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Global Food Safety as a Complex Adaptive System: Key Concepts and Future Prospects

Rounaq Nayak* and Patrick Waterson**

*Food Technology and Innovation Department, Harper Adams University, Newport TF10 8NB, UK

**Human Factors and Complex Systems Group, Loughborough Design School, Loughborough University, Loughborough LE11 3TU, UK

Corresponding author: Rounaq Nayak. Tel: +44 (0)1952 820280. E-mail: RNayak@harper-adams.ac.uk. Address: G43, Jubilee Adams Building, Food Technology and Innovation Department, Harper Adams University, Newport TF10 8NB, Shropshire, UK.

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Abstract

Background

Over the last few decades the food production, distribution and consumption chains have become complex as a result of globalisation and food travelling over large distances. The food supply chain is a multi-layered structure with multiple interactions across and within the hierarchical levels across the entire food system. As unwanted factors and food safety behaviours could lead to global food poisoning catastrophes, it is important to adopt a systems approach to gain a whole-system perspective of the global food system.

Scope and Approach

In this review the importance of adopting a complex systems approach towards the global food system and a possible systems analysis method that would help capture this perspective are described. This study emphasizes the importance of adopting a proactive approach, starting with identifying the similarities between the characteristics of complex systems and the food system and the importance and benefits of adopting a whole system approach in the global food system.

Key Findings and Conclusions

Adopting a complex systems approach to the global food system is of paramount relevance as this would help further understand the interconnectivity of food systems and how multifaceted factors across systemic levels play a major role in achieving food safety. Using a systems analysis model such as the Systems-Theoretic Accident Models and Processes (STAMP) model provides the ability to tackle the limitations of event chain models and analyse the complex interactions among various components in the complex food system. It is the need of the hour to study food systems at micro and macro-levels and develop a model that would have the ability to identify food safety related issues across the global food system.

Key words: Complex systems; Globalisation; Food safety; Food safety system; Systems approach; Human Factors

1. Introduction

Globalisation has led to a world-wide demand for a variety of food products and as a direct consequence, food production, distribution and consumption chains have become distributed, intricate and complex. A combination of population explosion and food scarcity where more than 800 million people remain food insecure (FAO, WFP, & IFAD, 2012), is another reason for the widespread export and import of food across the world. By 2050-2052, it is projected that the global population will reach 8-9 billion people, and at such a point, the dynamics between population, climate and diet would have a more direct effect on the global food systems than what it is today (Lee, 2014; Randers, 2012). A population's diet is determined by a complex interplay of social, economic and technological forces (Schlosser, 2001; Johnston *et al.,* 2014). The food supply chain, from subsistence farmers to multinational food companies, can be viewed as a multifaceted structure with multiple interactions across and within factors distributed across hierarchical levels in the entire system. These intricate levels of interactions are a result of globalization of the agri-food system (Busch, 2004; Inglis, 2016).

Products that were once only locally available are now easily available all over the world (Busch, 1997). This has brought together large populations who lived within defined boundaries by introducing complex governance to deliver sufficient quantities and quality of food (Hueston & McLeod, 2012). Food safety policies help to orient local, regional, national and global food systems. These policies are formed as a result of interactions between a set of stakeholders, some, if not all of who might seek to defend either theirs or their allies' interests (Maetz, 2013a). The degree of influence of each stakeholder depends on their capacity to have an impact on the institutional framework at the regional, national and global levels within which the policies are being formulated. Governments at various levels often tend to make policies in favour of the vast majority of the population that elected them and the private companies that invest in their party (Maetz, 2013b; Pennington, 2003). The other relevant stakeholders are multinational firms whose main objective is to maximise profit. These firms often have a global impact as they operate in several countries at a time. Therefore, they provide fiscal and social benefits to multiple governments and countries (Maetz, 2013b).

Food regulations such as Regulation (EC) No 2073/2005 in the UK (Food Standards Agency, 2005) and the Food Safety Modernization Act (FSMA) in the US (Food and Drug Administration, 2015) make it mandatory for all food businesses to complete microbial testing of their premises as well as of high-risk food products. As a result, there is a tendency to rely solely on microbial analyses (Griffith *et al.*, 2017). Although such reactive preventative methods produce a safe food supply system in the short-run, it is limited in its scope over the medium to long-term. Food poisoning outbreaks are still a global issue; every year, millions of people get ill, thousands require hospitalization and hundreds die from food-related illnesses (Walczak & Reuter, 2002). It was estimated by the World Health Organisation's Foodborne Disease Burden Epidemiology Reference Group that in 2010, there were 582 million reported cases and 251,000 reported deaths associated with 22 different foodborne enteric diseases (WHO FERG group, 2015). The reason for this is the narrow microbiological base on which preventative efforts are based. Processes such as time and temperature control, safe food handling procedures, employee hygiene, cleaning and sanitizing techniques and a Hazard Analysis and Critical Control Point (HACCP) plan or a HACCP-based plan are proven to be effective (Walczak & Reuter, 2002). Despite the existence of reactive approaches, the issue still remains – how to minimize population exposure to foodborne pathogens? Concepts relevant to adopting proactive techniques such as understanding the food system and stakeholders' behaviours and interactions can be helpful in understanding how and why food safety violations occur.

Food systems are quite fragile. Events such as the 1996 *E.coli* O157 outbreak in Scotland (Pennington, 1997), 2009 Godstone Farm *E.coli* O157 outbreak in England (Griffin, 2010), 2011 sprouted foods *E.coli* outbreak in Germany (World Health Organization, 2011) and the 2018 *E.coli* outbreak in the United States of America (Adam Bros. Farming, 2018; Centers for Disease Control and Prevention, 2019) highlight the consequences of such fragility. With food traveling over larger distances in the modern world, food safety related concerns are often raised. This has also led to an increase in the number of factors in the food system that have responsibilities and accountabilities. Due to globalisation of the food industry, it is essential to look at the food system from a global perspective and to identify and address all the flawed factors associated with the food system. Although stricter and more detailed regulations have been established since the above mentioned food poisoning incidents under the assumption that there will be strict compliance, there is a general lack of understanding of compliance and performance variability (Hollnagel, 2009) within the food system.

1.1. Aims and objectives

The overall aim of this paper is to outline the complex systemic properties of the global food system. The specific objectives of the paper are threefold:

1. To outline the properties of a complex system and demonstrate its relevance to the global food system and food safety.

2. To outline the possible effects of globalisation of the food system on food safety behaviours.

3. To illustrate the value of using systems analysis methods to understand interactions between and the functioning of the components of the food system.

In what follows, we first detail the history of globalisation of the food industry followed by a timeline indicating the development of food safety. The primary intention of the timeline is to indicate major developments related to food safety. The timeline also indicates a shift in consumption pattern from immediate consumption to storage and preservation for extending the shelf-life in order to help prevent food poisoning related illnesses and to carry out trade, i.e., export food locally, regionally, nationally and globally. In the later sections of the paper, the properties of a complex system and the relevance of these properties in the current global food system are discussed in great detail. Finally, we discuss a systems and control theory based model, STAMP (System-Theoretic Accident Model and Processes), its properties, general application and its possible applicability to understand the interactions between stakeholders within the food system.

2. Globalisation and the food industry

There have been cascades of changes on a global scale since the latter decades of the twentieth century (Gunderson & Holling, 2002). The factors that played a role in the globalisation of the food industry such as transition from local to global markets and shipping of food products over long distances also played a major role in the development of the concept of food safety by reasons mentioned below (Busch, 1997; Hueston & McLeod, 2012). Globalisation can also have a negative impact on the food industry – e.g., after the 1964 *Salmonella typhi* outbreak in Aberdeen caused by the consumption of canned sliced beef imported from Argentina, not only did tourism in Aberdeen drop, but there was also a reduction in the amount of corned beef consumed in the UK. This led to cattle raisers in countries specialized in exporting beef, such as Paraguay, Kenya and Tanganyika, suffering an economic loss (Pennington, 2003).

Food safety has evolved as a result of various practices carried out by people who interact with food in various forms in various stages of development and operations across the world. All these people have deemed the food they have handled as safe. Hence, food safety is dependent on the more or less predictable behaviour of chemical and biological entities as well as the behaviour of human beings who perform more or less predictable activities to achieve a certain level of food safety that is deemed acceptable by local and global standards. Thus, food safety is a socio-natural process (Busch, 2004).

2.1. Transition from local/regional to global markets

In today's world, food purchased at a store is mostly never entirely locally produced and consumed. Consumers have no idea about how or where the food gets produced and how it is transported from one place to another. Due to the lengthened networks, there is an absence of personal ties between consumers and producers and processors (Busch, 1997). Multinational producers, processors and retailers have deliberately discouraged the social dimensions of exchange. This has forced consumers to pick from the wealth of goods supplied. According to a report by Vasquez-Nicholson in 2015, one of the leading supermarkets in the UK stocks 40,000 product lines, of which 25,000 are food and beverage. Another leading supermarket store in the UK carries about 21,000 food and beverage items (Vasquez-Nicholson, 2015). In a supermarket, the process of retrieving goods involves locating them, placing them in carts, bringing them to checkout counters, placing them on conveyor belts and putting the purchased products in bags (Busch, 1997). This process has not changed much over the last 20 years, the only changes being certain advances in technology such as self-checkout counters and portable scanning machines. Face-to-face relationships exist higher up the food chain, for example, wholesalers always know who their suppliers and customers are. However, when it comes to the extreme ends of the process, relations become impersonal (Busch, 1997). It is also important to acknowledge that locally produced food has become the foci of food self-sufficiency among some consumers (Fang *et al.*, 2018), therefore, it is important to understand local food systems to establish the dynamics of interactions between the various stakeholders of these food systems.

