynamic behaviour of the system under study, thus providing qualitative insights into the system's behaviour which can be used to identify policy leverage points and aid in the policy design process. CLDs can serve as the blueprint for a computer simulation model but also as a basis for qualitative diagrammatic reasoning and analysis (Stave and Kopainsky, 2015) as is the case in this research.

2.2. Theoretical investigation using abductive reasoning

SD research projects are typically focused on solving a specific problem, often related to managerial decision making. This is evident in the usual first step of model building in textbooks and most research projects, namely “problem definition” or “problem articulation” (e.g., Sterman (2000), Roberts et al. (1983)) and is related to the “applied” nature of many SD projects. Generally, research methodology is divided into theoretical (fundamental) research and applied research. While many studies will not be strictly theoretical or strictly applied, but rather fall somewhere on the continuum between the two, it is important to be aware of the differences as the purpose and aims are different. Applied research is focused on a particular problem and preferably results in a solution to that problem. Theoretical research on the other hand has the purpose of expanding knowledge on a phenomenon and is not so much focused on a specific problem but rather on a system of interest (de Gooyert and Größler, 2018). This research is not focused on a specific problem but is rather a theoretical investigation of the phenomena that is the Norwegian farmed salmon industry and some puzzling behaviour it shows.

Theoretical investigations can take different forms depending on how one reasons or the logic of inference (e.g., how conclusions are drawn). Inferences can be deductive, inductive, or abductive. In deductive reasoning, often linked to quantitative research, general assumptions (accepted truths) are used to come to specific conclusions through hypothesis testing (e.g., by testing general theories using specific data). Inductive reasoning, often linked to qualitative research, goes from observed instances (cause and effect) to general conclusions (e.g., by building general theory from specific data). Abductive reasoning is relatively underrepresented in research compared to deductive (theory testing) and inductive (theory building) reasoning. Abductive inference, which is the form of investigation used in this study, goes from an observed fact to a hypothesis of a principle that explains that fact. The abductive process does not provide new evidence to generate theory nor test a theory but rather through a study of the evidence already known generates a hypothesis of the most likely explanation for an observed phenomenon (Spens and Kovács, 2006). Fig. 2 explains the difference between the deductive, inductive, and abductive research process in simple terms.

As an abductive form of inference, this study does not introduce new evidence or data, rather the main contribution is the reorganization of existing knowledge and the promotion of structural insight from variables already established in the literature. The main purpose is not to test this existing knowledge (like in deductive research) or add new evidence for theory building (like in inductive research), but rather to study the existing evidence and devise a likely explanation of how they came about. The aim is to construct a conceptual model of the system's

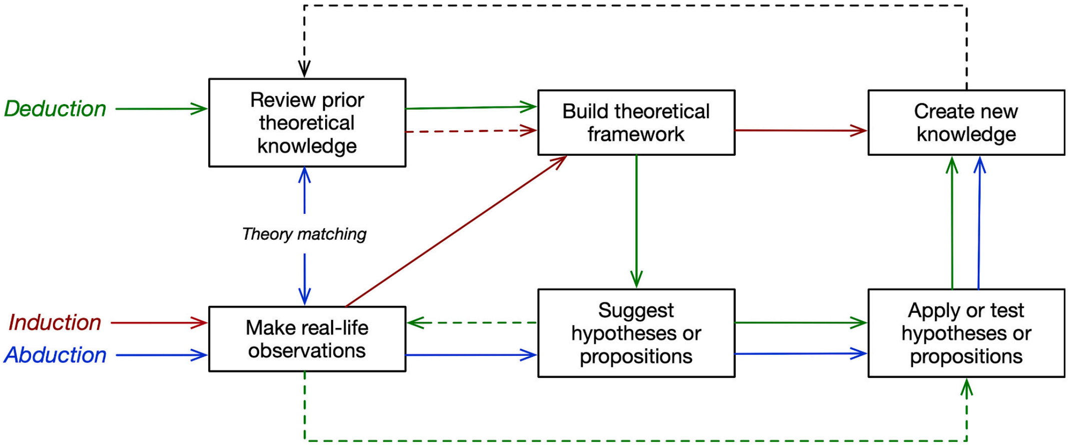

Fig. 2. Overview of the deductive, inductive, and abductive research processes. The deductive research process starts with the study of existing theoretical knowledge before proceeding to the building of a theoretical framework and a hypothesis that is then tested to generate new theoretical knowledge. The inductive research process involves theory building based on empirical observations influenced by the researcher's prior theoretical knowledge. Abduction starts with the observation of a phenomenon and then proceeds to study that phenomenon with reference to prior theoretical knowledge to come up with an idea about what is causing it. Diagram adapted from Spens and Kovács (2006).

internal feedback structure based on information about how the system has evolved over time and responded to known disturbances and policy changes. By better understanding how the system behaves and how it has responded to various disturbances including policy implementations, market shocks, productions shocks etc. we are better equipped to forecast the result of future policy implementations.

2.3. *Research process*

Fig. 3 describes the approach used in this research. In line with the abductive reasoning process, we start with an observation of a system showing puzzling or unexpected behaviour, namely the Norwegian salmon aquaculture industry. Through analysis of the system and prior theoretical knowledge a hypothesis is formed using SD structural

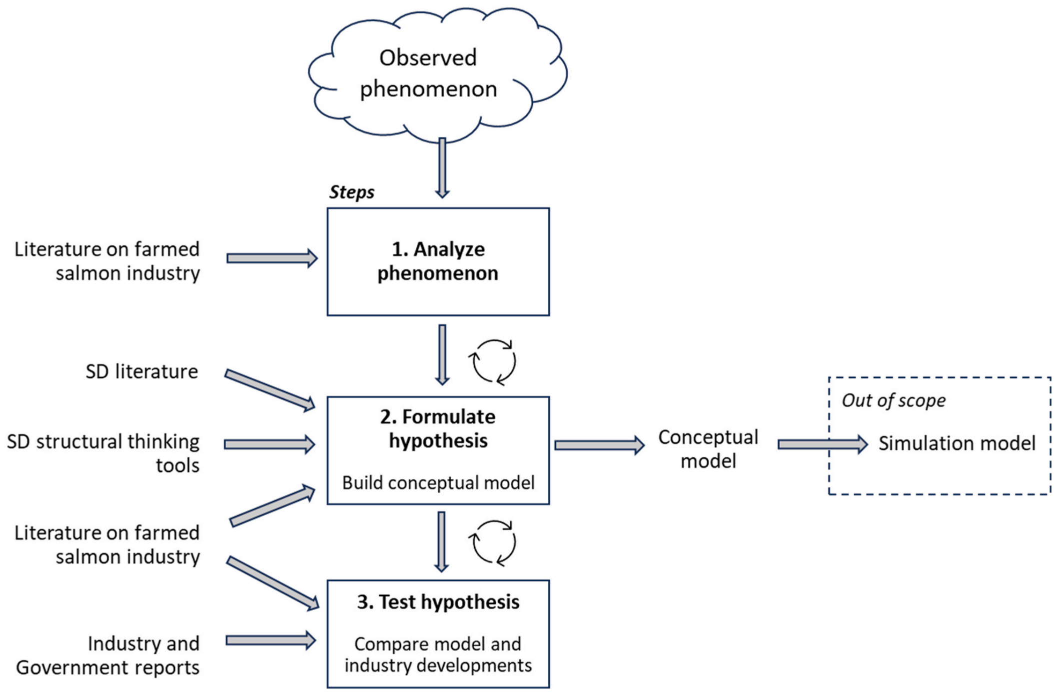

Fig. 3. The research process of developing and testing a dynamic hypothesis about the impact of the endogenous structure of the Norwegian farmed salmon industry on developments in the industry.

thinking tools. The hypothesis is presented in the form of a conceptual model (CLD), and then tested qualitatively by comparing it to developments in the Norwegian salmon aquaculture industry's history. Thereafter, the CLD is used to analyse the industry's current policy landscape in the context of the challenges facing the industry. This three-step process of generating insights about a system using abductive reasoning is iterative and the resulting conceptual model, or the hypothesis of what causes the observed phenomenon, can be continuously refined with new observations and evidence. Although outside the scope of this research, the conceptual model resulting from this iterative process can be used as a basis for the construction of a quantitative simulation model.

