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

Ingunn Ýr Guðbrandsdóttir[1], Anna Hulda Olafsdottir[1], Harald Ulrik Sverdrup[1], Sigurdur G. Bogason[2], Gudrun Olafsdottir[2] and Gunnar Stefansson[2]

1-Icelandic System Dynamics Centre, (ISDC) Industrial Engineering, University of Iceland, VR-II, Hjardarhagi 6, IS-107 Reykjavik, Iceland,
2-ASCS- Applied Supply Chain Systems Research Group - Industrial Engineering, University of Iceland, VR-II, Hjardarhagi 6, IS-107 Reykjavik, Iceland

iyg1@hi.is; annahulda@hi.is; hus@hi.is; sigboga@hi.is; go@hi.is; gunste@hi.is

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.

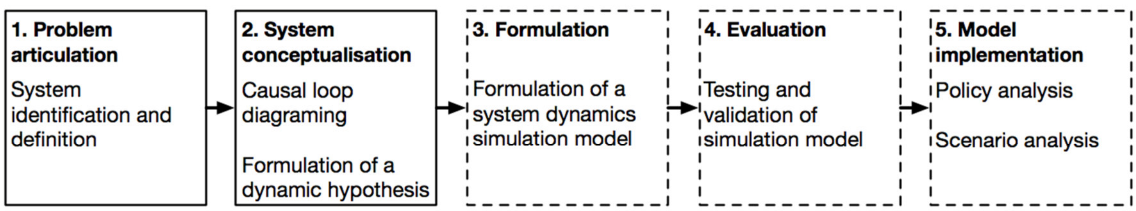

Figure 1 The research process. This paper presents ongoing work on the first two steps in the process

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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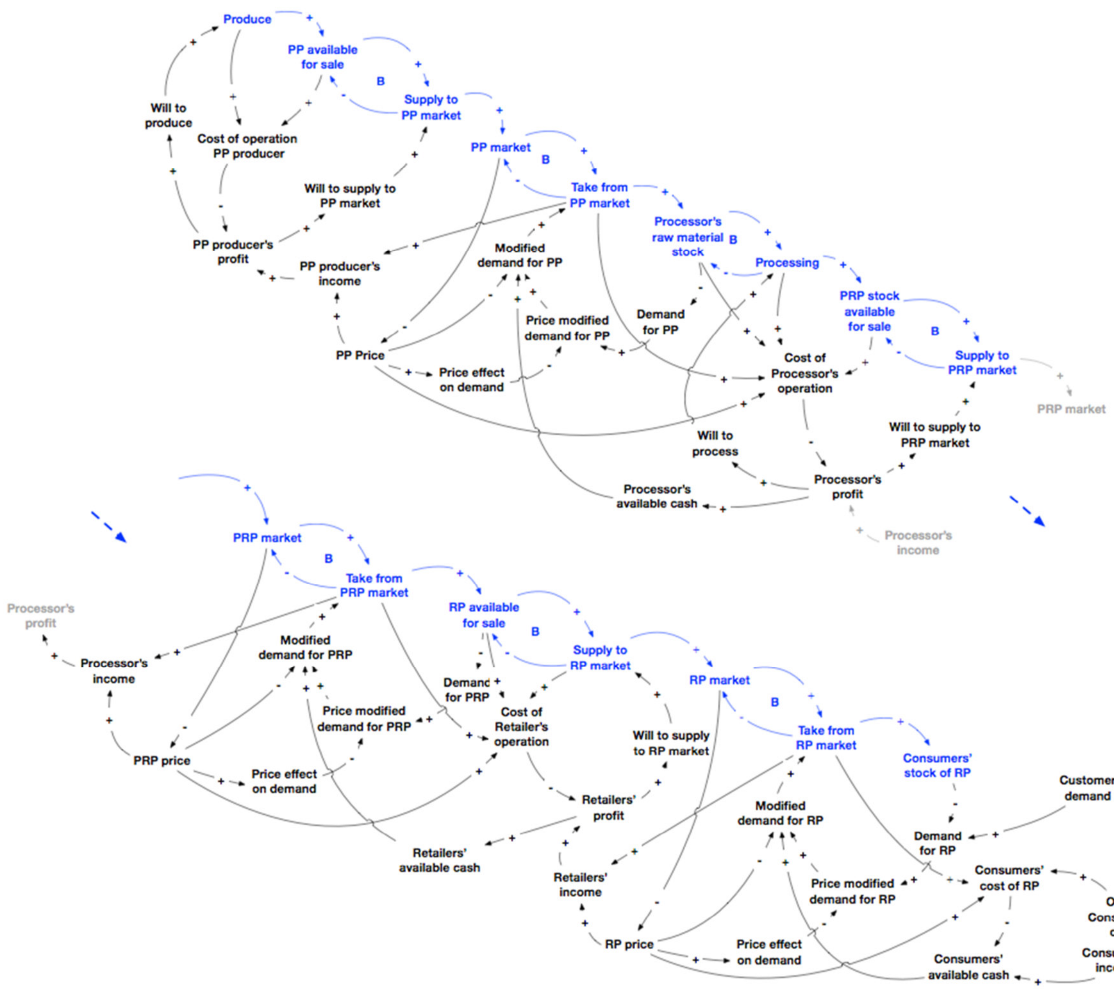