2.2. Industrialization of the food industry and the scale of production

Advances in technology and the aim to improve social organisations have helped increase scale of production (Busch, 1997). The first carload of fruits and vegetables was shipped eastward in 1869 and it was only a decade later that rail service permitted wider marketing areas (Busch, 1997; Levenstein, 1988). This led to the relocation of larger units away from metropolitan areas. Mechanization occurred in four areas in the food system; (1) mechanization of agriculture; (2) mechanization of organic substances; (3) mechanization of meat; and (4) mechanization of growth (e.g., artificial egg fertilization) (Giedion, 1948).

In the late 1800s, the Parris abattoirs of La Villette had an individual stall for each animal where each animal was slaughtered individually, whereas the abattoirs in Chicago were fully automated (Busch, 1997; Giedion, 1948). The scale of production has increased all over the world. Tomatoes were once a garden crop, but are now grown in large hectares of lands in the Netherlands and in the US (United States Department of Agriculture Economic Research Service, 2016). Kiwis which were grown in China as lowly berries are now grown on farms in New Zealand, Italy and the United States of America (Busch, 1997).

2.3. Modernisation of production practices and processing technologies

A rise in population has led to an increase in the demand for food (Hueston & McLeod, 2012; Kirezieva *et al.*, 2015; Reiher, 2012; WWF, 2016). Chickens that were once raised as pin money by American farm women are now bred everywhere with thousands of birds squeezed into small cages. This is also the case with cows and hogs (Busch, 1997). In order to feed these animals and birds, feed containing exotic nutrients were imported from all over the world in order to maximise growth and feed efficiency while trying to minimise cost. Addition of exotic nutrients could lead to new disease vectors. This is the cause of Bovine Spongiform Encephalopathy (Busch, 1997) which led to a large crisis between 1986 and 1996 despite the best efforts of regulators (Cassano-Piche *et al.*, 2006).

Along with the modernisation of farm practices, there has also been a development in the processing industry. Food processing is a post-harvest activity that adds value to the agricultural product (Wilkinson, 2004). The sudden boom of the food processing industry in the 1990s was caused by foreign direct investment (FDI) and this led to an increased revenue and employment generation and development of new knowledge and technology (Wilkinson, 2004). Canning was one of the first 'developments' in the food processing industry. This enabled the mobility of a wide range of foods to different parts of the world. New forms of food were also created because of this development (e.g., the invention of condensed soups by Campbell's Soup Company) (Busch, 1997; Levenstein, 1988). According to a report from the United States Department of Agriculture Economic Research Service (2016), 59% of the tomato consumption in the US was canned.

2.4. Shipping of a variety of products over long distances

There are two issues with shipping food over long distances: (1) the distance and (2) the food product shipped. If a ship does not have the required conditions, it is easy for the food product to spoil. For example, during the 1880s in the US, beef was shipped from stockyards in Chicago to slaughterhouses in New York and by the time the journey was completed, most animals would lose weight or die (Busch, 1997). During this period, butchers were aware of diseases related to cattle. Once refrigerated cars were invented and regulations were amended such that trained food inspectors inspected cattle, these butchers began getting lesser information.

2.5. Shift from supply-driven to demand-driven economies

Until the 20th century, countries had supply-driven economies where they followed a model of food self-sufficiency to ensure adequate domestic supplies of basic feedstuffs. This model permitted an increased supply, thereby reducing the costs of food. Countries that produced in excess used export markets and food aid programs (Hueston & McLeod, 2012). However, since the 20th century, there has been a rise in consumer demand for food. A rise in demand for chicken led to the development of the broiler industry. Certain parts of the world consume only white meat where chicken feet is regarded as a waste product whereas in other parts of the world, chicken feet and dark meat are considered a delicacy. Global food trade has provided suppliers the opportunity to supply all parts of the animals they breed whether or not there is any domestic demand. The world enjoys relatively inexpensive food as commodities and specialized products can be marketed worldwide (Hueston & McLeod, 2012).

3. Impact of globalization on food safety

As mentioned in Section 2, factors that played a role in globalization also helped in strengthening the conceptual framework required for food safety. Since food could not be shipped over long distances or stored for large periods of time, investment was made in the food preservation sector. The initial methods of food preservation involved drying. This was a method known even in the ancient times. Fermentation and pasteurization were the next developments in food preservation. The latter was applied to wine in China (Hueston & McLeod, 2012).

Canning and freezing helped revolutionize preservation techniques as they helped store and transport food in an almost fresh state. Since Napoleon's army had bouts of food poisoning during their conquests, he offered a reward for devising a method to help preserve food for a longer duration (Busch, 1997; Jay, 1992). In 1809, Appert succeeded in preserving meats in glass bottles that had been kept in boiling water for varying amounts of time. Thus began the technique of canning which still plays an important role in food storage today. The concept of freezing developed from storage in the Northern parts of the world where ice from frozen lakes was stored for use later in the year (Hueston & McLeod, 2012). Initially, slow freezing was carried out and this changed the texture and taste of food. Flash freezing was then discovered and this helped store food without changing its texture, colour or taste (Busch, 1997). The first refrigerated ship was the SS Dunedin in 1882 and it revolutionized the meat and dairy industries in Australia and New Zealand (Hueston & McLeod, 2012). Advances were also made in plant and animal disease control; pigs were moved indoors to decrease disease exposure and to enhance efficiency.

Food safety embraces all the steps in the food production process (processing, preparation and handling of food) and ensures that it is safe to eat. Poor understanding of the importance of food safety and hygiene has in the past contributed to a number of food poisoning outbreaks and at times, deaths (e.g. 2005 *E.coli* O157 Outbreak in Wales). Reports and studies carried out on these outbreaks identified a wide range of factors contributing to these accidents. Chief amongst these were the relaxed attitudes towards food safety, lack of adequate training provision and many other such human factors related errors (Pennington, 2003). The 2008 Maple Leaf Foods *Listeria* outbreak in Canada and the 2011 *E.coli* O104:H4 outbreak in Europe for example, are often seen as indicative of poor regard for hygiene and safety standards amongst food business operators (European Food Safety Authority, 2011; Jespersen & Huffman, 2014; Manning, 2017). The 2009 Godstone Farm *E.*coli O157 outbreak is seen as a substantial failure of health protection and the flaws of a complex regulatory structure were identified as a major contributing factor (Griffith *et al.*, 2010). This outbreak resulted in 93 cases, most of which were children. The food safety chain is only as strong as its weakest link and the responsibility lies not only with the producers and processors of food but also the governments and consumers (Griffith, 2006). Table 1 highlights the development of the food law in the UK – the purpose of this table is to highlight that regulations alone are not sufficient to ensure food safety and hygiene. It is important for all the stakeholders involved in the food system to work together to ensure food safety and hygiene.

Table 1 about here

4. Complex systems: key concepts

One of the most apt definitions for complex systems with regards to the food system is “A system comprised of a (usually large) number of (usually strongly) interacting entities, processes, or agents, the understanding of which requires the development, or the use of, new scientific tools, nonlinear models, out of equilibrium descriptions and computer simulations” (Rocha, 1999). A complex system contains large number of elements (Cilliers, 1998) and is one in which there are more possibilities than can be actualised (Luhmann, 1985). A complex system might appear to be pseudo-simple (e.g., a leaf) and a simple system might appear to be pseudo-complex (e.g., a combustion engine); "complexity is not located at a specific, identifiable site in a system" (Cilliers, 1998, p. 2). In his book "When Food Kills: BSE *E.coli* and Disaster Science" (2003), Pennington argues for the need to adopt a systems approach (with systems thinking) to ensure food safety - he uses the concept of a systems based approach to compare food poisoning outbreaks to the Chernobyl, Piper Alpha and railway accidents in Ireland and Britain (Nayak & Waterson, 2016).

4.1. Systems thinking

Systems thinking is a way of seeing and talking about reality as it helps us in understanding systems better. It is hence a perspective that uses unique vocabulary for describing systemic behaviour by using tools that help in visually capturing and communicating about systems (Kim, 1999). Systems thinking differs from the traditional reductionist, analytic view as it does not look for "root causes" (Salmon *et al*, 2016). A systemic perspective is an important complement to analytics thinking as it explains how a system works, the role humans play in these systems and it lets us function more effectively and proactively (Kim, 1999).

4.1.1. System of systems approach (SoS)

Most complex systems focus on performance optimization, robustness and reliability among an emerging group of heterogeneous systems to achieve their goals. Complex systems have a number of concurrent and distributed constituents/actors in a hierarchical order which on their own, are also complex. There needs to be a synergistic effect between the independent systems to achieve the desired overall system goal (Jamshidi, 2009; Kotov, 1997). System of systems can be defined as a "supersystem comprised of other elements" (Jamshidi, 2009) which work in a cooperative manner and interact with each other to achieve a common goal. This approach focuses on the total-system performance even when there is a change in only one or a few of its parts as certain systemic properties can only be treated adequately form a holistic point of view. A system of systems approach helps to effectively implement and analyse large, complex, independent and heterogeneous systems which either work in or are made to work in a cooperative manner (Ackoff, 1971; Jamshidi, 2009).