This study, while contributing insights into the endogenous feedback structure of the Norwegian salmon aquaculture industry, is subject to several limitations inherent to model-based analysis. Firstly, the accuracy and robustness of the results are constrained by data availability and quality. The reliance on available data may limit the depth of insights, as certain variables important to the system may be underrepresented or excluded. Furthermore, the CLDs developed in this research are, like other CLDs, limited in the sense that they are neither comprehensive nor final. Simplification is a key part of modelling complex systems, inherently leading to trade-offs between comprehensiveness and interpretability, and there are therefore multiple factors internal and external to the system under study that are disregarded. Furthermore, the CLDs are a representation of the current understanding of the system's feedback structure and may evolve as understanding improves, especially through continued communication with experts and stakeholders using the model. Consequently, the CLDs presented in this research are not exhaustive; they do not capture every internal and external factor influencing the system. As such, the insights provided should be viewed with the understanding that ongoing refinement and validation are essential as additional data and insights become available.

3. Theory

The conceptual model of the endogenous feedback structure of the Norwegian salmon aquaculture industry resulting from this research is based on a model of a generic supply system under market conditions (Section 3.1) but takes into consideration the specifics of the farmed salmon industry (Section 3.2).

3.1. The endogenous feedback structure of supply systems

Fig. 3 shows a simplified conceptual model of the main feedback loops in a generic supply system under market conditions which is adapted from Guðbrandsdóttir et al. (2018). It is based on the notion that profit maximization is a key element of the feedback structure of supply systems and that it is what drives growth through increased output (e.g., more revenues) and efficiency improvements (e.g., lower cost).

Supply systems, such as the aquaculture industry, can be conceptualized as a network of businesses that all have profit maximization as their main objective. Therefore, the reinforcing profit seeking loop (R1) that is highlighted in Fig. 4 is a key driver of the system. It is based on the idea that profit increases willingness to further grow the business and generate more profit. All else excluded, increased production will lead to more products on the market, which means that more products will be taken from the market, which in turn increases revenues and thereby profit, thus further increasing willingness to grow the business. This generates a profit maximization loop and as the supply system is a chain of agents, each aiming to maximize their profit, it adds up to a reinforcing profit maximizing supply system.

There are different ways to use profit to drive further profit. This was described by Brzezina et al. (2017). In a high or rising profit scenario companies will increase profit by increasing production, through reinvestment in more raw material, larger capacity, or better technology (R1). In a low or falling profit scenario companies will focus on efficiency improvements through innovation and scale economies to lower cost and thus restore profit (B3). The impact of economies of scale and cost reduction on profit and price are described by (Sterman, 2000).

The profit seeking behaviour of the system is balanced by several balancing feedback loops. Most importantly, like in any market driven supply system, the industry's profit maximization efforts are balanced by a market mechanism that balances growth through price setting. On the supply side, higher prices will increase profits, which eventually will drive producers to increase their production and thereby the supply in the market. However, as market supply goes up, prices go down, thus creating a negative feedback loop (B1) that regulates the reinforcing profit driven behaviour of the system. A second balancing feedback loop on the demand side (B2) also balances R1. As price goes up, demand is negatively affected. As demand is what determines how much is bought in the market the lower the demand the more is left in the market which in turn leads to a price decrease. Both these feedback loops, B1 and B2, which together regulate the market through price, are based on fundamental macroeconomic theory and are well documented in the SD literature (Meadows, 1969; Sterman, 2000).

This generic feedback structure which centres on the profit seeking behaviour of organizations and the balancing effect of market dynamics

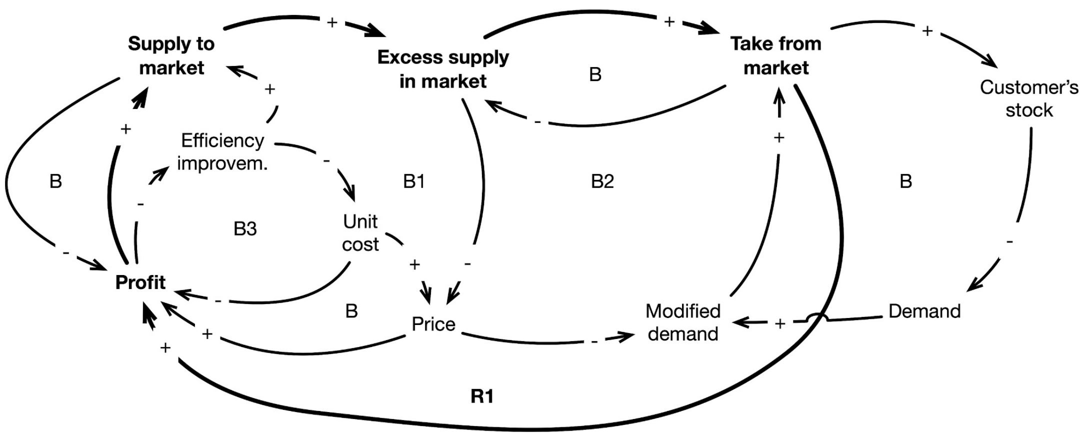

Fig. 4. Key feedback loops in a generic supply system under market conditions.

applies to different commodity industries consisting of for-profit organizations operating under market conditions. Although, having certain elements in common, commodity industries vary in many aspects. Now the specifics of the Norwegian salmon aquaculture industry will be discussed.

3.2. Specifics of farmed salmon value chain

Several characteristics of the Norwegian salmon aquaculture industry impact its feedback structure (compared to the generic one). The perishability of the product and the relatively long production cycle impact market dynamics. Farmers have limited opportunity to quickly respond to price changes by either adding to production or harvesting sooner than planned in a high price scenario or delaying harvest in a low-price scenario. Harvested fish can surely be frozen and sold later but fresh fish is currently preferred by consumers.

In addition to limited opportunities to respond to price changes in the short term there are also limitations on salmon farmers' opportunities to respond to higher profit prospects in the long term. Growth in the industry has been very constrained for over a decade by regulatory factors in addition to the biophysical and environmental limitations the industry already faces. In recent years social constraints on growth have also been rising as the industry struggles to maintain its social license to operate. The different constraints on growth impacting the industry will now be described.

3.2.1. Biophysical constraints on growth

Salmon farming is today based primarily on traditional open net-pen production. Salmon farms are in distinct geographical locations, in areas along the coast where they can take advantage of biophysical conditions such as appropriate sea temperature and ocean currents that deliver oxygen to the fish and disperse of their waste. Countries such as Scotland, Chile, Norway, and Iceland have a geography that benefits from an abundance of these fjordic enclosures, but they are less common in other countries (Asche and Bjørndal, 2011). Since these special conditions are needed for marine salmon farming and most of the suitable farming sites globally are already occupied this puts a constrain on the industry's ability to grow. In recent years however, in large part due to these growth constraints, developments in alternative technologies (e.g., land-based farming, closed/semi-closed sea pens, offshore farming) have been ramping up which could potentially, at least in part, remove this location-related barrier to growth (Afewerki et al., 2023).

3.2.2. Environmental and biological constraints on growth

The biological nature of the farmed salmon production system limits its growth. The production takes place in a natural environment that is not easily managed, and the production capacity of a site depends on site-specific growth conditions that can be affected by the impact of production on the local environment (e.g., waste, pollution), on fish health and welfare (e.g., diseases), and the prevalence of production shocks (e.g., algae bloom). The size of the environmental impact is directly related to the intensity of production. The production capacity of a site and thus opportunities for growth can also be impacted indirectly by environmental factors through regulation aimed at limiting environmental impact (e.g., growth constraints), and increased costs that influence profitability, both mitigation costs (e.g., medicine, delousing treatments) and costs related to production losses and downgrades (e.g., feeding cost of dead or downgraded fish) (Misund, 2022). While growth constraints are aimed at limiting environmental impact, they can have the opposite effect as they incentivize more intensity of production (this is covered in more detail in Section 6).

3.2.3. Regulatory constraints on growth

While biophysical, environmental, and biological limitations have shaped the development of salmon aquaculture so have different government policies and regulations (R. Naylor et al., 2023; Tveterås et al., 2020). Developments in the Norwegian salmon farming industry are very much dependent on the licensing scheme. This is apparent when one looks at how the salmon aquaculture industries in different countries have developed in the context of the regulatory system in each country (Osmundsen et al., 2017). The Norwegian licensing scheme has enabled much faster growth than in other salmon producing countries. In the UK, Canada, and the United States growth has been slower than could have been possible due to strict regulations, and in Chile, lack of regulation led to a disease-driven production decline for some time (Asche et al., 2009).