Figure 2 The fully integrated supply-, value- and decision chain. PP= primary product, PRP=processed product, RP=retail product

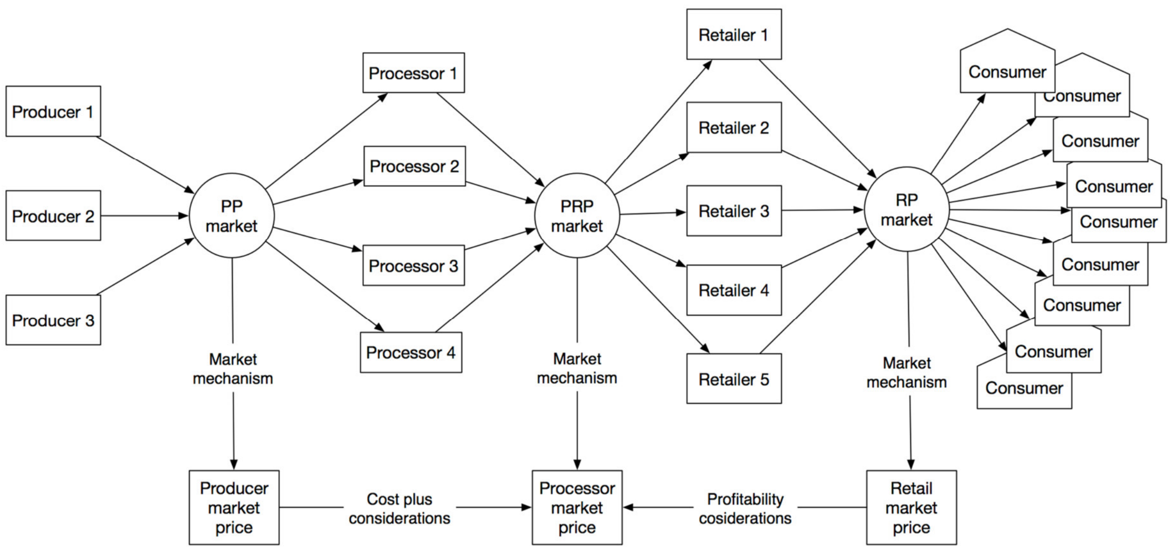

Figure 3 A simplified illustration of the supply chain on an aggregated level with markets between agent groups. The price generated on the macro level is the reference price in micro level business transactions. PP= primary product, PRP=processed product, RP=retail product

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.

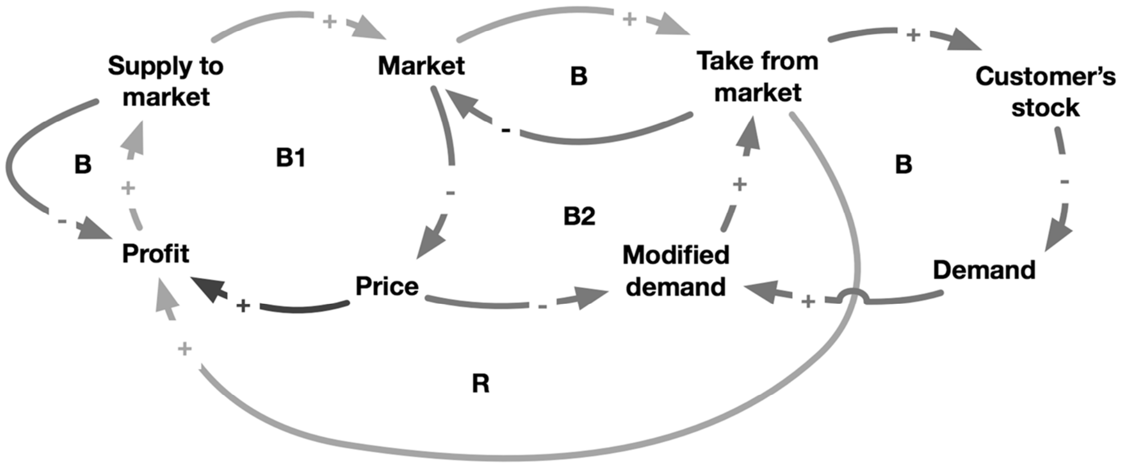

Figure 4 The reinforcing and balancing loops driving and regulating a supply system subject to market dynamics

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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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