There is a possibility of the total system not achieving its intended goals even if every part of an imperfectly organised system performs as well as possible relative to its individual objectives (Ackoff, 1971). For example, in the food system, although front-line employees might meet their targets (production of a certain amount of food per day) and management might meet their targets (generating a certain amount of profit), the food system might not achieve all its intended goals (e.g., providing safe and an adequate amount of food to a diverse range of people across the country/globe). It is important to note that the collective goal of the system and all its components is always the same; however, the components might also have additional targets/goals which would eventually lead to the system achieving its end target. Only if subsystems work coherently, will the system function effectively (Ackoff, 1971). The SoS concept already plays a major role in military and engineering applications, however, it is new to the sociotechnical systems world. The emergence of this concept indicates an increase in the complexity of the sociotechnical environment and foreshadows a major evolutionary shift.

4.2. Characteristics of complex systems

Since the food system is tightly interwoven globally and the pace is increasing continuously, it is important to be system-wise. All complex systems share several defining characteristics. Figure 1 illustrates a framework of the functioning of the food system using a human factors approach. Human factors emphasizes interactions between people and their environment contributing to the performance, safety (food and employee in this framework), quality of work life, and the goods and services produced (P. Carayon et al., 2006). This framework has been developed to characterize the many interactions between people and their environment in a concise and coherent manner, and illustrate their influence on performance variability of the various stakeholders of the food system. In the work system framework, *people* (shop-floor employees, line managers, engineers, organisational management, or consumers) perform a range of *tasks* using a variety of *tools and technology*. All these tasks are carried out within a certain *physical environment* and under specific *organisational conditions* (policies, guidelines, and standard operating procedures). All the five components of this work system interact and influence each other. These interactions produce different outcomes such as: (a) variable performance by employees; (b) variable quality of food products; and (c) variable quality of work life.

These outcomes are achieved through the occurrences of multiple processes either carried out by: (a) individual shop-floor employees; (b) production lines/teams; (c) consumers while and after purchasing food products. Since this is a descriptive framework, there is no specific guidance as to the critical elements. Further, there is no detailed discussion of processes, guidance for system redesign and improvement of food safety. This framework is an adaptation of the SEIPS framework from the healthcare industry (P. Carayon et al., 2006).

Figure 1 about here

4.2.1. Purpose

All complex systems have a purpose. It is this purpose that defines the system as a discrete entity and provides it with integrity to hold it together. It is a property of the entire system and not of its parts (Kim, 1999). For example, the purpose of the food supply system is to provide consumers with food that is safe to consume. This 'purpose' is the property of the entire food supply system and not just of its parts such as the farmers or retailers. In line with the purpose of the system, all complex systems have a history that leads to its constant evolution as well as its present behaviours (Cilliers, 1998).

4.2.2. Efficient functioning and presence of all parts of the system for the purpose to be achieved

A large number of elements are required for a system to be complex, else, even grains of sand on a beach would constitute a complex system. However, the number of elements alone does not determine whether a system is a complex one or not. Complex systems are interwoven globally and have complex interactions (Cilliers, 1998; Kirlik, 2011; Vicente & Christoffersen, 2006). It is not possible to have a few of its components missing. Elements within a system interact dynamically and these interactions could either be physical or involve exchange of information (Cilliers, 1998).

There is a critical difference between a collection and a system. A system has complex interactions across various systemic levels whereas a collection has no interactions

(Kim, 1999). Hence, taking a part out of a collection would not affect the nature of the collection, but taking a part out of a system or if a part does not function efficiently enough, it could adversely affect the entire system (Rasmussen, 1997). Since sociotechnical systems are dynamic in nature, an accident would develop over time due to normal efforts of individuals in a system and a normal variation in somebody's behaviour. Such variation could lead to accidents (Rasmussen, 1997). Interactions within a complex system are usually of a fairly short range. Although possible, long range interaction is not practical due to constraints. As the interactions are rich in nature (Cilliers, 1998), they still have a wide-ranging influence on the system and can be covered in a few steps. Therefore, these influences can be enhanced, suppressed and altered in a number of ways. Elements in a systemic level are therefore ignorant of the behaviour of the entire complex system and only respond to information that is available locally. If every element was aware of the behaviour of the entire system, it would no more be a complex system, but a complex element (Bar-Yam, 2012a).

4.2.3. Order of arrangement

Complex systems operate under non-equilibrium conditions and hence require constant flow of energy and information to maintain the organisation of the system in order to ensure its survival. Elements in a complex system interact with each other and thus, have the ability to influence to each other as well as the system (Cilliers, 1998). If the parts/elements of a collection can be arranged in any order, then they are only a part of a collection (Kim, 1999; Ottino, 2004a). The order in which the parts of a complex system are arranged affects the performance of the system. From Rasmussen's framework, it can be noted that a complex system often has multiple systemic levels - government, regulatory bodies, local area government, technical and operational management, physical processes and equipment and surroundings (Svedung & Rasmussen, 2002) and the same applies to the food system as seen in Figures 2 and 3 in the study conducted by Nayak and Waterson (2016). If the factors that make up a food system were to be rearranged, the links between them would be broken and hence would lead to a chaos. Interactions are primarily but not exclusively between neighbouring systemic levels or elements within the same systemic level (Cilliers, 1998).

4.2.4. Communication

Communication, which is the exchange of information and the transmission of meaning, forms the basis of a social system. It permits the input of human energy. The set tasks can only be completed if there is effective communication between people within and between subsystems. Exertion of influence, cooperation, social imitation and leadership are some of the social interactions that are often subsumed under communication (Katz & Kahn, 1978a). Systems that have a full and free flow of information are considered to be healthy. The power of communication is such that it has the ability to reveal as well as eliminate problems. However, miscommunication can also lead to obscuring and confusing existing problems. Effective communication only occurs when it is a two-way process (Nayak & Waterson, 2017), i.e., the orator as well as the receiver have performed their function. Complications of effective communication are best seen at play in large organisations where there is lesser opportunity than in small groups to get signals from those down the line as interactions in complex systems occur over smaller ranges (Cilliers, 1998). A similar problem also occurs in bottom-up communication. In global systems, communication is an even bigger problem due to language barriers (e.g., messages often meant to be orders are communicated merely as information).

4.2.4.1. Direction of communication flow

In any system, it is quite important to be aware of the direction of information flow, i.e., top-down, horizontal and bottom-up. It is important to have a good combination of all these types of communication as it helps keep the entire system connected (Gilmore, 2007). For example, in an organisation, the department chief knows about all the division heads and their respective divisions, whereas, each department chief only knows about his or her own division (Katz & Kahn, 1978a). Similarly, the department chief will not be aware of the problems and the real-world problems that arise in the lower levels of the hierarchical chain.

4.2.4.1.1. Top-down communication

The direction of this type of communication is from superior to subordinate and is the primary interpersonal relationship within an organisation. This type of communication is so important that it has the ability to determine how individuals identify with the organisation, the individual’s job satisfaction and commitment (Long & Vaughan, 2007). There are 5 types of top-down communication (Katz & Kahn, 1978a):

1. Job instructions - Specific task directives:

This type of communication is given priority in industrial, healthcare and military organisations. Direct orders are communicated from superiors in the form of training session, training manuals and written directives.

2. Job rationale - Information produced to help better understand the task at hand and its relation to other tasks:

This type of communication is designed to provide employees with a full understanding of the job and its possible links to other jobs within the same subsystem.

3. Details on organisational procedures and practices

In addition to the job description, employees also have obligations and privileges as a member of the system (e.g., benefits, vacations, sick leave, rewards and sanctions). These details complete the descriptions of the role requirements of the organisational member.

4. Feedback – Providing subordinates with performance feedback

Top-down feedback though often neglected, is an important aspect of healthy systems. Providing such feedback is a form of motivation for employees. It is also important to note that providing feedback to employees is not the only solution to the breakdown of a complex system. It is often quite tedious to provide individual employees a performance report.

5. Indoctrination of system and organisational goals – Inculcating a sense of mission by providing information of an ideological character

It is important for an organisation to instil its culture and goals in its employees. Similarly, it is also important for a system to have its own goals and to instil these in all its actors across the subsystems. For example, an employee working on the shop-floor at a food manufacturing plant who knows why he/she is following certain protocols is more certain to follow those protocols (e.g., hand-washing) and thus, it is much easier for him/her to develop an ideological commitment to the food system. The advantages of giving people fuller information on job understanding are twofold: (1) higher possibility of them carrying out their tasks more efficiently and (2) having an understanding of their job and its relation to the subsystem would increase their ability to identify with organisational goals.

4.2.4.1.2. Horizontal communication

This form of communication entails passing of information between people within the same hierarchical level and is one of the most difficult forms of communication. Employees receive instruction from the person immediately above them in the hierarchical order and would hence communicate with associates only for task coordination that are specified by rules. It is important to have the right amount of horizontal communication as too much of it could lead to detraction from maximum efficiency (Katz & Kahn, 1978a).

4.2.4.1.3. Stability through feedback mechanisms

Feedback is the transmission and return of information. This type of communication is usually from subordinates to their superiors and typically focuses on information about the subordinates themselves, their colleagues and either work-related or personal problems. Feedback can also include information about tasks to accomplish or organisational policies and practices (Long & Vaughan, 2007). This can either be positive (enhancing/stimulating) or negative (detracting/inhibiting). Both of these types of feedback are necessary (Cilliers, 1998; Johnson, 2001b) to help in the continuous development of the system. The importance of feedback is that it informs the system about how it is performing relative to the desired state (Johnson, 2001b; Kim, 1999). Three factors need to be addressed to ensure that a complex system has a proactive closed feedback loop: (1) identification of the decision-makers and actors involved in the control of productive processes; (2) definition of the work-space under their control; and (3) defined structure of the distributed control system (Rasmussen & Svedung, 2000).