The objectives and instruments of the Norwegian salmon aquaculture industry's licensing scheme have changed through the years, but they have mostly involved controlling output. Hersoug (2021) gives an overview of the main policy instrument used to regulate the Norwegian salmon aquaculture industry through its history. In the beginning the focus was on supporting rural development and building a small-scale industry. Later, due to trade wars with the EU and US the focus was on limiting output, although this was mostly unsuccessful, until the introduction of feed quotas at the end of the 1990s. Gradually environmental factors became more important and the Maximum allowable biomass (MAB) scheme, that was implemented in 2005 and still forms the backbone of the Norwegian industry's regulatory environment, was the first step in that direction as it relates to the environmental carrying capacity of production sites. From the implementation of the traffic light system in 2017 growth is directly contingent on environmental sustainability as measured by a single sustainability index (i.e., salmon lice induced mortalities of migrating post-smolts of wild salmon).

3.2.4. Social constraints on growth

The social legitimacy of the industry is increasingly an issue when it comes to access to new or larger production sites. Lack of space for aquaculture, or what has been coined the “area challenge”, is considered one of the major challenges facing the industry (Hersoug et al., 2014). This is not due to shortage of coastal space but rather lack of access to the best locations (i.e., ideal growth conditions) as the industry competes for space with other industries (e.g., fisheries, sea transport, tourism, and recreation), and restrictions on minimum distance between farms due to sea lice, limit expansion in the best areas (Hersoug et al., 2021). Research has also indicated that while the general impression of the industry is positive and acceptive there are growing public concerns about the environmental and fish welfare issues related to production and the distribution of economic benefits, which limit public acceptance for further expansion (Olsen et al., 2023). Therefore, for the industry to get access to more and better production areas to grow, increasing social legitimacy will be key (Hersoug et al., 2021; Olsen et al., 2023).

3.2.5. Technological constraints on growth

Key to the industry's success were major productivity improvements in the 70s, 80s and 90s. First due to farmers' learning by doing and later through scale economies and technological innovations (e.g., better breeding and feeding technologies) that enabled producing more output with the same input (Asche et al., 2013). Productivity growth stagnated in the mid-2000s when it seems that all the low-hanging fruits in terms of productivity improving technological innovations had been integrated and the industry became more dependent on external factors that they have less control over for growth (e.g., demand and inputs) (Asche et al., 2013; Vassdal and Holst, 2011). There is still room for growth-enabling radical innovations as exemplified by developments in alternative production technologies like offshore and land-based farming (Afewerki et al., 2023). However, these production methods are still not developed enough to compete with the highly efficient open net pen production technology and there is significant resistance within the industry as such transitions might threaten the highly profitable business models of large and powerful players (Gudbrandsdottir et al., 2021b).

4. The endogenous feedback structure of the Norwegian salmon aquaculture industry

In the previous section a generic model of a supply system under market conditions was introduced and the characteristics of the Norwegian salmon aquaculture industry that impact its feedback structure were described. An adapted model, based on the generic one, will now be presented.

4.1. Avenues of growth – Profit maximization ($R1_{a,b}$ and $B3_{a,b}$)

Restrictions in the salmon aquaculture industry's operating environment impact the avenues of growth open to industry players in their efforts to meet their objectives of producing outcomes. Due to the profit driven nature of the system, industry players will seek ways to grow within the limits imposed on them. Fig. 5 shows the key feedback loops in a supply system under market conditions, namely profit maximization ($R1_a$ and $R1_b$) and two market loops, B1 and B2, that balance the profit driven nature of the system through price setting. In a high or rising profit scenario profit will increase willingness to grow production. This can be done either by adding more inputs (e.g., smolt) to production or adding more capacity (e.g., MAB, new site).

Adding inputs to production will increase biomass in sea, which will eventually result in the harvesting of that biomass. The more biomass that is harvested, the more volume is produced that can be supplied to a market. The more volume that is in the market the more volume is taken (i.e. bought) in the market resulting in yet more profit that further increases the willingness to grow production, thus forming a profit seeking loop $R1_a$. Adding capacity will increase the available capacity, that is, the amount of biomass that can be added to production. More available capacity results in more added inputs, thus increasing biomass that can be harvested and sold and thereby increasing profit and willingness to grow production further forming the second profit seeking loop of the system, $R1_b$.

The profit driven nature of the system is balanced by two loops that regulate the market through price setting. On the supply side, a higher price positively affects profits, eventually leading to more supply in the market (due to R1). This, however, has a negative effect on price, thus creating a balancing loop (B1). Higher price also negatively impacts how much is taken from the market (demand) and therefore increases the amount of excess supply, which in turn will lead to a price decrease, thus forming a second balancing loop (B2). It is important to consider, in the context of growth constraints that B1 will also balance the negative impact of lower production volumes on profits as less supply in the market will lead to a price increase, thus supporting profits. In a market with strong demand growth drivers, the negative effect of price on demand (B2) will also be less prominent. Therefore, the combination of constrained volume and rising demand results in persistently high prices and profits that incentivize further growth despite the balancing effect of B1 and B2 on the profit driven nature of the system.

When profits are low or falling aquaculture producers will focus on lowering costs through efficiency improvements (Fig. 6). This can be

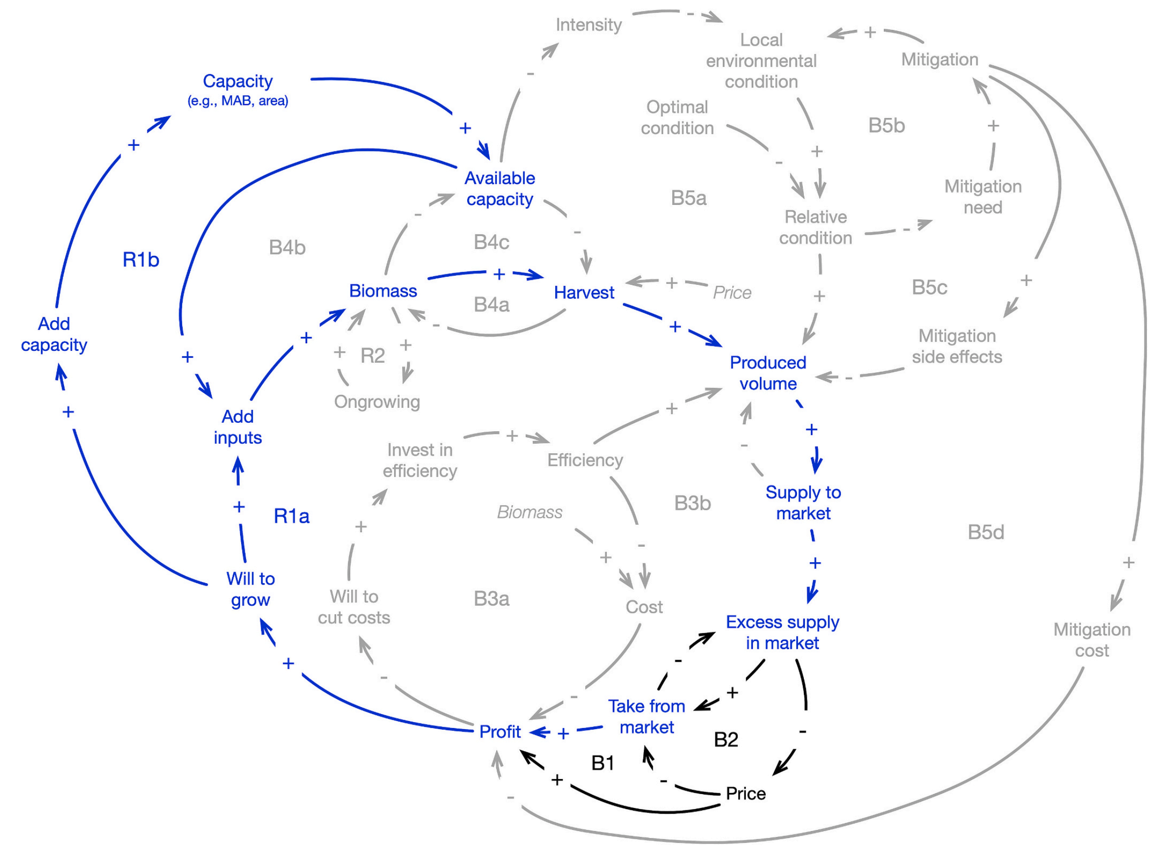

Fig. 5. Profit maximization. Avenues of growth in a high or rising profit scenario (R1) and balancing market dynamics (B1 and B2). Growth through more inputs ($R1_a$) and growth through more capacity ($R1_b$).