4.2.5. Holism

An organisation is a subsystem of one or more larger systems (Katz & Kahn, 1978b). The concept of holism involves putting the whole before its parts. Therefore, it does not involve breaking an organisation into parts and addressing local issues, but involves looking at the bigger picture, i.e., the entire system/organisation. In the modern world, food business operators and employees face increasing complexity, change and diversity (Bertalanffy, 1995; Jackson, 2006). Personnel higher up the hierarchical level are expected to manage and provide solutions to problems and issues that might arise in the level(s) whose functioning they overlook. Sometimes, the solutions that they offer and the support provided to them rarely seem to work. Often, these solutions that are offered are termed as 'simple solutions' (Jackson, 2006). The error in this approach lies in the desire to search for simple solutions that address the specific problem and not the other linked factors that either led to that particular problem or to new problems that could arise from this issue. This is often the result of either ignoring or not being aware of interacting factors. Therefore, holism and a practical approach are required to help personnel address complex problem situations' (Jackson, 2006).

Although a system consists of multiple subordinate systems, summing up the behaviour of the whole from the isolated parts is not a reliable method. Interactions between the various subordinated systems and the systems which are super-ordinated to them need to be taken into account to understand the behaviour of the parts (Bertalanffy, 1995). While studying a system, it is important to investigate the position of the various subsystems in the community and in the system as a whole prior. Adopting a holistic approach would help all businesses address broad, strategic and systemic issues as well as narrow, technical ones (Katz & Kahn, 1978b).

4.2.6. Emergence

"Emergence refers to the relationship between the details and the larger view" (Bar-Yam, 2012, p. 4). All natural systems are complex adaptive systems (Gunderson & Holling, 2002). Interactions in complex systems occur in randomised directions (Bar-Yam, 2004; Morowitz, 2002), i.e., they are not specifically either top-down, horizontal or bottom-up (Katz & Kahn, 1978a). From these interactions, patterns emerge and these patterns define the behaviour of the components/agents within the system and the behaviour of the whole system. Emergent behaviour relies on the concept of actors in the lower-level of the sociotechnical system leading to higher-level sophistication. Systems are not considered to be emergent if local interactions do not lead to any discernible behaviour higher up the hierarchical chain (Johnson, 2001a). The emergent property of complex systems makes them self-organizing and adaptive

(Ottino, 2004b). This property also enables a system to possess social organisation without the need for constant direction from actors higher up the hierarchical chain.

4.2.7. Interdependence

Interdependence is defined as “the existence of relationships between the behaviour of parts of a system” (Bar-Yam, 2012, p. 2). Complex systems are open systems whose parts are related to its whole and to its environment. This nature of complex systems is called interdependence as all the subsystems affect and are affected by each other. The ‘interdependence’ property of a complex system has a link with the ‘communication’ property as the latter leads to the former. The impact of interdependence is such that it has a bearing on the entire organisation (Bar-Yam, 2012; Goldhaber, 1990). For example, a line manager of a biscuit manufacturing plant taking a decision that work can continue despite there being a broken oven, resulting in under-baked biscuits, could have ramifications throughout the organisation such as significant economic impacts, unhappy superiors and subordinates losing faith in their superiors or loss of jobs. However, if used wisely, this property could also bear fruit. For example, effective and regular communication throughout the food system would not only keep the actors at the top of the hierarchical chain well informed, but would also keep the subordinates satisfied and happy, leading to a positive food safety culture and a reduction in the number of food poisoning related outbreaks.

4.2.8. The law of requisite variety

For a system to achieve maximum stability, the number of states of its control mechanism must be greater than or equal to the number of states in the system that is being controlled. A complex system with good stability only has the ability to adapt to a certain number of stimuli (Ottino, 2004b) – Ashby’s law of requisite variety states that ‘only variety can destroy variety’ (Ashby, 1999, p. 207). A system would only be able to survive as long as the range of responses it marshals (while adapting to the tensions imposed on it) successfully matches the range of situations (threats and opportunities) confronting it. When living systems are involved in such complex systems, behavioural responses are also included. Therefore, responses in complex systems are dependent on the type of stimuli provided and are a combination of behaviour and cognition. Responses of complex systems also vary based on their environments (Boisot & McKelvey, 2011a).

Most complex systems respond to representations of their environment and not to the actual environment (Boisot & McKelvey, 2011b). These representations of environments are complex schemas (Gell-Mann, 2002), i.e., they are structured descriptions of an objective external world that neither have too few or too many degrees of freedom. It is important that a system builds schemas in ways that distinguish meaningful information from meaningless stimuli. What constitutes information or noise is defined by the system's expectations and judgements about what is important (Boisot & McKelvey, 2011b; Gell-Mann, 2002). The characteristics of a complex system are summarized in Table 2.

Table 2 about here

5. Applying a complex systems perspective to food safety

In order to understand food systems and their food safety cultures better, they need to be analysed from two perspectives: (1) 'micro-perspective' and (2) 'macro-perspective'. Factors within the micro-perspective influence the functioning and behaviours of national level food systems. Whereas, factors within the macro-perspective influence the functioning and behaviours of the global food system. The food system is a complex sociotechnical system from both the perspectives (macro and micro) – and hence, needs to be analysed and understood in detail to address negative food safety cultures.

5.1. Micro (national) perspective

The micro-perspective helps to understand the food system within a country. When seen from this perspective, a range of factors and stakeholders play a key role in providing food safe for consumption (Pennington, 2003), which is the one of the purposes of the food system at the micro-level. As a system of system, the food system encompasses a wide range of processes - from manufacturing of raw materials to consumption of the finished food product by consumers. All these processes have food safety cultures of their own and being a complex system, influence the quality of food available for consumers and food safety. Thus, the complexity of the food system influences the food safety. At the micro-level, food system globally consists of the following systemic levels: (1) national government and regulatory bodies; (2) organisational management (upper-middle-lower); and (3) front-line actors (shop floor staff and the physical work place). Apart from this, there is also an additional level that plays an active role in national food safety culture – the ‘external level’; this consists of societal factors such as market forces, media and societal values and priorities, historic events and global politics (Nayak & Waterson, 2016; Rasmussen, 1997). Table 3 highlights the components of the food system across various systemic levels in the UK and the US, and the roles they currently play. It also highlights similarities in the structures of food systems at the national level across two major economic superpowers. Finally, Table 3 brings to light all the activities and resources that go into production, distribution and consumption; the drivers and outcomes of these processes; and the complex extensive relationships between the system participants and components (Neff & Lawrence, 2014).

Table 3 about here

Every country has a mix of large-scale food businesses as well as medium, small and micro-scale food businesses. Although disregard for hygiene practices is usually attributed to individuals, it is often related to the prevailing organisational culture (Clayton & Griffith, 2008; Griffith *et. al.*, 2010). A high level of trust within as well as between organisational levels as well as systemic levels is important to have a positive food safety culture. One of the factors that leads to development of trust and understanding in the food system at the micro-level is open and free flow of information across the system (Pennington, 2003), without which, there is an increased risk of food poisoning outbreaks (Nayak & Waterson, 2016; Pennington, 2009; Pennington, 1997). Behaviours at the lower-levels of the sociotechnical system lead to emergence in higher level sophistication. This is also true vice-versa as this is one of the factors that define employees’ job satisfaction. A negligent safety culture affects the behaviours of people across every systemic level in a complex system (Stanwell-Smith, 2013).

5.2. Macro (global) perspective

The best example to highlight the complexity of the current food supply chain is that of a cheeseburger. Researchers at the University of Minnesota mapped the global food supply chain of cheeseburgers produced at a large fast food chain. A cheeseburger contains more than 50 ingredients imported from countries in every continent except the Arctic (Hueston & McLeod, 2012). Food supplies move all over the world and as a result food-processing supplies move globally. These include processing equipment, packaging and chemicals such as disinfectants and preservatives. Agricultural inputs such as feed, fertilizer, vaccines, pharmaceuticals, harvesting and planting equipment also move worldwide (Hueston & McLeod, 2012).

A single food component (e.g., bread) contains ingredients that have travelled from all parts of the world, and multiple food components make up a food product (e.g., bread, cheese, meat, lettuce, ketchup together make a cheeseburger). Thus, it is imperative to understand and analyse the scale of stakeholders involved and the complexity of the relationships between the system components of the global food system in order to achieve food safety. The food miles (Pirog & Benjamin, 2003) described above also highlight the need for smooth, efficient and open top-down, bottom-up and horizontal communications for the food system at the macro-level to progress without major glitches.

At the macro-level too, the food system is a system of systems - government regulatory systems, private sector initiatives, educational efforts and consumer actions are a part of the food system. Food systems are linked to food safety and contamination can occur at any point in this complex system. There are an increasing number of food safety related controversies at a transnational level (Lien, 2004) due to the scale and complexities of food systems in the modern world (Ercsey-Ravasz *et al.*, 2012). Hence, it is important to have adequate and adaptive prevention and control strategies in place. Global consumers are vulnerable to changes in regulations, shifts in practices and routines that occur in any part of the world (Lien, 2004). The more complex a system gets, higher are the chances for things to go wrong, and the larger the scale of the operation, the more people are likely to get affected. The food system is a particularly high risk industry as consumers range from new born babies to the elderly, and a host of other immunocompromised population (Food Standards Agency, 2012; Jespersen *et al.,* 2016; Powell *et al.,* 2011; Whaetherill, 2009). Thus, the stakes are high in the event of a food poisoning outbreak.