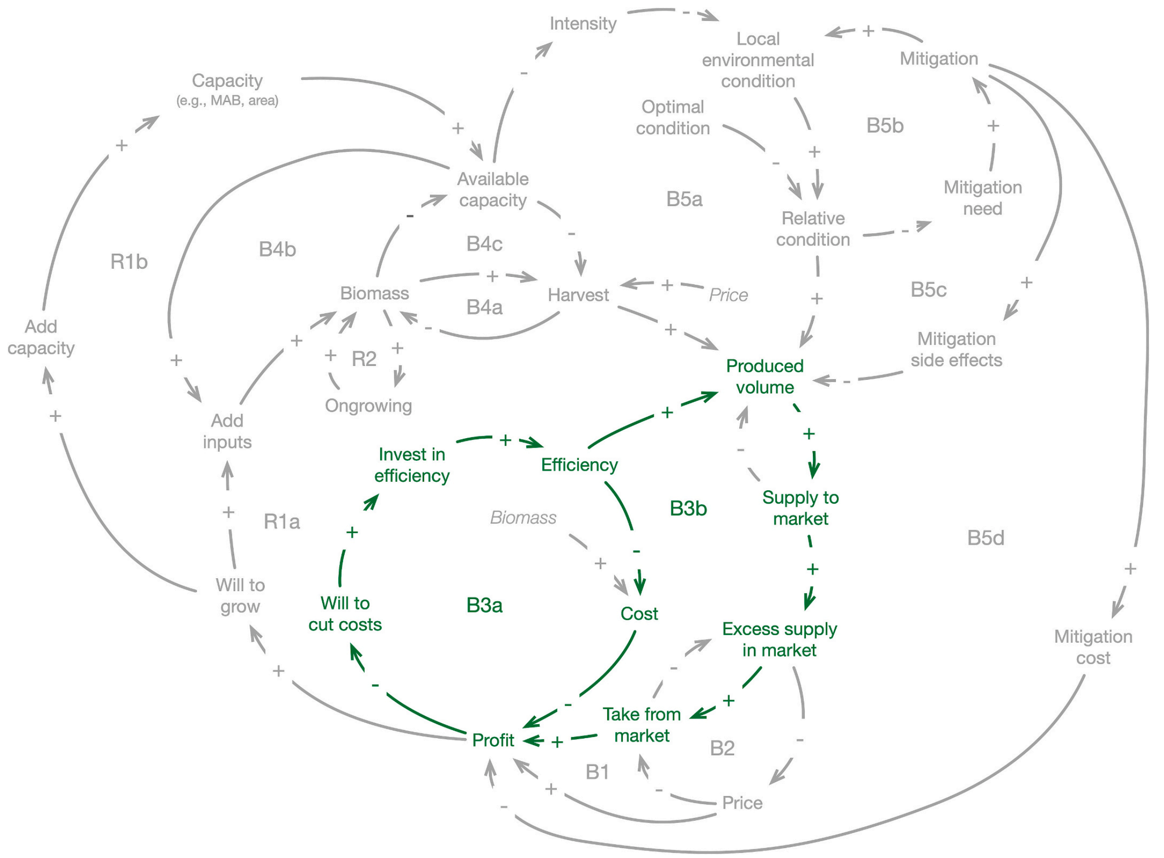

Fig. 6. Profit maximization. Avenues of growth in a low or declining profit scenario. Restoring profit through lower costs (B3a) and more output with same input (B3b).

done through technological innovation, including improved breeding and feeding technologies, and automation, or through scale economies in the form of larger farms and consolidation of farms. Efficiency improvements will often also result in increased production volume as more output is produced using the same input. All else excluded low or falling profit will increase willingness to cut costs which leads to increased investment in efficiency improvements that lower costs and thus restore profit ($B3_a$). Increased efficiency will also restore profit through more production volume as more output is produced using the same input, resulting in more products being sold ($B3_b$).

4.2. Production process – Production and harvesting management (R2, $B4_{a,b}$)

In very simple terms the aquaculture production process involves two key decisions: when to add inputs to production and when to harvest (Fig. 7). The amount that is added to production is dependent on two variables, the will to grow production and the available capacity. The more input that is added, the more biomass is in the sea and thus less available capacity due to biological and regulatory constraints. The less capacity the less input is added thus forming a loop $B4_b$ which balances the profit driven nature of the system. Biomass in sea grows in volume through a process of ongrowing (R2). The act of harvesting depends on three different variables: biomass in sea, available capacity, and market price. The fish is generally harvested once it reaches a certain size (e.g., in line with a contract), when the salmon producer needs to make room for adding new inputs due to capacity constraints, or because the market price is expected to go down and thus the farmer wants to capitalize on the high price. The more fish that is harvested the less biomass is in sea ($B4_a$).

4.3. Environmental constraints on growth – $B5_{a,b,c,d}$

The industry's willingness to increase production volume ($R1_{a,b}$) is balanced by the environmental constraints of the production system (Fig. 8). Due to the biophysical and regulatory constraints on growth on the extensive margin ($R1_b$) salmon farmers striving to maximize their profits will often resolve to grow production on the intensive margin ($R1_a$) through increased inputs. As capacity for growth is limited this leads to increased intensity of production (e.g., more stocking density).

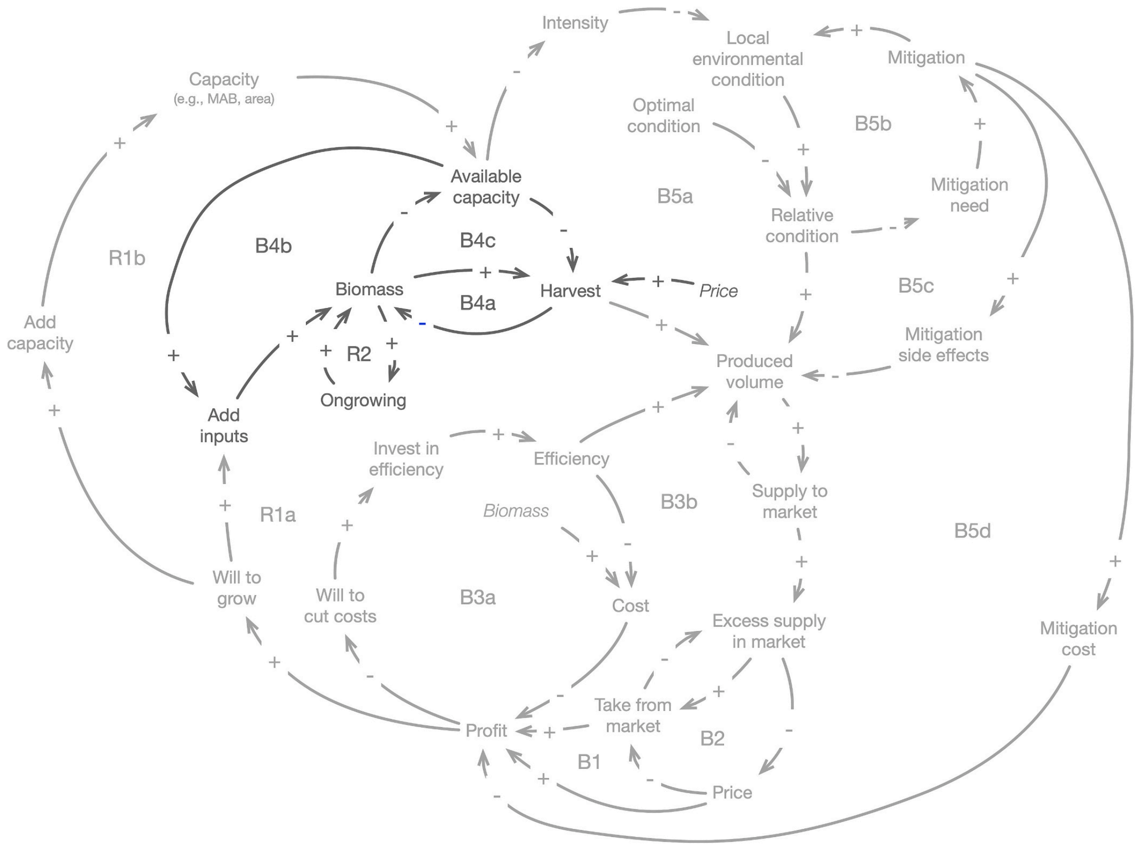

Fig. 7. Production process. Harvesting ($B4_a$) and production ($B4_b$) decisions.