The food industry comprises of various systemic levels (e.g., Board of Directors; upper, middle and lower management; and front-line employees). The structure of the national food system, much like many other systems, adheres to Rasmussen's socio-technical systems framework (Nayak & Waterson, 2016). These systemic levels have been referred to as subsystems by authors such as Hueston and McLeod (2012). Due to the short-range complex interactions across and between various systemic levels as highlighted in Nayak and Waterson (2016) and the holistic and interdependent nature of the food system, it is not possible to predict the properties if each systemic level when looked at in isolation. However, if systemic behaviour is understood, it is possible to anticipate behaviour and work with systems rather than being controlled by them (Kim, 1999). Behaviours at the lower levels of the sociotechnical systems also lead to emergent behaviours higher up the hierarchical chain.

Hueston and McLeod (2012) state that food systems can be called as adaptive systems as they have no boundaries, i.e., faulty individual actions can affect the entire food system and thus affect food production as well as consumption. However, it is imperative to keep in mind that every system has a boundary of acceptable behaviour (see Figure 2) to which behaviour will migrate to under the presence of strong gradients (Ashby, 1999; Rasmussen, 1997). It is also important to note that complex systems also have a memory (Hueston & McLeod, 2012; Nayak & Waterson, 2017) where present behaviour is affected by prior behaviour – hence, past successes as well as failures influence organisational behaviour.

Figure 2 about here

However, it is not possible to predict the overall behaviour of the food system based on the behaviour of individual elements (Cilliers, 1998). An example of this is the 2005 *E.coli* O157 Outbreak in South Wales. Faulty auditing by food inspectors (Government Level) led to lack of regard for hygiene practices at the Organisational level, which in-turn led to there being no protocol for cleaning leading to inadequate cleaning of equipment which led to cross-contamination (Nayak & Waterson, 2016). Another example is the 2012 *E.coli* O157 Outbreak in Canada where the inadequate provision of food safety training by the management led to the absence of product recall protocols. This in turn led to widespread confusion and panic when the first few incidents occurred leading to delays and widespread consequences on public health as well as the organisation (Jespersen *et al.,* 2017). These examples highlight the fact that the food system is non-linear, and a small perturbation may or may not have a large effect. However, being a high-risk industry, it would be risky and possibly catastrophic to take this chance, especially on a global scale.

Since food systems are dynamic and interdependent, it is not possible to have one system that meets all needs. However, as food systems are complex systems, even a small positive change would positively alter the entire system of systems. A relevant model that illustrates the various factors influencing performance and an effective complex system design is the 'onion model' by Wilson and Sharples (2015). This model applies a holistic approach to understand complex interacting systems and subsystems that involve people. It is important to apply the right approach instead of applying the right type of knowledge (Waterson & Catchpole, 2015). Table 4 highlights similarities in the gaps across various national food safety systems citing examples from the UK, the US and the European Union (EU). It is necessary to develop a model that would help identify the links between these factors in order to address issues related to global food safety.

Table 4 about here

6. Systems analysis of the global food systems using the STAMP methodology

The STAMP (System-Theoretic Accident Model and Processes) accident analysis methodology is underpinned by systems and control theory (Salmon *et al.*, 2016) rather than the traditional reliability theory (Leveson, 2015). Systems theory is an effective method to analyse accidents, particularly system accidents (Leveson, 2004; Rasmussen, 1997). According to Leveson (2004), accidents are either a result of inadequate control or inadequate enforcement of safety-related constraints on the development, design and operation of the system. "… accidents occur when external disturbances, component failures or dysfunctional interactions among system components are not adequately handled by the control system …" (Leveson, 2004, p. 250). In the food safety context for example, the model might suggest that one of the factors that could lead food poisoning outbreaks is when controls such as mandatory internal Hazard Analysis and Critical Control Points (HACCP) audits are not carried out diligently, thus failing to identify faults, rectify and report them.

STAMP views safety as a manageable control related incident if a well-designed control structure is in place. The goal of this control structure must be to enforce constraints on actors within the system. The STAMP method helps analysts identify the existing types of controls in a system/complex system and their failure points (Leveson, 2004; Salmon *et al.*, 2016). A generic structure of a STAMP model is presented in Figure 3 (Leveson, 2004). Most accident and system analysis models define safety management in terms of preventing component failure events; however, STAMP defines safety management as a "continuous control task to impose the constraints necessary to limit system behaviour to safe changes and adaptations" (Leveson, 2004, p. 251). According to this model, accidents are to be understood by identifying controls and analysing the reasons behind these controls not being effective or adequate enough to prevent or detect maladaptive changes and enforce the safety constraints in place. Hence, violated safety constraints also need to be identified. Constraints, control loops, process models and levels of control are the basic concepts in STAMP (Leveson, 2004).

Figure 3 about here

6.1. Basic concepts of STAMP

6.1.1. Role of constraints

Mariam-Webster dictionary (2017) defines constraints as a limitation or a restriction of performance of a specific action. Control is always associated with constraints, especially in systems theory. Instead of viewing accidents as the end result of a series of events, in the STAMP model, it is viewed as the result of a lack of constraints imposed on the system design and on operations across the various socio-technical levels. In systems theory, safety is viewed as an emergent property that arises when the components of a system interact effectively within an environment. These emergent properties are controlled and enforced by a set of constraints (control laws). Accidents occur due to a lack of appropriate constraints on the interactions (Leveson, 2004).

As an example, one of the unsafe behaviours in the 2011 listeriosis in Colorado, USA was the failure to use the correct equipment. The farm management team was legally obliged to audit employee work practices and provide them with regular training. The farm was also obliged to comply with regulations enforced by the US Food and Drug Administration (U.S. Food and Drug Administration, 2011). However, poorly designed food safety regulations and a significant delay in implementing the Food Safety Modernization Act led to an inadequate enforcement of constraints such as regular food safety inspections and facility design requirements. Similarly, several questions need to be answered to further establish why the employees used incorrect equipment - why was there a delay in implementing the new Act?; did the government not consider the implications of delaying the "implementation" phase of the new Act?; was the farm management not knowledgeable enough to understand the risks (health as well as financial) associated with disregard for hygiene and cleanliness in a food business, and not providing adequate information and guidance to employees? Such an approach allows one to reconsider the complexity of the food system such as the politicizing food safety regulations, the working structure of food safety regulatory bodies and the impact each they have on national/transnational food safety and food business policies and practices. It is important to identify all the constraints prior to designing the safety process in the system; these constraints also include social and organisational aspects of the system.

6.1.2. Control loops and process models

In systems theory, open systems are defined as interrelated components that are kept in a state of dynamic equilibrium through feedback loops of information and control. Complex systems are constituted by intricate sets of non-linear relationships and feedback loops which lead to whole system analysis becoming extremely complicated

(Cilliers, 1998; Leveson, 2004; Ottino, 2004b) unless there is a suitable model to do so. Only if a system's overall performance is controlled will it be able to produce the desired outcome while satisfying safety and quality constraints (Leveson, 2004). To possess control over a system, four conditions need to be met (Ashby, 1999): (1) the controller must have goals and objectives; (2) the controller must be able to affect the state of the system; (3) the controller must be or contain a model of the system; and (4) the controller must be able to ascertain the state of the system.

Controllers working within the system must have a mental model of the level of the hierarchical system of which they are a part and the relationships among system variables, the current state of the system variables and ways in which the process can change state. This helps controllers determine the control actions required and these are communicated back in the form of feedback. Accidents can occur if controllers form inaccuracies in the mental model (Leveson, 2004). In the 1996 *E.coli* O157 outbreak in Scotland employees working at the organisational level had no idea about who to report to in the event of disturbances in the food processing process. Also, as there were no documented systems in place, they were unaware of the current condition of the system variables. Most of the employees were not trained to handle food and hence they had no idea about how the process could change state (Nayak & Waterson, 2016). These were few of the major factors that led to the outbreak. If the entire food system is looked at, there are multiple human as well as automated controllers; however, the number of human controllers is greater in the food system.

6.1.3. Socio-technical levels of control

In systems theory, systems are viewed as hierarchical structures with systemic levels where each of these levels impose constraints on the activity in the level beneath it (Checkland, 1981; Leveson, 2004). There is also a possibility of there being constraints across one systemic level and this needs to be further investigated, especially in the food system. Constraints are required on the relationships between the values of system variables; such constraints are known as control laws. Safety-related control laws specify those relationships between system variables that would lead to non-hazardous system states (Leveson, 2004), for example, while handling raw meat, employees on the factory floor must wear a different set of uniform. Safe changes and adaptations in a complex system will only be assured if control processes enforce such constraints.

It is quite important that constraints on behaviour are reflected in the company policy and standards. There has been a change in the style of management from management by oversight to management by insight (Leveson, 2004). This has been a positive change as there are now greater levels of feedback control exerted over the lower levels and a change from prescriptive management control to management by objectives. The objectives are interpreted and satisfied according to the local context (Leveson, 2004; Rasmussen, 1997). Management are now delegating decisions to various employees across the lower levels of hierarchy. This requires an explicit formulation of the value criteria to be used and effectively communicating the values down the systemic levels. Although generic instructions and guidance are required from the level above in order to avoid accidents, execution of the guidance can be left to lower levels (Leveson, 2004).

6.2. Understanding flaws in the control structures that lead to outbreaks

Section 6 mentioned that accidents were caused by inadequate control where the control loop creates dysfunctional interactions in the process. Hence, by understanding the flaws in the control structures (development and operations), the process that leads to accidents can be understood (Leveson, 2004). These flaws have been classified by Leveson (2004) to make it easier to identify the factors involved in an accident during accident analysis or while designing models to prevent accidents.

There are multiple control loops within a complex system and each control loop can contribute to inadequate control. At any point in a control loop where humans or organisations are involved, the context in which decision are made may vary and hence need to be evaluated in order to analyse the behaviour shaping mechanisms. This helps in understanding how and why unsafe decisions were made (Leveson, 2004). Accidents may also occur due to basic component failures such as inadequate constraints on the process; inadequate and faulty designs; lack of feedback and correspondence between individual component capacity (including humans) and task requirements; environmental disturbances; inadequate maintenance; and physical degradation (of machines or the entire system) over time (Leveson, 2004). In order to avoid component failure, it is important to make the components resistant to internal and external influences that are detrimental to the system dynamics. Although management by insight is a better approach, there must be safety margins within which a system should operate. Another method to avoid component failure is by having operational controls in order to ensure that the component operates within its designed environment and through periodic, effective and thorough inspections. The STAMP model helps identify the reasons behind component failures (Leveson, 2004) and this could be very helpful as it would help prevent future whole system failures.

Figure 4 illustrates an example of a STAMP model of the UK food system. This model was developed based on information gathered from various sources such as government documents (e.g., Miller, 2014), stakeholder websites (e.g., Food Standards Agency and the UK government websites) and academic literature (Nayak & Waterson, 2016; Pennington, 2003). One of the researchers constructed a draft version of the UK food system as seen in Table 3 in Section 5.1. Following this, a STAMP model was constructed to fit the UK food system. Actors who resided at each of the control structure levels were identified and the control and feedback loops existing between different control structure levels were mapped. The model was reviewed by the other researcher who is experienced in constructing STAMP models.

Using system theory to model complex organisations involves dividing the entire complex system into various hierarchical systemic levels (Leveson, 2004; Rasmussen, 1997). Figure 2 (in this article), as well as multiple Accimap analyses of global food poisoning outbreaks (Nayak, 2018) highlight that food systems across the world have multiple hierarchical complex socio-technical systemic levels. As seen from Figure 6, the STAMP model can also be applied to a food system. The advantage of this model over the model designed by Rasmussen and Svedung in 2000 (Rasmussen & Svedung, 2000) is that the former divides the development and operations stages, therefore giving a more detailed analysis. As seen in Figure 4, there are two hierarchical control structures: (1) system development on the left and (2) system operation on the right with interactions between them. A food manufacturer, for example, would only have development under its immediate control, however, safety involves development (growing, manufacturing, processing, packaging and inspections and regulations related to these) as well as operations (import, export, transport and inspections and regulations related to these) of food manufacturing.

Figure 4 establishes that although the links between various systemic levels can be established using existing documents, further studies need to be carried out to further elaborate on and analyse the control and feedback structures of the food system across the world. The outcomes of such a study would help identify and address potential and existing flaws in the control and feedback structures of food systems at a global scale, learn from well-designed and well-structured food systems and develop proactive and systemic-level interventions to improve global food safety.

Figure 4 about here

7. Conclusions, limitations and future work

Global interconnected food systems play a major role in the modern society to harness a multiplicity of complex supply chains. Globalisation of food networks has introduced an unprecedented level of complexity to the global food system; this has not only brought significant benefits, but also systemic risks. Due to the interconnectivity across systemic levels, disruptions at one point in the system would lead to reverberations in the form of economic, social and political impacts throughout the entire system (Maynard, 2015). Hence, understanding the entire food system is the need of the hour to enhance global resilience to systemic food system failures. Globalisation of the food system initiated a change in the food safety domain. New techniques were and are still being developed to further the reach of the food system globally.

As seen in above sections, the characteristics of the global food system resonate with the characteristics of complex systems. Therefore, it is necessary to use systems analysis methods to understand the interactions between the components of the food system. With the use of STAMP, leading indicators can be identified (Leveson, 2015) and this would help identify the potential for a food poisoning outbreak before it occurs. STAMP can be used to identify food system specific leading indicators which would then help in designing appropriate and specific models. Similar to accidents in other high-risk industries, food poisoning outbreaks also have warning signs before they occur. Before an outbreak occurs, ‘weak signals’ are only viewed as noise (Leveson, 2015).

Systems analysis models such as STAMP have the ability to tackle limitations of event chain models. It not only has the ability to address single component failures but also can analyse interactions among various components in the complex food system (Leveson, 2004). Such models also adopt a whole system approach where they consider the entire safety control structure to determine reasons behind inefficiencies of existing constraints on safe behaviour. It is quite difficult to analyse the performance of complex systems, especially when looking at the 'whole system' (Cilliers, 1998; Leveson, 2004). Currently, individual components are analysed and any inadequacies are addressed accordingly. Safety metrics could be identified by the use of system accident models and basic concepts of safety constraints. Determining adequacy of control over constraints, evaluating potential design errors, assessing the organisational structure and human behaviour leading to hazards, detecting errors in the developmental and operational environments and identifying maladaptive changes over time (Leveson, 2004) could be few of the causal factors that could be identified and analysed using this model.

One of the limitations of STAMP is that it does not specify an accident investigation process. Since variations exist among investigation reports, if food outbreaks alone are used to develop a control process model, the model might be biased towards the report used to analyse accidents and outbreaks (Stoop & Benner, 2015). Identifying all stakeholders relevant to the food system and conducting interviews and focus group discussions with them, in addition to analysing outbreak reports, would help tackle this limitation. This would permit gathering all the possible perspectives and factors that play a role in providing food safe for consumption at the micro and macro-levels in the food system. It is important to note that it is not possible to use a single systems analysis method in isolation to help identify key insights for interventions, and hence, there is a need to develop new methods or further adapt existing methods to understand dynamic adaptive systems (Thatcher *et al.,* 2019).

Figure 4 illustrates the influence of external factors (macro-environment) on the micro-environment of food businesses. Regulatory bodies, national policies and politics impact the performance of the food industry as the former play a critical role in drafting and enforcing all food-related regulations (such as safety, production, import and export). Any anticipated change in regulations leads to confusion and panic among stakeholders – such uncertainty often sets the food system up to fail. An example of the influence of uncertainty on food businesses and food safety due to external factors has been highlighted in Section 6.1.1. The delay in implementing the new regulations in the US led to confusion and panic, eventually leading to a food poisoning outbreak.

This past event should serve as an important learning point as there exists a risk of a similar such occurrence during and after Brexit – at the time of writing this article, it is a well-known fact that the UK is struggling to reach a deal with the European Union (EU) regarding trade policies after the UK leaves the EU in 2019. This uncertainty has already led to the media speculating possible food safety risks and the dangers to consumer and stakeholder safety should the UK government not be successful in reaching a favourable trade agreement with the EU (Rees-Mogg, 2018; Rayner, 2017, 2018). Hence, it is the need of the hour to further investigate methods of reducing negative external influences on the food system.

While every country across the world has its own prescribed food safety system, a vast majority of them engage extensively in the export and import of food products. This results in food systems being composed of interrelated subsystems, each with its own hierarchical structure, all of which lead to the lowest level within an elementary subsystem (Simon, 1962; Thatcher *et al.*, 2019). Further evidence across multiple disciplines characterise these multiple interacting systems in the form of nested hierarchies with smaller, less complex systems embedded within larger, more complex systems (Carayon *et al.*, 2015; Clegg *et al.*, 2017; Gunderson & Holling, 2002; Thatcher *et al.*, 2019; Thatcher & Yeow, 2016). Larger systems provide the broader framework which helps understand smaller systems, while smaller systems provide the functional elements that enable larger systems achieve stability and function in a specific manner.

As food travels long distances in the modern world, a global model is required to help identify factors that occur at any point in the global food system. Conducting the above-mentioned process at a global scale would help develop a "prototypical food system" model – this would provide a global benchmark and a backbone structure upon which country-specific food systems could be designed. Being able to look at the whole picture, identify emerging control/constraint failures and learn from high performing food system models would not only benefit all the stakeholders of the global food industry, but also protect consumers from food poisoning related ill health and deaths.

Therefore, it is the need of the hour to adopt a proactive approach and study food systems at micro and macro-levels globally and the interactions between various factors within and between food systems. This would help in the development of a truly global model that would have the ability to identify food safety related issues across the food system.

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Table 1: Development of the food safety law in the UK

Regulation/Act/Development	Year of enactment	Domain	Purpose	Drawback(s)	Primary target population protection
Assisa Panis et Cervisiae (Assize of Bread and Ale	1266	Food adulteration	Medieval English Law to regulate the price, weight and quality of manufactured beer and bread.	Did not regulate the quality of bread and beer.	Consumers
Regulation of quality standards conducted by guilds (corporations of craftsmen).	Middle Ages	Food adulteration	Market protection from adulteration.	As guilds were only present in towns and cities, adulteration outside these areas was unregulated.	Market/Internal stakeholders
		Food adulteration		Consumer protection (if any) was pure coincidental.	
The Treatise on Adulterations of Food and Culinary Poisons	1820	Food adulteration	Book containing list of all the possible food adulterants and adulterers.		Consumers
The Adulteration of Food and Drugs Act	1860 (revised in 1872)	Food adulteration	Provision for the appointment of public analysts and regulations against food adulteration		Consumers
Sale of Food and Drugs Act	1875	Food adulteration	Regulation of sale of food and drugs.		Consumers
Society of Public Analysts	1874	Food adulteration	Official society consisting of public analysts		
The Milk and Dairies Act	1914	Food safety	Production and sale of clean and safe milk for human consumption		Consumers