Generally, more intensity of production will have a negative impact on the local environmental condition which will negatively affect growth conditions and thereby produced volume. All else excluded, less produced volume will lead to lower supply in the market which means that less is taken from the market and therefore profits decline. Lower profit results in reduced willingness to add inputs, lessening the biomass in sea and thus freeing up capacity. More available capacity reduces intensity of production thus forming a balancing loop ($B5_a$). The negative impacts of intensity on the local environmental condition are to an extent balanced by mitigation ($B5_b$) but mitigative action can also have side effects (e.g., mortality related to lice treatment) which negatively impact output ($B5_c$). The profit seeking behaviour of the system is further balanced by environmental factors through mitigation cost which negatively impacts profit ($B5_d$).

4.4. Regulation

The Norwegian salmon aquaculture industry is heavily regulated, and regulations have substantial impact on the dynamics that result from the system's profit seeking behaviour and the balancing impact of environmental and biological factors. The objectives of the regulatory system have changed over time (e.g., rural development, trade wars, environmental concerns) but the different objectives have usually been reached through controlling output by constraining growth, both on the extensive margin (by restricting $R1_b$) and the intensive margin (by restricting $R1_a$).[1] Fig. 9 gives an overview of key policy instruments that the Norwegian government has used through the years to fulfil their changing objectives and the impact those instruments have had on the dynamics of the system in terms of restricted and dominant profit seeking loops ($R1_a$, $R1_b$ and B3).

To summarize Fig. 10 shows the consolidated endogenous feedback structure of the Norwegian salmon aquaculture industry and entry points of constraints on growth. The system is mainly driven by profit maximization efforts through volume growth ($R1_{a,b}$) and efficiency improvements ($B3_{a,b}$). These efforts are balanced by market dynamics (B1, B2), environmental and biological constraints ($B5_{a-d}$), regulation and other external factors that constrain the system by impacting the profit maximization efforts. Specifically, the social license (SL) and Traffic light system (TLS) constrain growth on the extensive margin ($R1_b$), while most regulation (e.g., smolt quotas (SQ), net pen volume restrictions (NPV), feed quotas (FQ), density restrictions (DR), and MAB) restrict growth on the intensive margin. The "one man, one license" regime (OMOL) constrained efficiency improvements via scale economies ($B3_a$) and efficiency improvements through technological innovation are limited by the extent of technological knowledge (TL).

In the next section the interplay between this profit seeking

[1] See Hersoug (2021) for detailed overview of Norwegian salmon aquaculture regulatory developments.

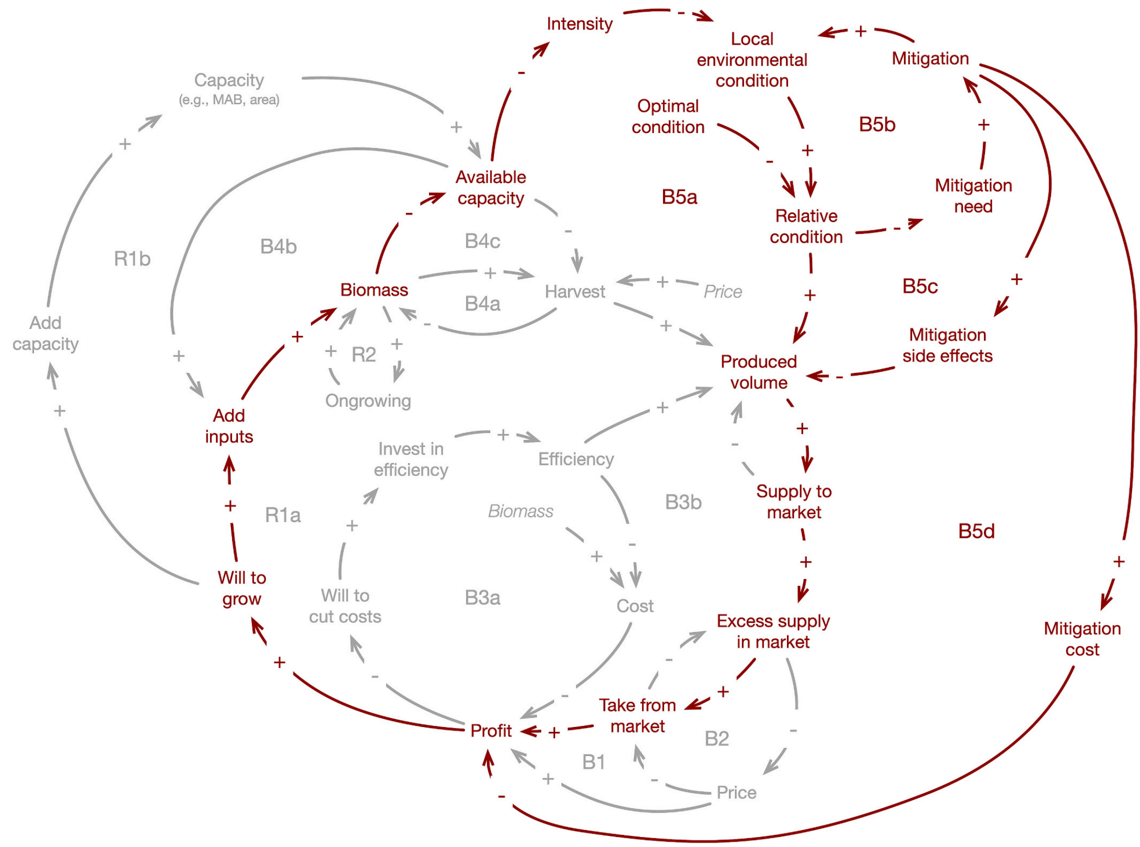

Fig. 8. Environmental constraints on growth.

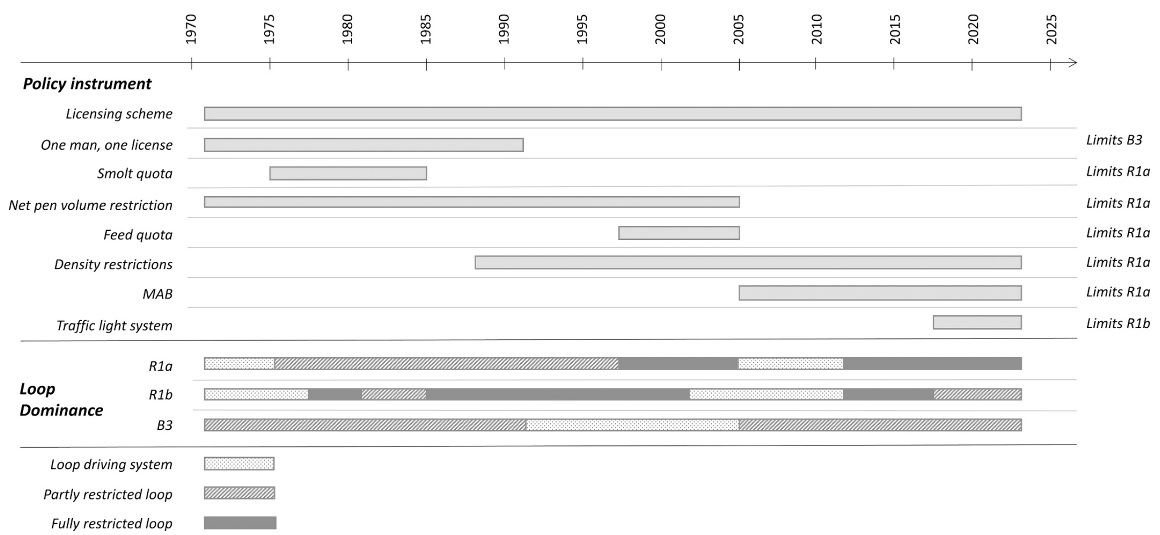

Fig. 9. Overview of Norwegian salmon aquaculture policy instruments (Hersoug, 2021) and how they have impacted the profit seeking behaviour of the system in terms of restricted and system driving loops.

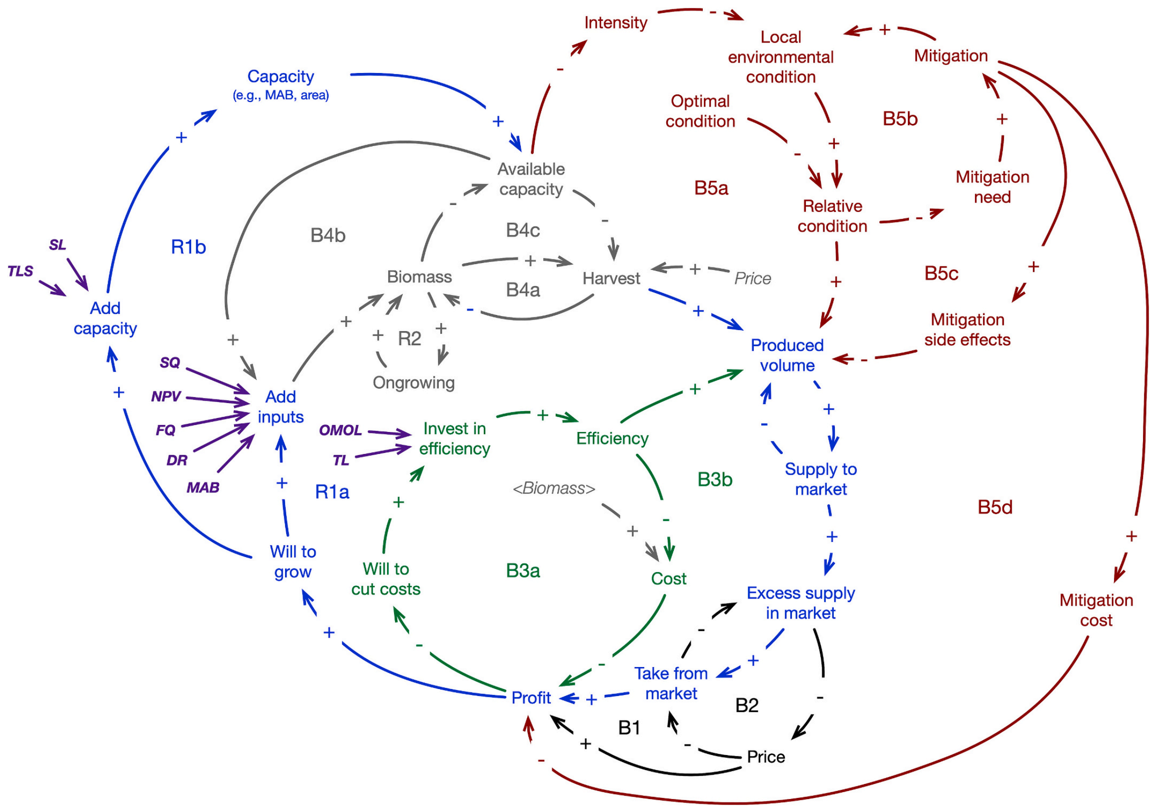

Fig. 10. The endogenous feedback structure of the Norwegian salmon aquaculture industry and policy instruments and external factors impacting it. Abbreviations; SL: Social license, TLS: Traffic light system, SQ: Smolt quota, NPV: Net pen volume restriction, FQ: Feed quota, DR: density restriction, MAB: Maximum allowable biomass, OMOL: "One man, one license", TL: Technological limit, LL: Lice limit.

endogenous structure and the external factors constraining it will be analysed to qualitatively validate the model in Fig. 10.

5. The interplay between the internal feedback structure and external factors in the context of industry development

The development of the Norwegian salmon aquaculture industry can be captured clearly by the graph in Fig. 11. By viewing the development of production quantity, production cost, and export price in the context of loop dominance one can explore how the industry's profit seeking feedback structure ($R1_{a,b}$, B3), in combination with market dynamics (B1/B2), and environmental factors ($B5_{a\text{-}c}$), has impacted its development and how policy has played its part by restricting some feedback processes (e.g., limiting scale during the "one man, one license" regime) and enabling others (e.g., making growth contingent on lice levels within the traffic light system).

Now industry developments in terms of production volume, cost, and price, will be analysed with reference to the system's feedback structure and the active policy instrument.[2] In the analysis the industry's history is divided into five sub-periods: 1) *1986–1991: "One man, one license"*, 2) *1992–2004: Scale economies and productivity*, 3) *2005–2012: Grow up to MAB*, 4) *2013–2017: Growth restrictions*, 5) *2018–2022: Traffic light system*. Note that the industry had its beginnings in the late 1960s/early 1970s, but data is only available from 1986 and therefore the model is validated from that point in time. All references to production volume, price, and cost refer to Fig. 11.

5.1. 1986–1991 (end of) "one man, one license"

From 1986 to 1991 the granting of new licenses was limited to 30 licenses in northern Norway in 1989 and therefore growth on the extensive margin ($R1_b$) was limited in this period. In terms of growth on the intensive margin ($R1_a$), smolt production had recently been liberalized and growth was limited through net pen volume restrictions only, although quite unsuccessfully, as farmers had found out that they could use deeper net pens as the volume measurement was taken at a certain depth and therefore production volume was rising fast. Also driving the system, as extensive growth was restricted, were efficiency improvements (B3) resulting from farmers' learning by doing, their increased control over the production process, and ability to influence growth conditions, all resulting in lower costs and supporting volume growth as more output was produced from same input. However, as demand was not rising as fast, prices were on a downwards trend (B1/B2). Density restrictions (limiting $R1_a$) were introduced in 1988 in response to serious disease challenges as production intensification in an industry

[2] Price and cost data are from the Norwegian Directorate of Fisheries (Norwegian Directorate of Fisheries, 2023), production data from FAO (FAO, 2023), and information about industry and policy developments are based on key references in the field covering the history of the industry (e.g., Afewerki et al. (2023), Hersoug (2022), and Hersoug (2021)).

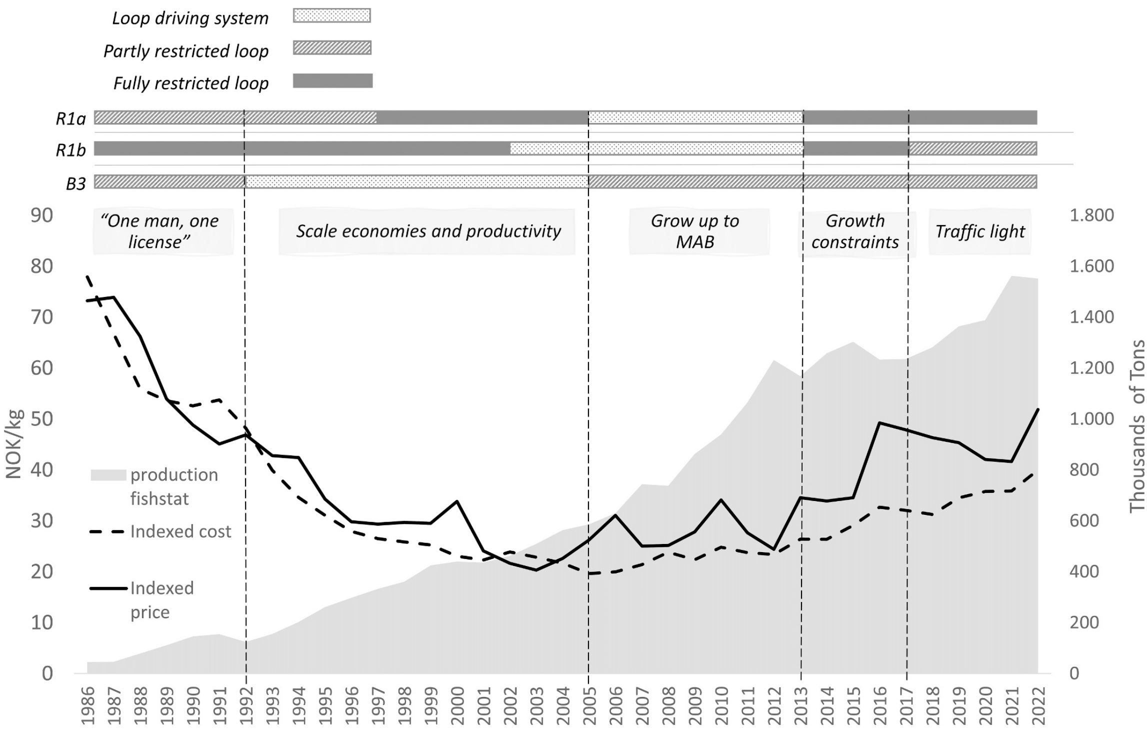

Fig. 11. Norwegian salmon aquaculture quantity (right axis), price, and cost (left axis) over the period from 1986 to 2022. Price and cost data from Norwegian Directorate of Fisheries and Production data from FAO.