Regulation/Act/Development	Year of enactment	Domain	Purpose	Drawback(s)	Primary target population protection
Food and Drugs (Adulterations) Act	1928	Food adulteration	Consolidation of the Sale of Food and Drugs Act.		Consumers
Food and Drugs Act	1938	Falsifying information	Introduction of penalties for false or misleading labels and advertising.	Greater focus on falsifying information and not enough focus on food safety and food adulteration.	Consumers
Defence (Sale of Food) Regulations	1943	Food safety and food adulteration	Crisis plan to ensure efficient use of available food. Detailed information regarding the minimum requirements for labelling.	No mention about the need to provide quantities of ingredients.	Consumers
Medicines Act	1968	Food and medicine safety and adulteration	Legalisation related to food and control of medicines for human and veterinary use.		Consumers
Trade Descriptions Act	1968	Falsifying information	Prohibition of false and misleading advertisement and product claims, false indication of the price of goods and the false use of royal awards.	Focus only on prevention of falsifying information	Consumers
Food Act	1984	Intention to cover food safety, food adulteration and falsifying information	Consolidated previous food safety provisions	Failed to impose satisfactory standards within the food industry and was not thorough enough. Hazard and	Consumers

Regulation/Act/Development	Year of enactment	Domain	Purpose	Drawback(s)	Primary target population protection
				safety were not a part of this Act.	
Food Safety Act	1990	Food safety, food quality and trading standards	Provides the framework within which all modern food legislation is written.		Consumers
General Food Law Regulation (Regulation (EC) No 178/2002)	2002	New laws on safety, traceability, withdrawal and recall requirements			
General Food Regulation	2004	Further modified the definition of food as originally in the Food Safety Act 1990			
EU Hygiene Regulations No 852/2004, 853/2004, 854/2004, 2073/2005 and 2075/2005, 834/2007	2006	Food safety for different foods and hazard prevention within the food industry	Implementation of the Hazard Analysis and Critical Control Points (HACCP) system by the European Union		Internal and external stakeholders
Official Feed and Food Controls (England) Regulations 2009	2009	Food safety, agricultural policy, veterinary and phytosanitary measures	Protection of public health and measures relating to feed produced for or fed to food producing animals		Internal and external stakeholders
Regulation (EU) No 1169/2011, 1924/2006, 609/2013, 1829/2003, 1830/2003, 1308/2013	2003-2013	Food labelling and food information, health and identification marks	EU food law to harmonize labelling of labelling of food placed on the EU market.	Changes would need to be made once the UK withdraws from the European Union	Consumers
Food Safety and Hygiene (England) Regulations 2013	2013	Certain provisions of Regulation 178/2002	Food safety, food hygiene, bulk transport by sea of		Internal stakeholders

Regulation/Act/Development	Year of enactment	Domain	Purpose	Drawback(s)	Primary target population protection
			liquid oils, fats and raw sugar		
Regulation (EU) 2015/2283	2018	Novel foods	Import and manufacture of new and innovative foods in the EU market		Internal stakeholders and consumers

Table 2: Summary of the characteristics of a complex system

Characteristics of complex systems		
Purpose	Defines the system and provides it with integrity to hold it together Property of the entire system History of a complex system leads to the constant evolution of the purpose of the system and its behaviours	
Efficiency	Complex systems have efficient, short-range and dynamic interactions between elements It is essential that all the interacting elements are present for efficient functioning of a complex system	
Order of arrangement	The order in which in which the parts of a complex system are arranged affects the performance of the system Rearranging elements would break the links between interacting elements leading to chaos	
Communication	Forms the basis of a social system There are 3 directions of communication flow:	
	Top-down	Direction of communication is from the superior to subordinates Determines how individuals identify with the organisation
	Horizontal	Involves passing of information between people at the same hierarchical level One of the most difficult forms of communication and requires the right amount of information to be passed to avoid inadequate or over-communication
	(Bottom-up) Feedback	Feedback helps inform a system about its performance and behaviour Feedback can be of two types – positive and negative. Both are necessary to help in the continuous development of the system.
Holism	Holism is about looking at the bigger picture and not just addressing the local issues in the subsystem	

Characteristics of complex systems	
	This approach does not just look for simple solutions that address a specific problem, but looks at other linked factors and problems that could arise in the future
Emergence	Interactions in a complex system leads to the emergence of patterns that define the behaviour of the components/agents within the system and the behaviour of the entire system
Interdependence	Open systems have parts that are related to its whole and to its environment – this is known as interdependence A change in any part of the system will affect the entire system
Law of requisite variety	Too much variety in a complex system can destroy the entire system A system would only be able to survive as long as the range of responses it marshals successfully matches the range of situations confronting it

Table 3: Components of the food system across various systemic levels in the UK and the USA

Adapted from Nayak and Waterson (2016); and Keenan *et al.*, (2015).

Systemic level	**Component**		**Role played in the food system**
	United Kingdom	*United States of America*	
External	Media, Market forces, Societal values and priorities, Historic events and Global politics		Conveying new regulations and budget allocations to consumers as well as manufacturers; publicizing wrong-doings and breaches of regulation. Media are essentially the link between consumers and manufacturers, as well as consumers and the government.
Government	European commission, Council of Ministers and European Parliament	United States Congress	Initiation and approval of new laws.
	UK Parliament		Implementation of regulations in the national food law; making decisions over how to implement directives into the country's food regulations; deciding on budget allocation.
	Food Standards Agency	Food and Drug Administration (FDA) and the Food Safety Inspection Service (FSIS)	Protection of public health in relation to food; helping local councils understand food regulations; making decisions on how to split the allocated budget.
	Local councils	State and local agencies (health and agriculture departments)	Ensuring that the regulations are actually implemented; inspecting food businesses; helping food businesses establish and better themselves.
Organisational/Workplace	Management		Conveying information from food inspectors to the shop-floor employees; ensuring that food manufactured is safe for consumption; ensuring that food safety and hygiene regulations are complied with; administration work; bringing in orders for the food business; hiring contractors (cleaning, temporary employees, full-time employees, transportation); ensuring that employees have the required training.
	Shop-floor employees		Working on the shop floor; following training provided diligently; ensuring that they follow protocols; making sure that they know what they are doing; production of food safe for

Systemic level	**Component** *United Kingdom*	 *United States of America*	**Role played in the food system**
			consumption; efficient cleaning of shop-floor; transporting food; storing and organizing food in stores .

Table 4: Common gaps across food safety systems in the UK, US and Europe

System level (based on the Onion model)	Example issues within the food safety domain	Current focus	Gaps in knowledge and the underexploited aspects
Wider physical and virtual work environment	Food poisoning outbreaks investigations, food safety related issues	Root cause analysis, audits and inspections by food safety inspectors	Adopting proactive measures such as understanding the food business' work environment and using these to support wider organisational learning. Using methods of incident investigation (e.g., FRAM) that are commonly used in other industries and take into account interactions between a range of systemic factors that lead to food poisoning outbreaks.
Personal physical and virtual workspace	Safety culture	Survey instruments, benchmarking, microbial testing, rapid testing techniques	Qualitative methods provide richer assessments of the safety culture of food businesses; multiple methods should be used to assess the safety culture (e.g., interviews with staff, questionnaires, workshops)
Tasks	Demands, decision making, workload, situational awareness	Focus on mistakes and blame culture	Use of cognitive work analysis to get deeper insights into how complex tasks and team work are accomplished. Understanding antecedents (early warning, near misses) that lead to negative behaviours.
People	Team work, temporary agency workers	Team training and making every employee understand company protocols and the health and safety protocols	Understanding staff better to help them achieve job satisfaction, ensuring that the workload is no too much and making sure that the team is able to achieve everything together (socio-cultural aspects of team work – trust and organisational commitment).
Technology	Temperature control thermometers, rapid hygiene testing devices	Usability, reliability and validity	Understanding the impact of technology on working practice

System level (based on the Onion model)	Example issues within the food safety domain	Current focus	Gaps in knowledge and the underexploited aspects
Tools	Hazard Analysis and Critical Control Points (HACCP) used globally; Safer Food Better Business (SFBB) and Food Hygiene Rating Scheme (FHRS) in the UK; the FDA-iRisk® and Virtual Deli in the US; the Rapid Alert System for Food and Feed (RASFF) used in the European Union.	Compliance, standardisation	Involving stakeholders while designing the implementation process in order to provide appropriate local solutions. Understanding that tools are complex interventions that depend on other system attributes (e.g., communication, culture)