constraining extensive growth reached biological limits ($B5_a$) and production growth halted and mitigation costs (e.g., anti-biotic use) sky-rocketed ($B5_d$). The resulting margin pressures shifted the industry's focus towards finding ways of cutting costs and improving efficiency ($B3_a$) which resulted in the introduction and wide-spread use of oil-based vaccines in 1991 and with that production growth took off again. To improve the profitability of the industry a more intensive production method was needed. Farmers were already gaining the control over the production process needed for a more intensive production, but intensity also requires capital and therefore scale is important. In the "one farmer, one license" regime farmers could not reach the size necessary to access further economies of scale as any consolidation of farms was fully restricted (limiting $B3_a$). In 1991, following years of low profitability due to low prices, the bankruptcy of the producer owned sales organization (FOS), was the final blow and many farmers went bankrupt. This paved the way for policy changes and a restructuring in the industry.

5.2. 1992–2004 scale economies and productivity

In 1991 the "one man, one license" regime was abolished and with that a wave of consolidation and resulting scale economies flooded the industry. In the next two decades productivity improvements resulted in a 2–3-fold growth in supply ($B3_b$) despite no new licenses being awarded (restricting $R1_b$) for a large share of the period (until 2002) and a very successful indirect constraint on inputs, feed quotas (restricting $R1_a$), being implemented in 1997. This spike in production volume resulted in price drops as demand was still not rising as fast as supply (B1/B2) and Norwegians were accused of price dumping by competing salmon producing nations on both sides of the Atlantic. Norwegian authorities tried different ways of taming production growth but it was not until the introduction of the feed quotas in 1997 that they had some success and the impact is visible in Fig. 11 as shortly after (when one considers the length of the production cycle), production growth stagnates as both $R1_a$ and $R1_b$ are constrained and at the same time the price goes up due to scarcity (B1/B2). At the end of the decade Norwegian salmon farmers were again dealing with the results of too much intensification as they reached their biological limits resulting in a disease outbreak ($B5_a$) and margins were negative from 2001 to 2004. The government gave in to pressure from farmers and in 2002 new licenses were awarded ($R1_b$) and volume growth resumed.

5.3. 2005–2012 grow up to MAB

In 2005 the Norwegian government implemented a new regulatory system with the aim of limiting environmental impact while allowing sustainable growth. The new system was based on MAB which limits the amount of biomass companies can have in the sea at any given time (restricts $R1_a$). Since the industry's biomass was well below this limit in 2005 this initially led to a rapid increase in production ($R1_a$) and from 2004 to 2012 production per license increased by approximately 85 %. Yet, studies have found that from around that time productivity growth ($B3_a$) started to slow down as the industry seemed to be nearing the limits to further improvements in production technology (Asche et al., 2013; Vassdal and Holst, 2011) and therefore costs stabilized before they started to rise later (especially after 2012) due, in large part, to increased biological challenges ($B5_d$). At the same time demand for salmon was starting to rise fast because of macroeconomic trends such as the growing middle class and increased focus on health and sustainability. Therefore, the tremendous increase in production did not result in a drop in price as in the 80s and 90s. Indeed, starting from the early 2000s salmon prices started rising due to increasing demand.

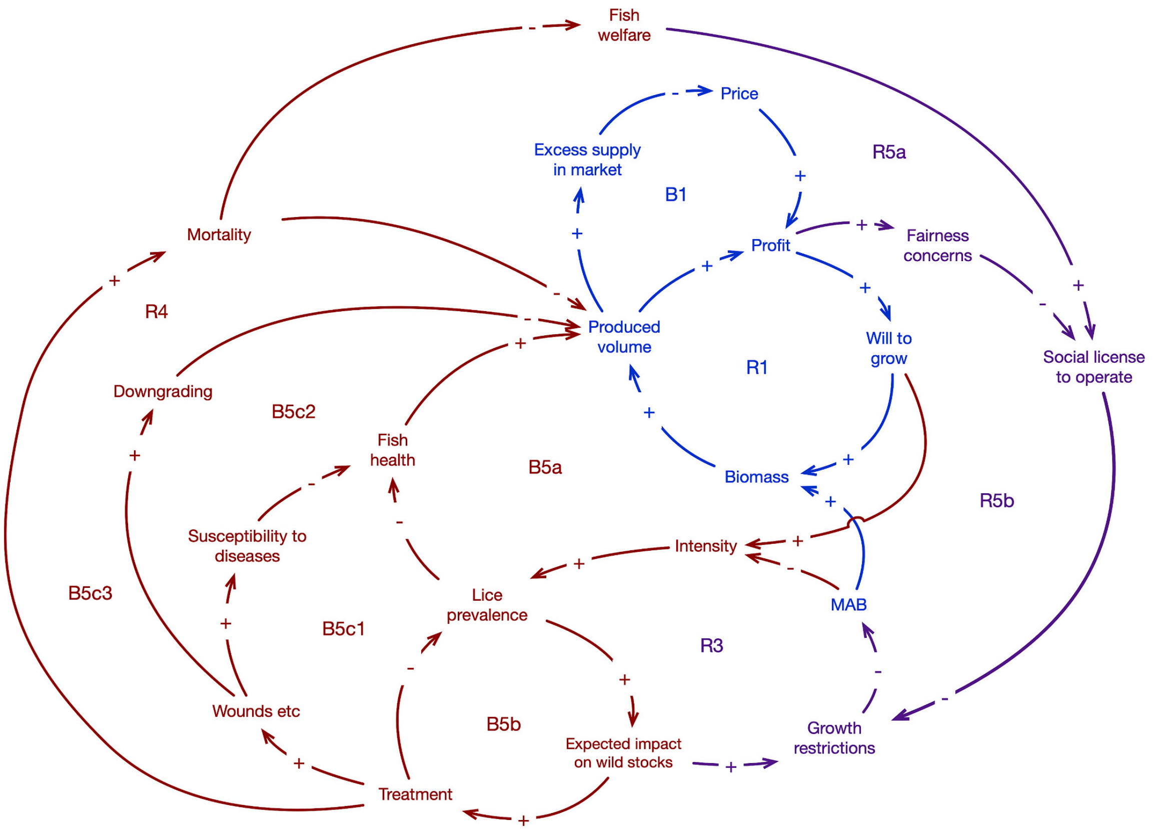

Fig. 12. Current challenges in the Norwegian salmon aquaculture industry related to growth constraints. This CLD is based on the CLD in Fig. 10 but for simplification some loops are disregarded (e.g., B2) and some are simplified (e.g., R1, B1). Furthermore, to focus on the current challenges some loops are extended (e.g., $B5_{c1-3}$) and others are added (e.g., R3, R4 and $R5_{a,b}$).

5.4. 2013–2017 growth constraints

From around 2012, production growth stagnated as farmers had reached their MAB, limiting growth on the intensive margin ($R1_a$), and the fact that new licenses were not being issued due to concerns about the environmental externalities of production and the area challenge, limiting growth on the extensive margin ($R1_b$). Furthermore, the productivity improvements ($B3_b$) witnessed during the 80s and 90s had slowed down as the industry matured and neared the limits of technological improvements. With these three avenues of growth ($R1_a$, $R1_b$, $B3_b$) constrained, volume growth stagnated 2012–2018 after an annual average growth of 10 % from 2002 to 2012. Some noted implications of this stagnation in volume growth at a time when demand was rising and the Norwegian krone was weakening, were exceptionally high prices and a rise in production intensity and the externalities that come with it as farmers strive to maximize profits within their MAB limits. A slight reduction in production during the period is in large part due to increased biological challenges ($B5_a$). Increased stocking density is the result of restrictions on growth as farmers find ways to grow at the intensive margin ($R1_a$) when the extensive margin is blocked ($R1_b$). Another consequence of growth restrictions, intensive production, and biological challenges were high and rising biological costs ($B5_d$).

5.5. 2018–2022 traffic light system

In 2017 the traffic light system (TLS) was implemented as a mechanism to control environmental externalities, specifically salmon lice, but at the same time allow growth for the highly profitable salmon farmers with their large willingness to increase production ($R1_{a,b}$). Also contributing to extensive growth in this period were development licenses and non-commercial, special purpose licenses. The impact is clearly visible in Fig. 11 as production volume starts increasing again (R1) and prices stabilize a bit (B1). However, price decreases in this period are also due to soft demand (B2) related to the covid-19 pandemic as foodservice is a large outlet for salmon and sales were thus hurt by the lockdowns. In this period cost continued to rise, in large part due to intensity induced biological issues ($B5_d$).

Now we have used the conceptual model to explore how the endogenous feedback structure of the Norwegian salmon aquaculture industry impacts industry developments in a highly regulated environment. In the next section the model will be used to conceptually analyse the key challenges currently facing the industry, including high mortality and reduced fish welfare and the industry's problems related to their social license to operate. Using the model, the way in which these challenges are interlinked and reinforce each other to create the perfect storm of social-, economic-, and environmental- sustainability challenges, will be explored.

6. Policy analysis using the model

The second objective of this research was to explore how SD structural thinking and diagramming tools can contribute to understanding challenges related to balancing economic sustainability with environmental and social sustainability.

In terms of economic sustainability, the Norwegian salmon aquaculture industry has been extremely successful since the 2000s and especially in the last 10 years as is evident from the exceptionally high profit margins of Norwegian salmon farmers. However, when it comes to environmental and social sustainability there are more challenges. The current regulatory scheme, the TLS which came into action in 2017 was intended to answer the call for predictable yet sustainable growth (Norwegian Ministry of Trade Industry and Fishery, 2015). Recent developments in the industry, however, indicate that the TLS, although successful in limiting growth in output, results in new challenges and maintains others, through incentivizing more intensive production methods, via three reinforcing loops: R3, R4 and R5 in Fig. 12.

6.1. R3: growth restriction induced intensification of production

The growth restrictions related to the TLS are aimed at reducing the negative externalities related to salmon production through balancing the profit seeking behaviour of the system (R1), based on the underlying rationale that salmon lice prevalence is related to the total production in a production area (Tveterås et al., 2020). The growth restrictions limit MAB, thus constraining the amount of biomass in sea at any given time, and the resulting production output. However, an aggregate industry reduction in output will result in higher prices thus increasing profit (B1), especially in the case of salmon, as demand is rising fast due to macro drivers such as population and economic growth and consumer trends related to health and sustainability. This offsets the impact that less output has on profit and results in an increased willingness to grow production (R1). In the absence of other avenues of growth, this leads to intensification of production as farmers strive to capitalize on the high prices within the limits of their MAB by realizing profits earlier with "race to raise strategies" (e.g., more stocking density, smaller fish, earlier harvesting) (Asche et al., 2019; Oglend et al., 2024). The problem is that intensification of production increases the prevalence of salmon lice (Sommerset et al., 2024), thus leading to more potential impact on wild stocks and thus, within the TLS, more restrictions on growth, further reinforcing the high prices that incentivize intensification of production in the first place (R3).

6.2. R4: mitigation side effects

As salmon farmers are driven by profit maximization, they seek ways to grow within the constraints imposed on them. As growth is contingent on lice levels within the TLS this includes developing and using delousing treatments that reduce lice prevalence, thus limiting the expected impact on wild stocks ($B5_b$), ultimately leading to less restrictions on growth. These treatments, especially the non-medicinal ones that have dominated in recent years due to increased resistance to medicinal treatments, have at least two negative consequences (Sommerset et al., 2024): 1) damage to the fish (e.g., wounds), that leads to both more susceptibility to diseases and thus reduced fish health ($B5_{c1}$), and increased downgrading of fish ($B5_{c2}$), and 2) increased mortality ($B5_{c3}$). Both the wounds and mortality negatively impact production output, thus reinforcing the high prices (B1) that incentivize the increased intensity in production driving the use of treatments, thus generating a reinforcing loop (R4) as farmers treat the symptom (lice prevalence) to be allowed to grow, but not the main cause (stocking density).

6.3. R5: Social license

It is not only regulators' concerns about externalities that maintain growth constraints but also societal pressure. Concerns about environmental externalities (e.g., impact on wild fish stocks) and increasingly the welfare of farmed salmon are deteriorating the industry's social license to operate (Hersoug et al., 2021). Additionally, the unheard-of profits that the industry has witnessed in the last decade has raised fairness concerns related to society's share in the value created (Hersoug et al., 2021; Olsen et al., 2023). The growth constraints reinforce the deterioration of the social license through decreased fish welfare resulting from increased delousing treatments ($R5_a$) and more profits due to scarcity induced high prices ($R5_b$).

Here, using SD structural thinking and diagramming tools, we have seen how the current unfortunate state of fish health and welfare in the industry relates to its feedback structure. The combination of the profit driven nature of the system, the environmental impacts of production, the growth constraints imposed on farmers, and the market mechanism that balances the market through price setting, creates a vicious cycle of deteriorating fish health and welfare while, regrettably, supporting industry profitability. This finding suggests that in the ongoing process of shaping aquaculture policy it would be beneficial to take a system's perspective and be aware of the system's feedback structure, that is, what drives its behaviour, and what balances that behaviour. Furthermore, an understanding of the system's drivers and restraints, could help in accelerating the industry's transition towards sustainability by designing regulatory incentives that support the phase out of unsustainable activities and the phase in of more sustainable ones. Norwegian aquaculture is an example of an industry where a sustainability transition may threaten the economic positions and business models of very large and powerful players (Gudbrandsdottir et al., 2021b). Therefore, as there are limited incentives for incumbent players to adopt more sustainable production systems, the transition towards sustainability will largely depend on political support and governments using regulation as an acceleration tool (Schøning et al., 2023).

7. Conclusion

In this research an abductive SD approach has been used to study the endogenous structure of the Norwegian salmon aquaculture industry and how it has shaped its development and contributed to the issues facing it today. It has been concluded that the industry's dynamics are to an extent determined by the system's internal feedback structure and especially how the system's drivers influence how it responds to external factors like policy interventions. Furthermore, we have used SD structural thinking and diagramming tools to analyse current challenges in the industry and found that they are a case of unintended policy consequences and that the TLS, although successful in some respects, may maintain and even exaggerate the behaviour that it is supposed to constrain by incentivizing a detrimental level of production intensity. These findings support the notion that a systems perspective is useful in policy design and could possibly support a shift from a regulatory system focusing on current issues (e.g., salmon lice) to one that has more long-term focus and intent to shape the direction of the industry towards sustainability. Indeed, these unintended consequences of the TLS are not the only example of policy failures in the Norwegian salmon aquaculture industry that seem to result from lack of whole-system, long-term thinking. In the last 10–15 years the focus on environmental restrictions has resulted in higher profits and thus, in the absence of other avenues of growth, intensification of production and increased environmental impact (Oglend et al., 2024). Earlier, in the 1980s, farmers aiming to maximize their profits were able to circumvent growth constraints by using deeper net-pens which eventually led to biological challenges, overproduction and eventually market failure (Afewerki et al., 2023) and in the late 1990s feed quotas successfully constrained volume growth but at the cost of less sustainability and fish welfare as farmers responded by changing the formulation of feed to allow for more production (Hersoug, 2021). It seems that throughout the history of the industry consideration of companies' incentives, and specifically their profit driven nature, has often been lacking, resulting in policies that solve some problems while creating new ones. Therefore, in line with de Gooyert et al. (2024), we find that the understanding of the endogenous feedback structure of the Norwegian salmon aquaculture industry and how it impacts the response to different policy instruments, resulting from this study, can inform future research aimed at developing methods to model the industry's transition towards sustainability and thus support the design of policy instruments that could accelerate such a transition.

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CRediT authorship contribution statement

Ingunn Yr Gudbrandsdottir: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Gudmundur Valur Oddsson:** Writing – review & editing, Supervision, Conceptualization. **Hlynur Stefansson:** Writing – review & editing, Supervision, Conceptualization. **Gudrun Olafsdottir:** Writing – review & editing, Supervision, Conceptualization. **Sigurdur G. Bogason:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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