Figure 1: Socio-Technical Framework of the Functioning of the Food System

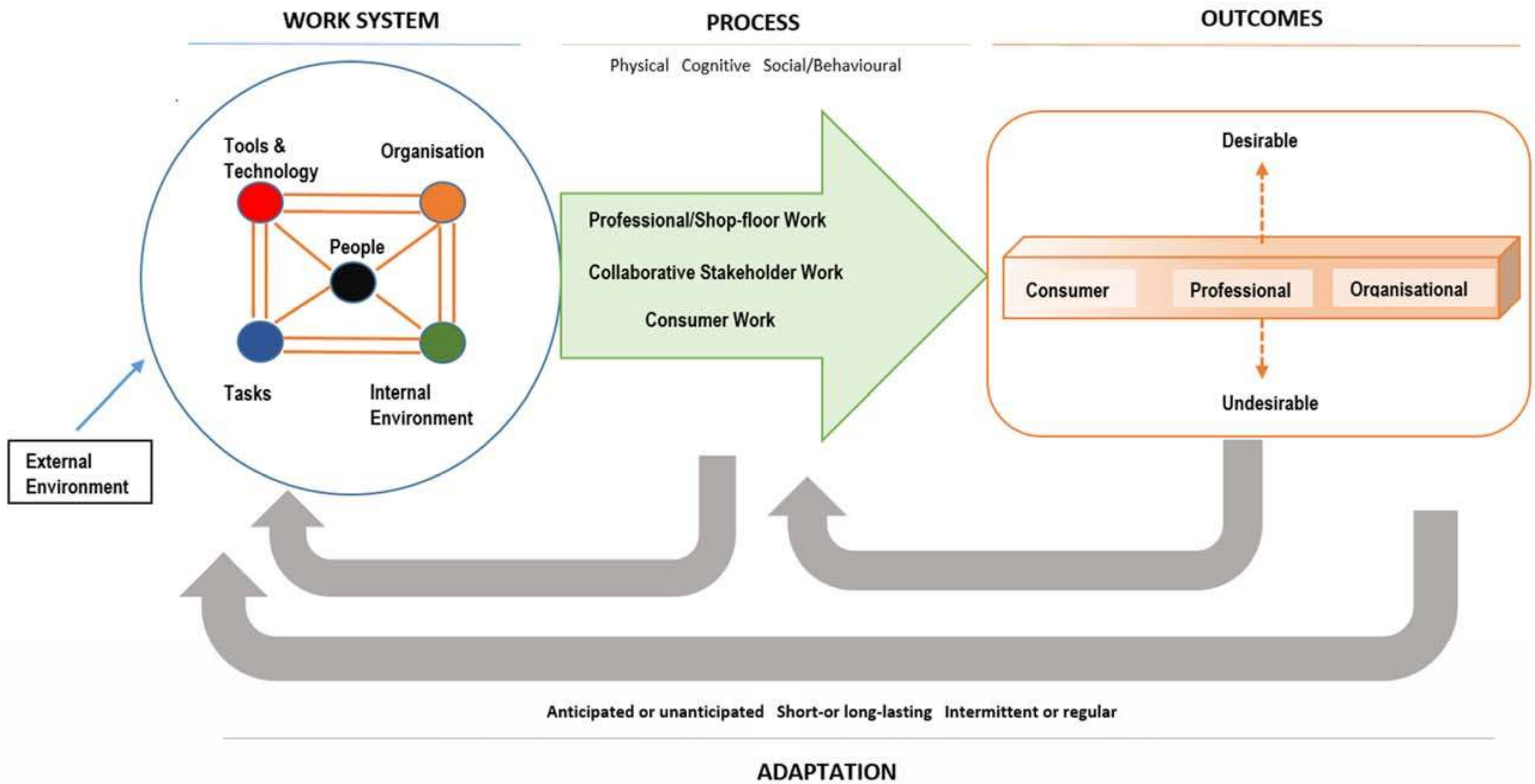

Figure 2: Boundaries of acceptable behaviour

Adapted from Rasmussen (1997)

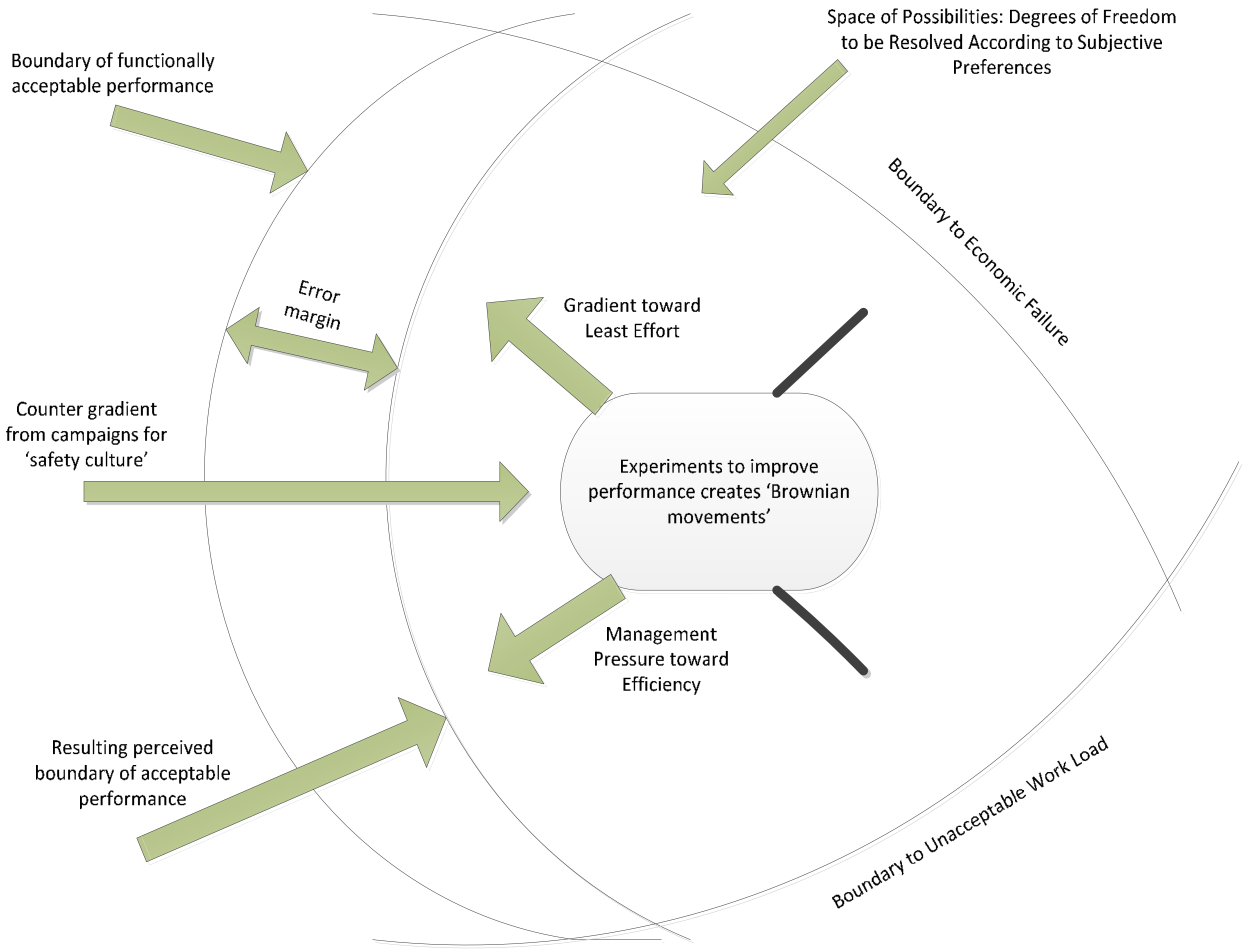

Figure 3: General form of a STAMP model

Adapted from Leveson (2004) p. 257.

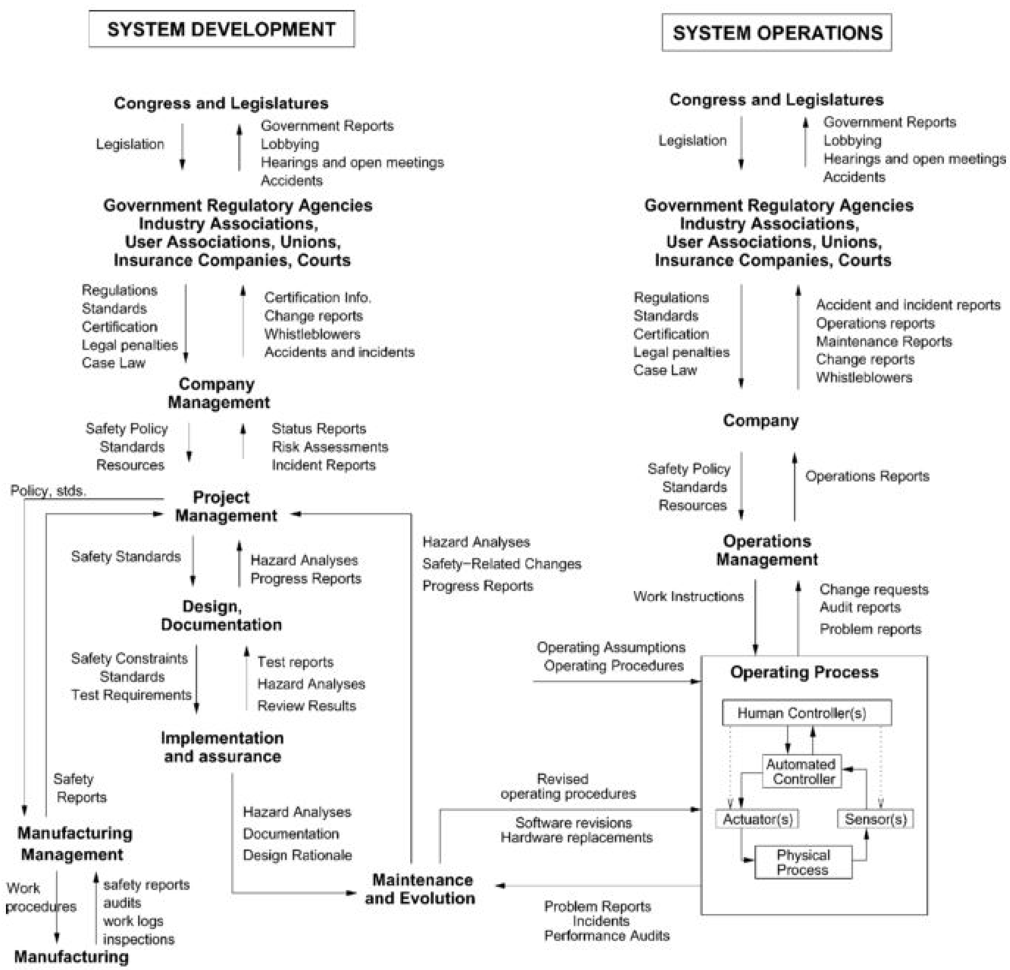

Figure 4: An example STAMP model of the control and feedback structure of the UK food system